BIOCHEMICAL METHANE POTENTIAL OF CASHEW PEDUNCLE WASTE DISCARDED IN THE FIELD

POTENCIAL BIOQUÍMICO DE METANO DO PEDÚNCULO DE CAJU DESPERDIÇADO NO CAMPO

POTENCIAL BIOQUÍMICO DE METANO DEL PEDÚNCULO DE ANACARDO DESECHADO EN EL CAMPO

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ABSTRACT

The significant increase in demand for renewable energy sources, together with the commitments made by countries to reduce greenhouse gas emissions, has generated growing interest in the energy use of agro-industrial residues. This search for sustainable alternatives has led to greater consideration of how waste generated in agricultural and industrial production can be transformed into energy, thus contributing to a cleaner and more efficient energy matrix. Within the specific context of cashew farming, an agricultural practice developed in the northeastern region of Brazil, it is observed that the waste of the cashew apple (peduncle)—a part of the plant often discarded in the field—contrasts significantly with the fact that this same peduncle has highly relevant organic content. This discarded material can be converted into biogas through a process known as anaerobic digestion. This type of conversion not only offers environmental advantages but also presents benefits in energy generation and economic contributions that can be quite significant. The research adopts a qualitative and quantitative (hybrid) approach. The following research procedures were employed: bibliographic research, documentary research, and experimental and laboratory research. The general objective of this study is to evaluate the methanogenic yield of cashew peduncles wasted in the field through a Biochemical Methane Potential assay, in order to verify their feasibility as a substrate for biogas production within the environmental, energy, and socioeconomic context of Brazilian cashew farming. The research met its proposed objectives by demonstrating that the cashew peduncle has technical viability for biogas generation, representing an alternative that can increase rural producers' income and help meet national policies for reducing greenhouse gas emissions.

Keywords: Biogas. Cashew Peduncle. Methanogenic Yield.

RESUMO

O aumento significativo na demanda por fontes de energia que sejam renováveis, junto com os compromissos assumidos pelos países em relação à redução das emissões de gases

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que contribuem para o efeito estufa, tem gerado um interesse crescente na utilização energética de resíduos provenientes da agroindústria. Essa busca por alternativas sustentáveis tem levado a uma maior consideração sobre como os resíduos gerados na produção agrícola e industrial podem ser transformados em energia, contribuindo assim para uma matriz energética mais limpa e eficiente. Dentro do contexto específico da cajucultura, que é uma prática agrícola desenvolvida na região nordestina do Brasil, observa-se que o desperdício do pedúnculo, uma parte da planta que muitas vezes é descartada no campo, contrasta de maneira significativa com o fato de que esse mesmo pedúnculo possui um conteúdo orgânico extremamente relevante. Esse material que é desprezado pode ser transformado em biogás através de um processo conhecido como digestão anaeróbia. Esse tipo de conversão não apenas oferece vantagens para o meio ambiente, mas também apresenta benefícios na geração de energia e contribuições econômicas que podem ser bastante significativas. A pesquisa adota abordagem qualitativa e quantitativa (híbrida). Foram empregados os seguintes procedimentos de pesquisa: a pesquisa bibliográfica, a pesquisa documental e a pesquisa experimental e laboratorial. O objetivo Geral deste estudo é avaliar o rendimento metanogênico do pedúnculo de caju desperdiçado no campo, por meio de ensaio de Potencial Bioquímico de Metano, a fim de verificar sua viabilidade como substrato para produção de biogás no contexto ambiental, energético e socioeconômico da cajucultura brasileira. A pesquisa atendeu aos objetivos propostos ao mostrar que o pedúnculo de caju possui viabilidade técnica para a geração de biogás, sendo uma alternativa que pode aumentar a renda do produtor rural e ajudar no atendimento às políticas nacionais de redução das emissões de gases de efeito estufa.

Palavras-chave: Biogás. Pedúnculo de Caju. Rendimento Metanogênico.

RESUMEN

El aumento significativo en la demanda de fuentes de energía renovables, junto con los compromisos asumidos por los países en relación con la reducción de las emisiones de gases de efecto invernadero, ha generado un creciente interés en el aprovechamiento energético de residuos provenientes de la agroindustria. Esta búsqueda de alternativas sostenibles ha llevado a una mayor consideración sobre cómo los residuos generados en la producción agrícola e industrial pueden transformarse en energía, contribuyendo así a una matriz energética más limpia y eficiente. Dentro del contexto específico de la cajucultura, una práctica agrícola desarrollada en la región nordeste de Brasil, se observa que el desperdicio del pedúnculo del anacardo—una parte de la planta que a menudo se descarta en el campo—contrasta significativamente con el hecho de que este mismo pedúnculo posee un contenido orgánico altamente relevante. Este material descartado puede transformarse en biogás mediante un proceso conocido como digestión anaerobia. Este tipo de conversión no solo ofrece ventajas ambientales, sino que también presenta beneficios en la generación de energía y contribuciones económicas que pueden ser bastante significativas. La investigación adopta un enfoque cualitativo y cuantitativo (híbrido). Se emplearon los siguientes procedimientos de investigación: investigación bibliográfica, investigación documental e investigación experimental y de laboratorio. El objetivo general de este estudio es evaluar el rendimiento metanogénico del pedúnculo de anacardo desperdiciado en el campo, mediante un ensayo de Potencial Bioquímico de Metano, con el fin de verificar su viabilidad como sustrato para la producción de biogás en el contexto ambiental, energético y socioeconómico de la cajucultura brasileña. La investigación cumplió con los objetivos propuestos al demostrar que el pedúnculo de anacardo tiene viabilidad técnica para la generación de biogás, constituyendo una alternativa que puede aumentar los ingresos del productor rural y contribuir al cumplimiento de las políticas nacionales de reducción de emisiones de gases de efecto invernadero.

Palabras clave: Biogás. Pedúnculo de Anacardo. Rendimiento Metanogénico.

1 INTRODUCTION

The transition to energy matrices with lower carbon intensity has occupied a central position in the climate and energy agendas, both internationally and nationally. In Brazil, the strengthening of biogas and biomethane is part of this movement, especially due to the wide availability of agricultural and agro-industrial residues with aptitude for energy conversion by anaerobic digestion. At the same time, commitments made in the field of emission mitigation and recent regulatory instruments have stimulated the valorization of organic waste as a strategy associated with the reduction of greenhouse gases, the promotion of the circular economy and the diversification of the energy matrix.

In this scenario, northeastern cashew farming presents a relevant contradiction. Although it has significant economic and social importance, a large part of the cashew stalk is still wasted in the field, especially when the exploitation is concentrated in the nut. Considering the high fraction of carbohydrates present in this material, its use for biogas production can represent a technological alternative in line with current environmental guidelines and, at the same time, contribute to the recomposition of producers' income. Evaluating the methanogenic yield of this waste becomes, therefore, a necessary step to support technical and economic decisions about its insertion in renewable energy generation systems.

The research adopts a qualitative and quantitative (hybrid) approach. The following research procedures were used: bibliographic research, documentary research and experimental and laboratory research. The general objective of this study is to evaluate the methanogenic yield of the cashew stalk wasted in the field, by means of a Methane Biochemical Potential assay, in order to verify its viability as a substrate for biogas production in the environmental, energetic and socioeconomic context of Brazilian cashew farming. The specific objectives are as follows: to analyze the framework for the energy use of cashew stalks in the light of the environmental scenario, public policies and national regulatory instruments aimed at biogas, biomethane and the mitigation of greenhouse gas emissions; to examine the biochemical foundations of anaerobic digestion applicable to substrates with high carbohydrate content, relating the physicochemical characteristics of the cashew stalk to its methanogenic performance under controlled experimental conditions; to discuss how the energy conversion of cashew stalks can contribute to the diversification of revenues and to the economic balance of cashew farming, especially in the face of structural challenges that affect productive activity.

The article in question consists of four sections. The first part is the Introduction, where the theme of the research is contextualized and its relevance is explained. Next, the

Methodology section presents the procedures that were used for the collection and analysis of experimental data. The third section brings the Theoretical Foundation, which conceptually supports the research. Finally, the Final Considerations are presented, in which the most significant results and their implications are discussed.

