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Original Article

Biogas production from solid residues generated in bioethanol production using banana biomass[1]

Produção de biogás com resíduos sólidos gerados na produção de bioetanol utilizando biomassa da bananicultura

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HIGHLIGHTS:
A high biochemical potential of biogas was obtained by residues generated in bioethanol production from banana biomass.
The composition of the biogas produced meets the criteria for use, with adequate percentages of CH_4 and CO_2.
The Gompertz model described biogas kinetics for banana pseudostem bagasse, banana peels, and vinasse with $R^2 > 0.99$.

ABSTRACT: Santa Catarina is a significant banana producer, responsible for 722 tons annually. For every 1,000 kg of bananas harvested, approximately 3,000 kg of pseudostem, 650 kg of peels, and 350 kg of rejected fruit are generated. Studies have evaluated the use of banana residues for bioethanol production. Solid residues like banana pseudostem bagasse, banana peels, and vinasse (fermented broth residue) are produced during this process. This study aimed to quantify and characterize these residues for biogas and methane production. Banana peels and vinasse were more suitable for containing lower total solids content and favorable C:N (carbon:nitrogen) ratios (10-30:1), yielding higher biochemical potential of methane (260 mL_{CH4} g_{vs}^{-1}) compared to banana pseudostem bagasse (201 mL_{CH4} g_{vs}^{-1}). However, vinasse had a high hydrogen sulfide content (0.0783%), necessitating desulphurization for safe biogas use. The results indicate that banana pseudostem bagasse, banana peels, and vinasse have substantial potential for biogas and methane production due to their high degradation rates. The biogas composition meets the criteria for use, with adequate methane and carbon dioxide concentrations, highlighting the viability of these residues for energy generation and contributing to sustainability in banana cultivation.

Key words: renewable energy, biofuel, sustainable agriculture, anaerobic digestion

RESUMO: Santa Catarina é um importante produtor de banana, responsável por 722 toneladas anuais. Para cada 1.000 kg de banana colhida, são gerados aproximadamente 3.000 kg de pseudocaule, 650 kg de cascas e 350 kg de frutos rejeitados. Estudos avaliaram a utilização de resíduos de banana para produção de bioetanol. Resíduos sólidos como bagaço de pseudocaule de banana, cascas de banana e vinhaça (resíduo de caldo fermentado) são produzidos nesse processo. Este estudo teve como objetivo quantificar e caracterizar esses resíduos para produção de biogás e metano. Cascas de banana e vinhaça foram melhores por conterem menor teor de sólidos totais e relações C:N (carbono:nitrogênio) favoráveis (10 - 30:1), proporcionando maior potencial bioquímico de metano (260 mL_{CH4} g_{vs}^{-1}) em comparação ao pseudocaule de bananeira bagaço (201 mL_{CH4} g_{vs}^{-1}). No entanto, a vinhaça apresentou alto teor de sulfeto de hidrogênio (0,0783%), necessitando de dessulfurização do biogás gerado para seu uso seguro. No geral, os resultados indicam que o bagaço do pseudocaule da banana, as cascas de banana e a vinhaça têm potencial substancial para a produção de biogás e metano devido às suas altas taxas de degradação. A composição do biogás atende aos critérios de utilização, com concentrações adequadas de metano e dióxido de carbono, destacando a viabilidade desses resíduos para geração de energia e contribuindo para a sustentabilidade no cultivo da banana.

Palavras-chave: energia renovável, biocombustível, agricultura sustentável, digestão anaeróbica

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Introduction

In 2022, Santa Catarina state was responsible for 10.5% of national banana production, totaling around 722 tons per year (EPAGRI/CEPA, 2022). In the northern region of the state, ten of the fifteen municipalities with the highest production account for 48% of the state's production. Considering banana production, it is estimated that for every 1000 kg of bananas harvested, approximately 3000 kg of pseudostem (~70%), 650 kg of peels (~14%), and 350 kg of fruit (~7%) rejected for sale are generated, in a wet mass ratio of 10:2:1, respectively, as well as 8% of leaves and 2% of stalks (Souza et al., 2017a).

In the literature, studies have been conducted aiming at the production of bioethanol and biogas using various agro-industrial residues (Santos et al., 2015; Arreola-Vargas et al., 2016; Pellera & Gidarakos, 2016; Varol & Ugurlu, 2016; Souza et al., 2017a, b; Rempel et al., 2019; Sonwai et al., 2019; Santos et al., 2020; Uchôa et al., 2021; Silva et al., 2021; Regazi et al., 2021; Serna-Jiménez et al., 2021; Santos et al., 2021; Volpi et al., 2022; Oliveira et al., 2023). Among these studies, few have utilized banana residues as a substrate for alcoholic fermentation processes and biogas (Souza et al., 2017a, b; Uchôa et al., 2021; Serna-Jiménez et al., 2021).

According to Uchôa et al. (2021), commercial-scale production of bioethanol from banana biomass is not yet viable, as production costs are higher than those of corn or sugar cane. Thus, the need to minimize energy costs becomes evident. In the preparation of the substrate to produce bioethanol from banana biomass, residues are generated, such as banana pseudostem bagasse (R1), banana peels (R