2 METHODOLOGY

The research adopts a qualitative and quantitative (hybrid) approach. The qualitative aspect refers to the consultations carried out in the following groups of scientific works: scientific articles, dissertations, official documents, laws, international and national documents and books. As for the quantitative aspect, it is justified because part of the study is based on the objective measurement of the volume of methane generated from the anaerobic digestion of the cashew stalk wasted in the field, through a test of Biochemical Potential of Methane carried out in an accredited laboratory according to ABNT NBR ISO/IEC 17025:2017. The production of numerical data, obtained under controlled and standardized conditions at the Biogas Laboratory of CIBiogás, allows the evaluation of the performance of the substrate based on physicochemical and biochemical parameters, ensuring analytical rigor and reproducibility, in line with technical references of anaerobic digestion and with national and international guidelines related to emission mitigation and energy transition (Proetti, 2018).

As for nature, it is an applied research, as it seeks to generate knowledge directed to the energy use of an agro-industrial residue widely available in northeastern cashew farming. By investigating the conversion of the stalk into biogas, the study dialogues with concrete demands of the productive sector, with the socioeconomic challenges of the activity and with the regulatory framework focused on biofuels, decarbonization and the valorization of organic waste. The focus is on proposing a technically viable alternative that contributes to the diversification of the producer's income and to the reduction of emissions associated with inadequate waste management (Severino, 2017).

The following research procedures were used: bibliographic research, documentary research and experimental and laboratory research (Cellard, 2008; Rodrigues Júnior, 2011; Cavalcante; Oliveira, 2020). It is especially noteworthy the experimental and laboratory research in which samples of cashew stalks were collected directly in the field, followed by forwarding them to the Biogas Laboratory of CIBiogás, an institution with recognized technical competence and national accreditation for the testing of Biochemical Potential of Methane. In a controlled environment, standardized protocols were applied to determine the methanogenic yield, ensuring control of variables, traceability of results and compliance with current technical standards. It is, therefore, an experiment conducted under rigorously monitored conditions, with a view to obtaining reliable data on the conversion of waste into biogas.

3 THEORETICAL FOUNDATION

3.1 ENVIRONMENTAL, ENERGY AND REGULATORY CONTEXT OF BIOGAS AND BIOMETHANE IN BRAZIL

Climate change is one of the main global challenges of the twenty-first century, imposing increasing pressures on productive, energy, and environmental systems (IPCC, 2019; 2021). The need to reduce greenhouse gas emissions, while maintaining energy security and economic competitiveness, has driven the search for technological solutions capable of reconciling these objectives (IEA, 2022). In this context, the energy transition assumes a strategic role, covering not only the replacement of fossil sources with renewable sources, but also the adoption of more efficient production models integrated with the logic of the circular economy (UNEP, 2020).

The energy use of organic waste is part of this scenario as an alternative that combines environmental management and energy generation. Residual biomass, from agricultural, agro-industrial, urban, and sanitation activities, represents a relevant environmental liability when inadequately managed, but it can be converted into an energy asset, through consolidated biological processes, such as anaerobic digestion (CIBIOGÁS, 2023).

From this process, it is possible to produce biogas and, after additional purification steps, transform it into biomethane, a renewable fuel with the potential to replace natural gas of fossil origin in various applications (ABIOGÁS, 2022). However, the adoption of these technologies requires careful technical analysis, since the environmental and energy benefits associated with biogas and biomethane are not automatic. Aspects related to the origin of the waste, the efficiency of the process, the control of emissions, and the regulatory framework directly influence the feasibility and effectiveness of the projects (IEA, 2020). Thus, this topic aims to contextualize the role of biogas and biomethane in Brazil, addressing the environmental fundamentals, climate commitments, regulatory framework, production potential and the main limitations for the expansion of these solutions in the country.

3.1.1 Residual biomass and emission mitigation

Residual biomass comprises organic materials generated as by-products of agricultural, livestock, industrial, urban, and sanitation activities, such as animal waste, agro-industrial waste, sludge from sewage treatment plants, and the organic fraction of urban solid waste (MCTI 2021). Traditionally, these materials have been associated with environmental challenges, including diffuse methane emissions, soil and water contamination, and health impacts (SEEG, 2023). The energy use of this biomass, through anaerobic digestion, makes it possible to transform the organic load present in the waste into biogas, while simultaneously reducing the polluting potential of the treated material (CIBIOGÁS, 2023). From a climate point of view, this technological route has relevant advantages, especially due to the capture and use of methane that would otherwise be released directly into the atmosphere during the uncontrolled decomposition of waste (IEA, 2020).

It is important to note, however, that biomass should not be automatically considered carbon neutral. The environmental performance of waste energy use depends on factors such as collection logistics, efficiency of digestion systems, control of fugitive emissions, and destination of the digestate (IPCC, 2019; 2021). Thus, the assessment of the climate benefits associated with biogas and biomethane must be carried out based on life cycle analyses, considering all stages of the process (ISO, 2018).

3.1.2 Brazil's climate policies and commitments

International climate governance was consolidated from the United Nations Framework Convention on Climate Change, established in 1992, to which Brazil is a signatory, with the objective of stabilizing greenhouse gas concentrations in the atmosphere (UNFCCC, 1992). In 1997, the Kyoto Protocol represented an advance by establishing mandatory emission reduction targets for developed countries, even though developing countries, such as Brazil, had not made quantitative commitments at that time (UNFCCC, 1997).

In 2015, the Paris Agreement consolidated a new paradigm by involving all signatory countries in voluntary mitigation commitments, expressed through Nationally Determined Contributions (UNFCCC, 2015). Under this agreement, Brazil presented its NDC, revised in 2023, establishing greenhouse gas emission reduction targets of 48.4% by 2025 and 53.1% by 2030, compared to 2005 levels, in addition to the commitment to achieve climate neutrality by 2050 (Brasil, 2023). At the domestic level, the National Policy on Climate Change, instituted by Law No. 12,187/2009, establishes principles and guidelines for the implementation of these goals, serving as a basis for the formulation of sectoral plans and economic instruments aimed at the decarbonization of the economy (Brasil, 2009).

3.1.3 Biogas and biomethane in the context of the energy transition

Biogas is the product of the anaerobic digestion of organic matter, composed mainly of methane and carbon dioxide, as well as traces of other gases (CIBIOGÁS, 2023). This biogas can be used directly to generate thermal or electrical energy, contributing to the reduction of fossil fuel consumption (IEA, 2020). When subjected to purification processes, biogas can be converted into biomethane, with a high methane content and energy properties similar to those of natural gas (ABIOGÁS, 2022). In the context of the energy transition, biogas and biomethane occupy a strategic position because they integrate waste management, energy generation, and emission mitigation, offering continuous and predictable energy production (IEA, 2022).

3.1.4 Government strategies and programs

The development of the biogas and biomethane sector in Brazil is influenced by different public policies and legal instruments. The National Policy on Climate Change (Law No. 12,187/2009), which establishes guidelines for the reduction of greenhouse gas emissions (Brasil, 2009), stands out. Another relevant instrument is the National Biofuels Policy (RenovaBio), instituted by Law No. 13,576/2017, which created the carbon credit market, with the potential to encourage the use of biogas and biomethane as mitigation vectors (Brasil, 2017). In addition, federal strategies aimed at reducing methane emissions have been structured, especially in the urban solid waste, sanitation, and agriculture sectors (MMA, 2022).

Law No. 14,993/2024 establishes the National Sustainable Aviation Fuel Program (ProBioQAV), the National Green Diesel Program (PNDV) and the National Program for the Decarbonization of Natural Gas Producers and Importers and Biomethane Incentives, known as the Fuel of the Future Law, which represents a relevant regulatory framework for the consolidation of biogas and, above all, biomethane in Brazil. This law explicitly integrates gaseous renewable fuels into the national strategy for the decarbonisation of the transport and fuel sector, recognising biomethane as a direct substitute for natural gas of fossil origin and as a strategic vector of the energy transition. By establishing guidelines for reducing the carbon intensity of fuels and expanding the scope of decarbonization policies, the law creates institutional conditions favorable to the expansion of the biomethane market, reducing regulatory uncertainties and encouraging the signing of long-term contracts, essential for the economic viability of biogas projects.

In addition, by aligning with existing instruments, such as RenovaBio, the Fuel of the Future Law contributes to the environmental valorization of the reduction of emissions, especially methane from organic waste, strengthening business models based on the circular economy and boosting the energy use of residual biomass in the country (Brasil, 2024).

3.1.5 Potential for biogas and biomethane production in Brazil

Reports from the International Center for Renewable Energy — Biogas (CIBiogás) and the Brazilian Association of Biogas and Biomethane (ABIOGÁS) inform that Brazil has high technical potential for the production of biogas and biomethane from organic waste, considering agricultural, agro-industrial, urban, and sanitation chains (CIBIOGÁS, 2023; ABIOGÁS, 2022). Widely publicized estimates point to a theoretical potential for biomethane production in the order of tens of millions of cubic meters per day. The technical potential for biogas production is estimated at about 84.6 billion normal cubic meters per year (Nm³/year), considering organic waste available in different sectors of the economy.

In the short term, about 10.8 billion Nm³/year of this total can be harnessed with existing technologies.(CIBIOGÁS, 2023). The installed capacity is currently 4.7 billion Nm³/year, showing that only a small portion of the potential already mapped is actually explored. (CIBIOGÁS, 2024).

3.1.6 Potential of Biogas and Biomethane according to ABiogás

Biogas has a great energy potential, especially in regions with high biomass production, such as rural and industrial areas. The total biogas potential is 216 million cubic meters per day and is distributed in different sectors, including:

- Sugarcane: 110.2 million Nm³/day
- Animal Protein: 59.3 million Nm³/day
- Agricultural Production: 34.9 million Nm³/day
- Sanitation: 11.5 million Nm³/day

These sectors represent abundant sources of biomass that can be used for the generation of biogas, contributing to the diversification of the Brazilian energy matrix and the strengthening of sustainable practices. Biomethane, in turn, has an even more expressive energy potential, as it can be used in various applications, directly replacing natural gas. The Brazilian biomethane potential is 120 million cubic meters per day from different sectors, with emphasis on:

- Sugarcane: 57.6 million Nm³/day
- Animal Protein: 38.9 million Nm³/day

- Agricultural Production: 18.2 million Nm³/day
- Sanitation: 6.1 million Nm³/day (ABIOGÁS, 2022).

However, only a fraction of this potential is currently used, evidencing the difference between theoretical potential and achievable potential, conditioned by technical, economic, and regulatory factors (ABIOGÁS, 2022). The divergences between the numbers of CIBiogás and ABiogás are mainly due to their different methodologies and analysis objectives. While CIBiogás focuses on the real and "census" mapping of existing units, ABiogás often highlights the country's total theoretical potential for the purpose of promoting the sector.

3.1.7 Production Scale, Challenges and Limitations

The current panorama of biogas in Brazil shows the consolidation of the sector as a strategic vector of the national energy transition. In 2024, the country accounted for 1,633 registered biogas plants, of which 1,587 were in operation and 46 were in the implementation phase, with a total installed capacity of approximately 4.7 billion Nm³/year, representing a growth of about 16% compared to 2023. The recent advance is mainly driven by the urban solid waste and sanitation sector, which accounts for approximately 63% of the installed capacity, followed by the industrial and agricultural sectors. Although about 75% of the plants are small, large projects concentrate more than 70% of the volume produced, evidencing high structural asymmetry in the sector. The predominant energy use remains the generation of electricity, however the rapid expansion of biomethane is observed, with 79 plants that already have purification technology, totaling an installed capacity of around 2.7 million Nm³/day. According to projections based on authorization processes with the ANP, the national supply of biomethane may more than triple by 2026, indicating growing technological maturity and greater insertion of biogas and biomethane in the Brazilian energy matrix (CIBiogás, 2024).

The expansion of biogas and biomethane in Brazil faces challenges related to the geographical dispersion of waste sources, high investment costs, the need for adequate infrastructure, and regulatory predictability (IEA, 2020; ABIOGÁS, 2022; CIBiogás, 2024). These factors explain the difference between the estimated potential and the current level of utilization, indicating that overcoming these limitations requires technological solutions, appropriate business models, and consistent public policies.

3.2 TECHNICAL FUNDAMENTALS OF ANAEROBIC DIGESTION APPLIED TO CARBOHYDRATE-RICH SUBSTRATES

Anaerobic digestion is a widely consolidated biotechnological process for the treatment of organic waste and for the production of biogas, based on the integrated action of different microbial groups in a strictly anaerobic environment. The efficiency and stability of this process depend directly on the metabolic balance between the biochemical steps involved, namely, hydrolysis, acidogenesis, acetogenesis and methanogenesis, as well as on the adequacy of the operating conditions to the physicochemical characteristics of the treated substrate. Thus, understanding the technical fundamentals of anaerobic digestion is essential for the correct sizing, operation and control of biodigesters, especially in systems that deal with significant variations in waste composition.

Substrates predominantly rich in carbohydrates, such as effluents from the food industry, sugary agro-industrial residues and streams with a high concentration of starches and simple sugars, have high potential for biogas production due to their high biodegradability. However, these same properties impose relevant operational challenges, since the rapid conversion of these compounds can result in accumulation of metabolic intermediates, such as volatile fatty acids and hydrogen, compromising the stability of the process when there is no compatibility between the production and consumption rates of these intermediates. Thus, based primarily on Kunz et al. (2022), this work presents the biochemical and operational principles of anaerobic digestion, with emphasis on the particularities associated with the treatment of carbohydrate-rich substrates, highlighting the critical factors for maintaining the stability and performance of biodigesters.

3.2.1 Biochemical Steps of Anaerobic Digestion

Anaerobic digestion occurs through a sequence of interdependent metabolic steps, traditionally divided into hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Although described separately, these steps occur simultaneously inside the reactor, and the balance between them is decisive for the stability of the process.

3.2.1.1 Hydrolysis

Hydrolysis corresponds to the initial stage of anaerobic digestion, in which complex organic polymers are converted into soluble compounds of lower molecular weight. On carbohydrate-rich substrates, this step mainly involves the degradation of polysaccharides, such as starch and cellulosic fractions, into fermentable monosaccharides. According to Kunz et al. (2022), carbohydrate hydrolysis generally occurs faster than protein and lipid hydrolysis, which gives these substrates a high biodegradation rate. In many cases, this step is not the limiting factor of the process, shifting operational attention to subsequent steps.

3.2.1.2 Acidogenesis

In acidogenesis, monomers resulting from hydrolysis are rapidly converted by fermentative bacteria into volatile fatty acids, alcohols, hydrogen, and carbon dioxide. In systems fed with predominantly carbohydrate substrates, this step is characterized by high reaction kinetics and intense production of organic acids, especially acetic, propionic and butyric acids. According to Kunz et al. (2022), the high speed of acidogenesis can generate imbalances when the acid production rate exceeds the conversion capacity of the later steps, resulting in accumulation of intermediates and a drop in pH. This behavior makes carbohydrate-rich substrates particularly sensitive to acidification, requiring greater rigor in operational control.

3.2.1.3 Acetogenesis

Acetogenesis consists of the conversion of longer-chain volatile fatty acids and alcohols into acetate, hydrogen, and carbon dioxide, compounds directly assimilable by methanogenic archaea. This step is thermodynamically dependent on the partial pressure of hydrogen in the medium and the synergistic activity between acetogenic bacteria and hydrogen-consuming microorganisms. In substrates rich in carbohydrates, acetogenesis plays a strategic role in the stabilization of the process, since the excess of fermentative products can compromise its efficiency if there is no adequate consumption of intermediates. Imbalance in this step can result in acid accumulation and inhibition of the methanogenesis process (Kunz et al., 2022).

3.2.1.4 Methanogenesis

Methanogenesis corresponds to the final stage of anaerobic digestion, in which methane is produced mainly by two metabolic pathways: the acetoclastic pathway, responsible for converting acetate into methane and carbon dioxide, and the hydrogenotrophic pathway, which uses hydrogen and carbon dioxide as substrates. In systems fed with carbohydrate-rich substrates, the acetoclastic pathway tends to predominate, due to the high production of acetate during fermentation. However, methanogenic archaea have high sensitivity to variations in pH, temperature, and the presence of inhibitory compounds, and the maintenance of stable operating conditions is essential for process performance (Kunz et al., 2022).

3.2.1.5 Critical Operating Parameters for Carbohydrate-Rich Substrates

The performance of anaerobic digestion depends directly on the control of operational parameters, which assume even greater importance when it comes to substrates with great fermentation potential.

3.2.1.6 pH, alkalinity and volatile fatty acids

pH control is one of the most critical aspects in systems fed with carbohydrate-rich substrates. The rapid production of volatile fatty acids during acidogenesis can reduce the pH of the medium, compromising methanogenic activity. Alkalinity acts as a buffering mechanism, being fundamental for the stability of the process. Kunz et al. (2022) highlight that the joint monitoring of the concentration of volatile fatty acids and alkalinity allows anticipating situations of instability, being widely used as an operational control tool.

3.2.1.7. Volumetric organic load and hydraulic detention time

The high biodegradability of carbohydrate-rich substrates requires caution in defining the volumetric organic load applied to the reactor. Excessive load increments can intensify acid production at a rate higher than the methanogenic consumption capacity, leading to acidification of the system. The hydraulic detention time must be compatible with the kinetics of the slower steps, especially methanogenesis, ensuring the proper conversion of the formed intermediates (Kunz et al., 2022).

3.2.1.8 Nutrients and trace elements

Although high in carbon, carbohydrate-rich substrates are often deficient in nitrogen, phosphorus, and essential micronutrients. Adequate supplementation of these nutrients, including trace elements such as nickel, cobalt, and iron, is critical to sustaining microbial activity and avoiding metabolic limitations (Kunz et al., 2022).

3.2.1.9 Suitability of anaerobic reactor technologies for predominantly carbohydrate-rich substrates

The choice of anaerobic reactor technology exerts a decisive influence on operational stability and process efficiency when applied to carbohydrate-rich substrates. These substrates have a high fermentation rate, which can result in accumulation of volatile fatty acids and system instability if the reactor is not properly selected. UASB reactors, widely used in the treatment of liquid effluents, have limitations when applied to predominantly carbohydrate substrates, due to the risk of localized acidification of the sludge blanket and the destructuring of the granules under organic load shocks. These conditions can compromise biomass retention and process efficiency. In this context, two-stage anaerobic digestion systems have superior performance, since they allow the physical separation of the acidogenic and methanogenic phases. This configuration allows greater control of acid production in the acidogenic reactor, while preserving the stability of the methanogenic reactor, being particularly suitable for effluents rich in sugars and starches (Kunz et al., 2022).

3.3 ECONOMIC SUSTAINABILITY OF CASHEW FARMING AND THE NEED TO USE THE PEDUNCLE FOR ITS BALANCE/REVITALIZATION

3.3.1 Sustainability of Cashew Farming

Cashew farming has significant economic, social and environmental relevance, especially in the Northeast region of Brazil, where the cashew tree (*Anacardium occidentale* L.) has high adaptation to adverse edaphoclimatic conditions, such as low fertility soils, high temperatures and water deficit. This characteristic gives the crop a strategic role in generating rural income and maintaining jobs, especially in off-season periods of annual crops (EMBRAPA, 2016).

The economic sustainability of Brazilian cashew farming has structural limitations that compromise its viability, especially due to the almost exclusive dependence on the nut as a source of income, especially in production systems that depend on hired labor. Brainer (2022) demonstrates that the remuneration obtained by producers is insufficient to cover basic costs of maintenance and adoption of practices that increase productivity, which is aggravated by the volatility of nut prices and international competition. The low productivity of traditional orchards, composed mostly of common cashew trees in physiological decline, and the slow renewal of areas reinforce the drop in national production. In addition, the absence of consistent national public policies keeps the activity with low economic attractiveness and reduces the capacity for investment and modernization of the chain (Brainer, 2022).

In view of the structural challenges that compromise the economic sustainability of cashew farming, such as low productivity, the aging of orchards and the strong dependence on nuts, the use of the peduncle emerges as a strategic component for the recomposition of producers' income. This relevance is even more evident in the semi-arid regions, where the cashew tree has a high adaptation to drought conditions and concentrates its harvest precisely in the dry season, contributing to the generation of income at times of less availability of other agricultural activities. The article by Brainer (2021) reinforces this perspective by highlighting that the use of the peduncle is a fundamental part of the revitalization of national cashew farming, expanding the production base and reducing the economic vulnerability associated with the exclusive commercialization of the nut. Despite this finding, the stalk remains largely underutilized. Although it represents about 90% of the total weight of the fruit, it is estimated that only 12% of this volume is effectively used by the industry, especially in the production of whole juice, which shows a significant waste of raw material and the loss of opportunities to add value (Paiva, 2000). Among the factors that restrict its use are the high post-harvest perishability, the insufficiency of local agro-industries, and the low adoption of processing technologies Embrapa (2016). Thus, even in the face of its high economic and social potential, especially during the dry season, the peduncle remains underutilized, indicating the need for public policies, investments and coordinated actions that promote its effective insertion in the agro-industrial dynamics.

From an institutional point of view, different agencies converge on the potential of full use of the fruit, although they highlight structural obstacles to its consolidation. The Brazilian Agricultural Research Corporation highlights the technological and agro-industrial potential of the peduncle, while the Technical Office of Economic Studies of the Northeast (ETENE) emphasizes limitations related to infrastructure, access to credit, technical assistance, and the collective organization of producers (EMBRAPA, 2016; Brainer, 2022). Thus, the economic viability of cashew farming depends not only on agricultural productivity, but also on the articulation between technological innovation, public policies and governance of the production chain. The financial feasibility study by Amorim and Viana (2025) shows that the economic sustainability of the enterprise varies according to the production model adopted. Systems that combine the exploitation of the nut with the use of the stalk and the production of derivatives have superior financial indicators compared to the exclusive exploitation of the nut. In family farming enterprises, the use of their own labor reduces operating costs and anticipates the return on invested capital, while employer systems tend to depend on greater value addition to achieve financial balance (Amorim; Viana, 2025).

The analysis presented by Silva (2019) demonstrates that the economic sustainability of cashew farming is directly associated with the production model adopted, showing that diversified systems, which include the processing and use of the peduncle, have superior performance compared to the exclusive exploitation of the nut. The study identifies that producers who adopt processing and value-adding practices achieve better sustainability indicators, especially in the economic component, driven by the use of family labor, which reduces operating costs and increases production efficiency. Thus, the research confirms that diversification and processing are determining factors for the economic viability of the activity, reinforcing the importance of integrated production models for small farmers. Thus, the economic viability of cashew farming is directly related to the diversification of revenues, the technological level of the orchards and the ability to add value to the products. Enterprises that incorporate circular economy practices, agro-industrial processing, and efficient management tend to have greater economic resilience. On the other hand, systems based exclusively on the sale of nuts in natura, with low productivity and high labor costs, present a greater risk of financial unfeasibility. Thus, the sustainability of the sector depends on the integration between primary production, technological innovation, collective organization and incentive policies, configuring itself as a central element for sustainable rural development.

3.3.2 Technical feasibility of the cashew stalk

Agro-industrial residues with high carbohydrate fraction have great potential for biogas production due to their high biodegradability and rapid biochemical conversion during anaerobic digestion. As described by Kunz et al. (2022), the hydrolysis step, responsible for the initial breakdown of macromolecules, occurs in a few hours for carbohydrates, while proteins and lipids require several days, making carbohydrate substrates more easily degradable and accelerating the entire subsequent metabolic process. In addition, during acidogenesis, carbohydrates such as glucose are rapidly converted into pyruvate and, subsequently, into short-chain organic acids, which are direct precursors of methanogenesis, favoring the formation of methane and increasing the overall efficiency of the process. These factors justify the high energy potential of carbohydrate-rich residues when used as substrates in anaerobic biodigesters.

The cashew stalk has a composition that is highly favorable to anaerobic digestion due to its high content of soluble carbohydrates, evidenced by the values of 10.47 to 12.63 °Brix, in addition to expressive concentrations of total phenolic compounds, ranging between 1.72 and 2.54 mg EAG·g^{-1}, as characterized by Silva et al. (2021). Although the high content of simple sugars favors rapid hydrolysis and acidogenic conversion, the significant presence of phenols constitutes a critical point, as these compounds have recognized antimicrobial activity. According to Kunz, Steinmetz, and Amaral (2022, p. 17), "the efficiency of anaerobic digestion depends on the coordinated action of fermentative bacteria and methanogenic archaea, groups particularly sensitive to substances that interfere with cell integrity and microbial metabolism". Also according to Kunz, Steinmetz, and Amaral (2022), highly fermentable substrates require greater control of the formation of volatile fatty acids, since carbohydrate hydrolysis occurs "in a few hours", and can acidify the environment and inhibit methanogenesis if there is no adequate regulation. For this reason, the authors point out that full-mix reactors with strict load control, or two-stage anaerobic digestion systems, in which the acidogenic and methanogenic phases are physically separated, tend to perform better on substrates with rapid degradation. Thus, the cashew stalk can be efficiently converted into biogas when associated with reactor configurations that ensure greater stability in the face of its high fermentation rate.

3.3.2.1 Cashew Stalk Collection and Pretreatment Procedure

In order to estimate the real potential of the cashew stalk for biogas production, material was collected in an orchard located in the municipality of Beberibe-CE. The plot had been fully harvested eight days before sampling, so that all the material present in the soil corresponded to the natural fall that occurred during this period. Figure 1 shows the original *locus* of this research:

Figure 1

Cashew orchard in the municipality of Beberibe, Ceará

Source: Researcher data.

The collection was carried out in a single cashew tree, and all fruits present in the soil were collected, including nuts and peduncles. Subsequently, the chestnut and the peduncle were manually separated. The peduncles were packed in plastic buckets and stored in a thermal box with ice to preserve the physicochemical characteristics and reduce the microbiological activity until processing. Pre-treatment was initiated approximately five hours after collection. Initially, the peduncle was fragmented into smaller parts with the aid of a manual cutting instrument. Next, mechanical pressing was performed using a domestic tool such as a manual vegetable juicer, promoting the separation of the liquid fraction from the solid fibrous fraction (See Figure 2 below).

Figure 2

Cashew stalk cut into pieces, instrument used to press the pieces

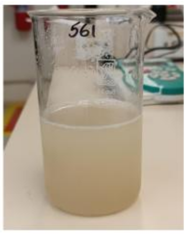
Source: Researcher data.

The pressing process resulted in an approximate yield of 65% of liquid fraction in relation to the total mass of the stalk in natura. The liquid fraction obtained was immediately frozen to preserve the characteristics of the substrate and later sent to the International Center for Renewable Energy – CIBiogás, and the LABORATORY OF SOLID WASTE AND EFFLUENTS – LARSE, being identified as "liquid agricultural residue of the cashew crop". The main objective of the submission was the determination of the Biochemical Potential of Methane (PBM), as well as the physicochemical characterization of the sample, in order to evaluate its suitability for biogas production in anaerobic digestion systems. The tests were carried out in the Biogas laboratory, following technical and quality criteria, according to the methodologies described in the proposal. The PBM assay was conducted at a mesophilic temperature (37.0 ± 2.0 °C), using the inoculum produced and conditioned in the laboratory.

The inoculum of the biogas laboratory is a sludge rich in microorganisms responsible for consuming the organic matter of the substrates, and is kept in a complete mixture anaerobic reactor. Its basic composition is made of pig effluent and cattle manure, and has a balanced diet of carbohydrates, proteins and lipids. In the PBM assay, all samples were incubated in triplicates to ensure the repeatability of the results, including the Inoculum itself as a negative standard and Microcrystalline Cellulose as a positive standard. Cellulose is a standard used to measure the biological activity of the inoculum, and its recovery indicates that the inoculum is able to consume organic matter. (CIBiogás technical test opinion).

Figure 3

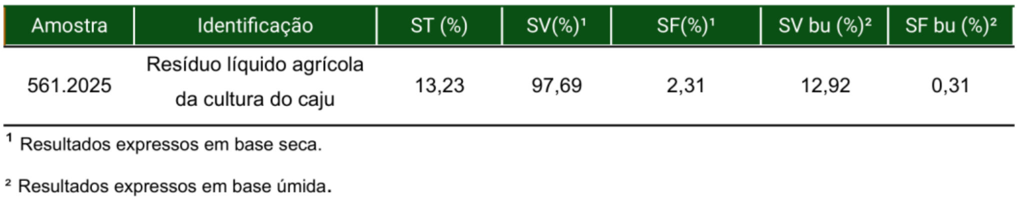
Sample appearance



Source: Researcher data.

Table 1

Physicochemical Characterization



Amostra	Identificação	ST (%)	SV(%)[1]	SF(%)[1]	SV bu (%)[2]	SF bu (%)[2]
561.2025	Resíduo líquido agrícola da cultura do caju	13,23	97,69	2,31	12,92	0,31

[1] Resultados expressos em base seca.

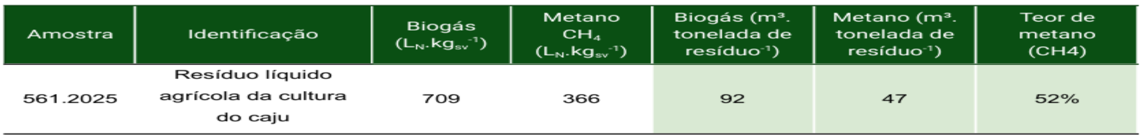
[2] Resultados expressos em base úmida.

Source: CIBiogás technical test opinion.

The Total Solids content represents the total amount of solid material in the sample. Low values indicate a high concentration of water, which influences the choice of biodigestion technology. High values indicate low water concentration, which may indicate the need for dilution of the material depending on the choice of biodigestion technology. The analyzed sample presented a TS content of 13.23%, which is in line with its composition given its description. The technologies most used in the Brazilian market have limitations ranging from 3% to 5% for covered lagoon models (BLC), and from 12% to 15% for continuous agitation models (CSTR). Therefore, the values obtained should be considered to determine the ideal biodigester model for each substrate. Volatile Solids (SV) are the measure related to the organic matter available for biogas production. High values (>70%) generally indicate good potential for biogas production. The sample showed 97.69% of SV, which indicates a high presence of organic matter. (CIBiogás technical test opinion).

Table 2

Biochemical Potential of Methane



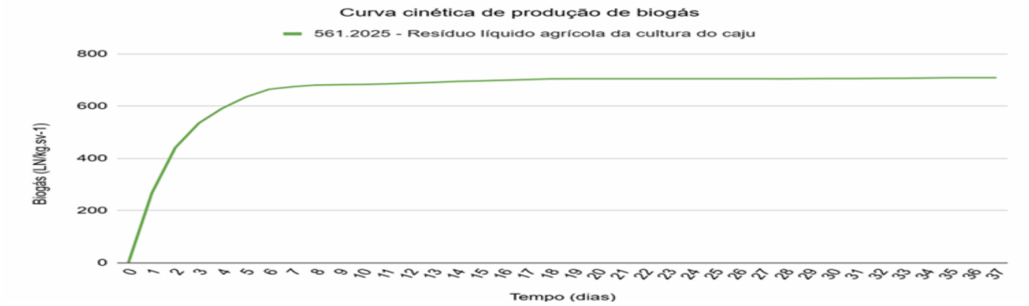
Amostra	Identificação	Biogás ($L_N.kg_{sv}^{-1}$)	Metano CH_4 ($L_N.kg_{sv}^{-1}$)	Biogás (m^3. tonelada de resíduo^{-1})	Metano (m^3. tonelada de resíduo^{-1})	Teor de metano (CH4)
561.2025	Resíduo líquido agrícola da cultura do caju	709	366	92	47	52%

Source: CIBiogás technical test opinion.

The value reported in the test report is realized in Standard Liters of biogas and methane per kilogram of Volatile Solids. This unit allows you to compare the potential of different samples, regardless of the amount of water present. The value indicated by cubic meters of biogas or methane per ton of waste is important to estimate full-scale production and can be estimated depending on the variation in the physicochemical characteristic of the substrate from the equation below. (CIBiogás technical test opinion). Biogas (LN/kgSV) *%SV (wet basis) = Biogas (m³/ton. of waste)

Figure 4

Analysis of biogas production and quality



Source: CIBiogás technical test opinion.

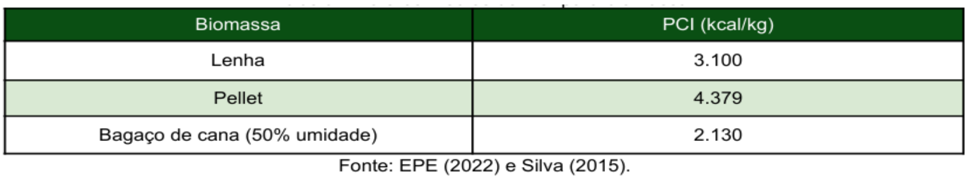
In Figure 4 it is possible to observe the biogas production curve with daily data for the analyzed sample. The experiment lasted 37 days, and the sample reached 90% of its production around the 6th day of the trial. This information serves as a subsidy for determining the Hydraulic Retention Time (TRH) when sizing a biodigester. (CIBiogás technical test opinion).

3.3.2.2 Theoretical comparison

The thermal energy generated from biogas can be determined from the lower calorific value of the methane present in the biogas, for this the concentration of CH4 present in the biogas is considered. In addition, the specific efficiency of the boiler for the chosen fuel should be considered. Based on EPE (2022) and Silva (2015), Table 1 presents the calorific value of biomass. Some equipment that uses these biomasses, such as boilers, need modifications to use biogas as a thermal energy fuel and this must be considered when choosing the source.

Table 3

Mean PCI values for biomass



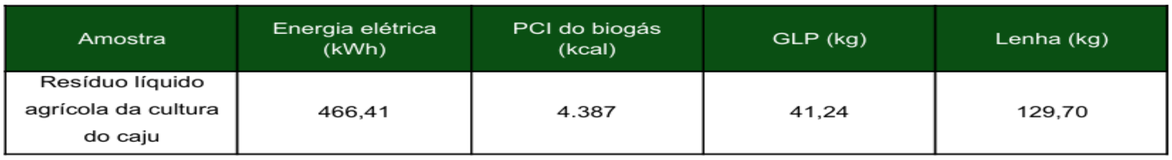
Biomassa	PCI (kcal/kg)
Lenha	3.100
Pellet	4.379
Bagaço de cana (50% umidade)	2.130

Fonte: EPE (2022) e Silva (2015).

Source: EPE (2022) and Silva (2015).

Table 4

Estimated values per tonne of waste



Amostra	Energia elétrica (kWh)	PCI do biogás (kcal)	GLP (kg)	Lenha (kg)
Resíduo líquido agrícola da cultura do caju	466,41	4.387	41,24	129,70

Source: EPE (2022) and Silva (2015).

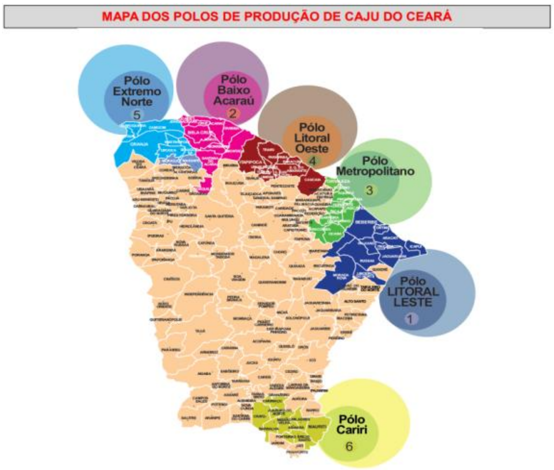
The values obtained and factors used for these conversions are average values and consider the data obtained in the laboratory, the factors and energy potential may diverge from the values indicated depending on the technological arrangement adopted, management and supplier requirements. (CIBiogás technical test opinion). The analyzed sample showed a good volume of biogas production with a good concentration of methane, when the production was analyzed as a function of the SV. In addition, the sample showed a high production of biogas and methane per ton of waste, due to the high content of Total Solids (TS). Given its production speed, the sample presents the feasibility of shorter HRTs. Because it is a residue of origin from the food sector, specifically from the production of cashew, the sample may have high levels of sugars, and because it has presented 52% of methane, such production is characteristic of its composition, which is similar to the production of other residues that have this profile.

The values obtained of TS are slightly above the technological limit of the most used biodigester models, the CSTR model biodigesters, depending on the manufacturer, can operate with up to 12% of TS, while the covered pond type biodigesters can operate with up to 5% of TS. Thus, for the use of the sample separately, it may be necessary that the substrate be combined with another available residue (codilation) to present values in the operating range of the biodigesters, depending on the technological arrangement used and the model of the equipment in question. In cases of codigestion, it is recommended that a new analysis of the compound mixture be carried out. In this way, the treatment of this waste enables the transformation of a possible environmental liability into an energetic and economic asset, allowing, in addition to the treatment of the organic matter present, the possibility of replacing its current energy matrix through the use of biogas, strengthening the company's image regarding its sustainable initiatives. (CIBiogás technical test opinion).

3.3.3 Regional potential of cashew stalk as a substrate for biogas production.

In this context, the cashew stalk stands out as a residual biomass of great relevance in the Brazilian scenario, especially in the Northeast Region, where most of the national production of cashew nuts is concentrated. Despite its expressive volume, this waste remains mostly underutilized, being frequently discarded in the field or destined for uses of low added value, which justifies its analysis from the perspective of energy use via anaerobic digestion. The cashew production chain has a unique characteristic: for each kg of nuts produced, it is estimated that approximately eight and a half kg of stalk is produced, which results in significant volumes of residual biomass. Official data from the Brazilian Institute of Geography and Statistics show that the national production of cashew nuts is strongly concentrated in a few northeastern states, especially Ceará, Rio Grande do Norte and Piauí, 92.83% in 2024. This regional concentration implies, consequently, a high spatially concentrated availability of cashew stalks, creating favorable conditions for the implementation of energy use systems on a regional or territorial scale (IBGE, 2024). In Ceará we can see a concentration of cashew production in regions near the coast and with highlights for some municipalities.

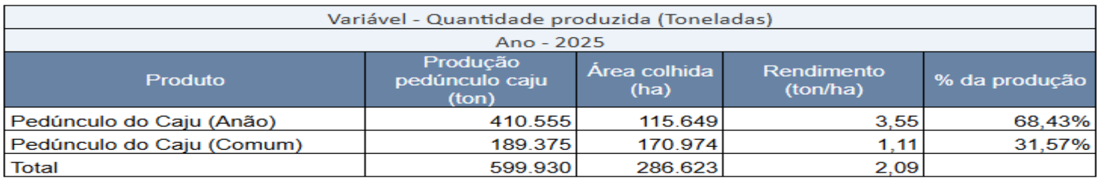
Figure 5



Source: Parente (2025).

Table 5

Information on cashew production in 2025



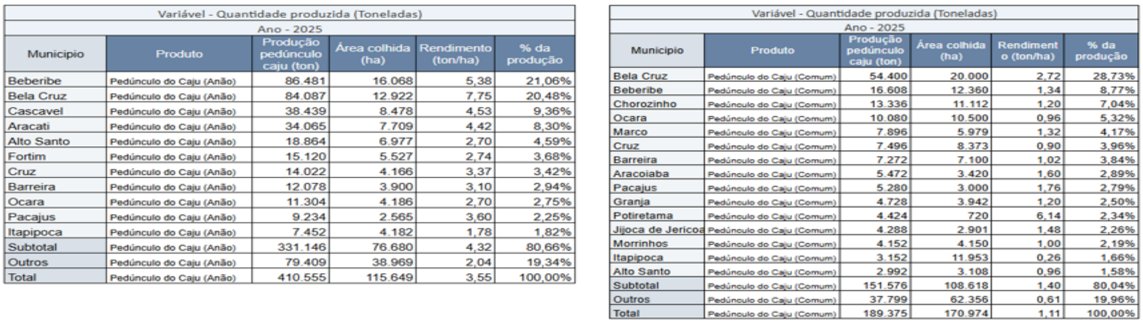
Variável - Quantidade produzida (Toneladas)				
Ano - 2025				
Produto	Produção pedúnculo caju (ton)	Área colhida (ha)	Rendimento (ton/ha)	% da produção
Pedúnculo do Caju (Anão)	410.555	115.649	3,55	68,43%
Pedúnculo do Caju (Comum)	189.375	170.974	1,11	31,57%
Total	599.930	286.623	2,09	

Source: IBGE 2026.

It is observed that the dwarf cashew tree has a higher productivity than the common cashew. This characteristic is important because harvesting costs are lower and the opportunities for mechanization of harvesting are greater.

Table 6

Production of cashew stalk (dwarf x common) by municipality in Ceará, with harvested area, average yield and relative participation in total production – 2025



Variável - Quantidade produzida (Toneladas)					
Ano - 2025					
Municipio	Produto	Produção pedúnculo caju (ton)	Área colhida (ha)	Rendimento (ton/ha)	% da produção
Beberibe	Pedúnculo do Caju (Anão)	86.481	16.068	5,38	21,06%
Bela Cruz	Pedúnculo do Caju (Anão)	84.087	12.922	7,75	20,48%
Cascavel	Pedúnculo do Caju (Anão)	38.439	8.478	4,53	9,36%
Aracati	Pedúnculo do Caju (Anão)	34.065	7.709	4,42	8,30%
Alto Santo	Pedúnculo do Caju (Anão)	18.864	6.977	2,70	4,59%
Fortim	Pedúnculo do Caju (Anão)	15.120	5.527	2,74	3,68%
Cruz	Pedúnculo do Caju (Anão)	14.022	4.166	3,37	3,42%
Barreira	Pedúnculo do Caju (Anão)	12.078	3.900	3,10	2,94%
Ocara	Pedúnculo do Caju (Anão)	11.304	4.186	2,70	2,75%
Pacajus	Pedúnculo do Caju (Anão)	9.234	2.565	3,60	2,25%
Itapipoca	Pedúnculo do Caju (Anão)	7.452	4.182	1,78	1,82%
Subtotal	Pedúnculo do Caju (Anão)	331.146	76.680	4,32	80,66%
Outros	Pedúnculo do Caju (Anão)	79.409	38.969	2,04	19,34%
Total	Pedúnculo do Caju (Anão)	410.555	115.649	3,55	100,00%

Variável - Quantidade produzida (Toneladas)					
Ano - 2025					
Municipio	Produto	Produção pedúnculo caju (ton)	Área colhida (ha)	Rendimento (ton/ha)	% da produção
Bela Cruz	Pedúnculo do Caju (Comum)	54.400	20.000	2,72	28,73%
Beberibe	Pedúnculo do Caju (Comum)	16.608	12.360	1,34	8,77%
Chorozinho	Pedúnculo do Caju (Comum)	13.336	11.112	1,20	7,04%
Ocara	Pedúnculo do Caju (Comum)	10.080	10.500	0,96	5,32%
Marco	Pedúnculo do Caju (Comum)	7.896	5.979	1,32	4,17%
Cruz	Pedúnculo do Caju (Comum)	7.496	8.373	0,90	3,96%
Barreira	Pedúnculo do Caju (Comum)	7.272	7.100	1,02	3,84%
Aracoiaba	Pedúnculo do Caju (Comum)	5.472	3.420	1,60	2,89%
Pacajus	Pedúnculo do Caju (Comum)	5.280	3.000	1,76	2,79%
Granja	Pedúnculo do Caju (Comum)	4.728	3.942	1,20	2,50%
Potiretama	Pedúnculo do Caju (Comum)	4.424	720	6,14	2,34%
Jijoca de Jericoa	Pedúnculo do Caju (Comum)	4.288	2.901	1,48	2,26%
Morrinhos	Pedúnculo do Caju (Comum)	4.152	4.150	1,00	2,19%
Itapipoca	Pedúnculo do Caju (Comum)	3.152	11.953	0,26	1,66%
Alto Santo	Pedúnculo do Caju (Comum)	2.992	3.108	0,96	1,58%
Subtotal	Pedúnculo do Caju (Comum)	151.576	108.618	1,40	80,04%
Outros	Pedúnculo do Caju (Comum)	37.799	62.356	0,61	19,96%
Total	Pedúnculo do Caju (Comum)	189.375	170.974	1,11	100,00%

Source: IBGE 2026.

It can be observed that dwarf cashew trees, with higher productivity, reaching 7.75 tons per hectare and 4.32 tons per hectare on average, in municipalities that represent 80% of production. In the common cashew crop, we have a lower productivity, with an average of 1.40 tons per hectare in the municipalities that produce 80% of the total. Additionally, it is observed that the expansion of dwarf cashew cultivation, especially in technified areas, has contributed to increased productivity per hectare, greater distribution over time, and regularity in the production of the stalk (Brainer, 2022). This aspect is particularly relevant because with the decrease in seasonality, it consequently provides greater stability in the operation of anaerobic digestion systems (Kunz et al., 2019).

From the integration of the productive data with the technical fundamentals of anaerobic digestion discussed above, it is verified that the energy use of the cashew stalk is technically feasible, as long as solutions compatible with its biochemical characteristics are adopted. As analyzed in the chapter on reactor selection, substrates with high potential tend to perform better in systems that offer greater control of acidogenesis, such as full-mix reactors with strict load control or two-step anaerobic digestion systems, in which the acidogenic and methanogenic phases are physically separated (Kunz et al., 2019). Thus, the regional potential of the cashew stalk should not be interpreted only in terms of the available volume, but also in light of its spatial distribution, producers' profile, and biochemical characteristics. The integration of these factors indicates that the use of cashew stalks for biogas production can play a relevant role in the diversification of the regional energy matrix, in the valorization of agro-industrial waste and in the promotion of circular economy models, as long as it is articulated with technological and organizational solutions appropriate to the specificities of the substrate and territory.

3.3.4 Potential of cashew stalk as substrate for biogas production and comparison with sugarcane stillage

The evaluation of the bioenergetic potential of the cashew stalk was conducted based on the physicochemical characterization of the substrate and the results obtained in a Biochemical Methane Potential (PBM) assay, carried out under controlled mesophilic conditions. The methodology adopted followed standardized procedures for the determination of total solids (TS), volatile solids (SV) and specific biogas production. The cashew stalk had a total solids content of 132.3 $g \cdot kg^{-1}$, corresponding to 132.3 $kg \cdot t^{-1}$ of fresh substrate. The fraction of volatile solids was 976.9 $g \cdot kgST^{-1}$, resulting in approximately 129.3 $kgSV \cdot t^{-1}$. The specific biogas production was determined at 709 $LN \cdot kgSV^{-1}$, with an average methane content of 52%. The volumetric production of biogas per ton of substrate was estimated according to Equation (x):

$$V\ biogas = ST \times SV \times Y\ biogas \qquad (1)$$

Where:

ST= total solids($kg \cdot t^{-1}$);SV= fraction of volatile solids ($kgSV \cdot kgST^{-1}$); Y biogas = specific production of biogas ($LN \cdot kgSV^{-1}$).

Substituting the values obtained experimentally:

$$V\ biogas = 132.3 \times 0.9769 \times 709$$

$$V\ biogas = 91.7\ Nm^3.t^{-1}\ (measured\ value\ 92\ Nm^3.t^{-1}) \qquad (2)$$

The corresponding methane volume was calculated by Equation (XX):

$$V_{CH4} = V\ biogas \times \%CH4 \qquad (3)$$

Where:

%CH4 represents the volumetric fraction of methane in the biogas.

CH4 V $= 91.7 * 0.52$

V $_{CH4}$ = 47.7 $Nm^3.t^{-1}$ *(measured value 47* $Nm^3.t^{-1}$*)* (4)

These results indicate high energy density per unit of mass processed, associated with the high concentration of volatile organic matter in the substrate.

Comparison with sugarcane vinasse: for comparative purposes, the data presented in Table 1 of the Biogas in the *Sugarcane Sector report* (GEF Biogás Brasil, 2022) were used, referring to vinasse generated in sugarcane mills. According to the document, vinasse presents:

- Total solids: 28.9 $g \cdot kg^{-1}$ (28.9 $kg \cdot t^{-1}$);
- Volatile solids fraction: 692.2 $g \cdot kgST^{-1}$;
- Specific biogas production: 586 $LN \cdot kgSV^{-1}$;
- Average methane content: 59%.

Applying the same methodology:

SV= 28.9 x 0.6922

SV= 19.99 kg SV t^{-1} (5)

Volumetric biogas production:

V biogas = 19.99 x 586

V biogas = 11.7 $Nm^3.t^{-1}$ *(measured value 11.2* $Nm^3.t^{-1}$*)* (6)

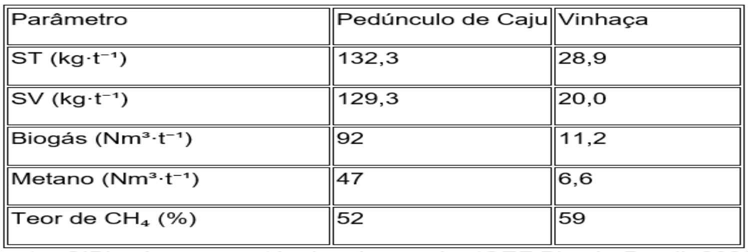
Methane production:

V $_{CH4}$ = 11.7 x 0.59

V $_{CH4}$ = 6.9 $Nm^3.t^{-1}$ *(measured value 6.6* $Nm^3.t^{-1}$*)* (7)

Table 7

Comparison of the potential for biogas production between cashew stalks and sugarcane vinasse



Parâmetro	Pedúnculo de Caju	Vinhaça
ST ($kg \cdot t^{-1}$)	132,3	28,9
SV ($kg \cdot t^{-1}$)	129,3	20,0
Biogás ($Nm^3 \cdot t^{-1}$)	92	11,2
Metano ($Nm^3 \cdot t^{-1}$)	47	6,6
Teor de CH_4 (%)	52	59

Fonte: CIBiogás parecer técnico de ensaio; (GEF Biogás Brasil, 2020)

It is observed that the substrate of the cashew stalk has methane production approximately seven times higher per ton of substrate in natura when compared to vinasse. This difference is not due to the specific efficiency of biological conversion, but to the higher concentration of volatile solids per unit mass in the peduncle. Vinasse, although it has high biodegradability and good specific conversion per kilogram of volatile solids, has a low concentration of organic matter per ton of substrate, resulting in lower final volumetric production. Therefore, from the perspective of energy density per mass processed, the cashew stalk demonstrates significantly higher bioenergetic potential, which may represent a logistical and operational advantage in decentralized biodigestion systems. And in an eventual comparison of the volume of existing biomass, for the sake of feasibility, it must be taken into account that 1 ton of substrate is equivalent to 7 tons of sugarcane vinasse.

3.3.5 Integrated potential for biogas, biomethane, electricity and GHG emission mitigation

Based on the production of cashew stalks in the state of Ceará presented in Table 1 (599,930 $t \cdot year^{-1}$), and considering that 65% of this volume has characteristics compatible with the laboratory tests conducted by CIBiogás and the Laboratory of Solid Waste and Effluents (LARSE), The amount that can potentially be directed to the anaerobic digestion process corresponds to 389,954.5 $t \cdot year^{-1}$. The Biochemical Methane Potential (PBM) tests indicated a specific production of 47 $m^3\ CH_4 \cdot t^{-1}$ of substrate in natura, with an average methane content in the biogas of 52%.

3.3.5.1 Annual biogas and methane production potential

The annual volume of methane was estimated according to Equation (x):

$$VCH4 = M \times YCH4 \qquad (8)$$

Where:

- (M) = annual substrate mass ($t \cdot year^{-1}$)
- YCH4 = specific methane production ($m^3 \cdot t^{-1}$)

$YCH4 = 389{,}954.5 \times 47$

$YCH4 = 18{,}327{,}862\ Nm^3.\ year^{-1}$ (9)

Considering an average methane content of 52%, the annual volume of raw biogas is given by:

$V_{Biogas} = V_{CH4} / 0.52$

$V_{biogas} = 35{,}245{,}888\ Nm^3 \cdot\ year^{-1}$ (10)

Therefore, the estimated annual potential corresponds to approximately:

- 35.25 million $Nm^3 \cdot year^{-1}$ of raw biogas
- 18.33 million $Nm^3 \cdot year^{-1}$ of methane

3.3.5.2 Biomethane production potential

Considering a purification process with an average methane recovery efficiency of 97%, the annual volume of biomethane is estimated by:

$V_{biomethane} = V_{CH4} \times 0.97 V_{biomethane} = 17{,}778{,}026\ Nm^3.year^{-1}$ (11)

This volume meets the quality specifications for vehicular use or injection into the natural gas network, according to the guidelines of the National Agency of Petroleum, Natural Gas and Biofuels -ANP (2022).

3.3.5.3 Net Electric Power Generation Potential

Adopting lower calorific value (PCI) of methane equal to 9.97 $kWh \cdot Nm^{-3}$ (EPE, 2022), the annual gross energy is given by:

$Raw\ E = V_{CH4} \times PCI$

$E_{gross} = 18{,}327{,}862 \times 9.97 E_{gross} = 183{,}278{,}615\ kWh.year^{-1} E_{gross} \approx 183.3\ GWh.year^{-1}$ (12)

Considering an average electrical efficiency of 35–40% for biogas motor generators (CIBIOGÁS, 2024), the annual net electricity is between:

$$E\ net = 64.1–73.3\ GWh.year^{-1} \qquad (13)$$

3.3.5.4 Potential for mitigating Greenhouse Gas (GHG) emissions

The replacement of fossil diesel with biomethane results in a significant reduction in emissions. Whereas:

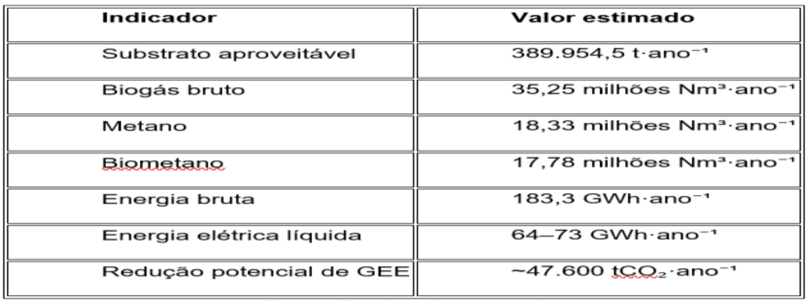
- Diesel emission factor: 2.68 kg $CO_2 \cdot L^{-1}$ (IPCC, 2006; 2019)
- Energy equivalence: 1 $Nm^3\ CH_4 \approx 1$ L diesel equivalent (approximate PCI basis)

The annual volume of biomethane (17.78 million Nm^3) could replace approximately the same volume of equivalent diesel. The estimated annual emission reduction is:

$$CO_2\ reduction = 17{,}778{,}026 \times 2.68 CO_2\ \text{reduction} \approx 47{,}645\ t\ CO_2.year^{-1} \qquad (14)$$

In addition to energy substitution, the mitigation of fugitive emissions associated with the natural anaerobic decomposition of the peduncle should also be considered, which expands the total climate benefit.

3.3.5.5 Integrated synthesis of the annual potential in the state of Ceará



Indicador	Valor estimado
Substrato aproveitável	389.954,5 t·ano⁻¹
Biogás bruto	35,25 milhões Nm³·ano⁻¹
Metano	18,33 milhões Nm³·ano⁻¹
Biometano	17,78 milhões Nm³·ano⁻¹
Energia bruta	183,3 GWh·ano⁻¹
Energia elétrica líquida	64–73 GWh·ano⁻¹
Redução potencial de GEE	~47.600 tCO_2·ano⁻¹

Fonte: Dados dos pesquisadores

3.3.6 Limitations of the study

The results presented derive from laboratory tests of biochemical potential of methane (PBM), representing the maximum theoretical performance of the substrates under controlled conditions. On an industrial scale, operational factors, system efficiency, compositional variations, and logistical limitations can reduce the observed yields. The state potential estimate considered annual availability of biomass and full use of the substrate suitable for biodigestion, not incorporating logistical restrictions, seasonal losses or implementation and operation costs. Emission mitigation was estimated according to an approach compatible with RenovaBio, based on average carbon intensity and energy substitution of fossil diesel. The effective generation of CBIOs depends on specific certification and complete lifecycle inventory. The results indicate high technical and environmental potential of cashew stalk for biogas and biomethane production.

4 FINAL CONSIDERATIONS

The research met the proposed objectives by showing that the cashew stalk has technical feasibility for the generation of biogas, being an alternative that can increase the income of the rural producer and help meet the national policies to reduce greenhouse gas emissions. With this, the work highlights the importance of the energy use of agro-industrial waste for sustainable development in the region.

The findings also signal the urgency of creating and reinforcing public policies that promote, encourage and finance the energy exploitation of cashew stalks. Technologically, biogas production represents a viable way to add value, but its large-scale adoption, especially among small and medium-sized producers, requires institutional instruments that encourage this practice.

Finally, it is suggested that research focused on reducing the seasonality in the availability of the substrate be carried out, to ensure a more constant production of biogas during the year. In addition, it is recommended to expand the analysis of economic feasibility and financing options, and to carry out detailed investigations on anaerobic digestion of the unstudied fraction, 35% of the cashew peduncle, of the two-stage anaerobic digestion with the cashew substrate, including to evaluate the feasibility of storing the product of the acidogenic phase.

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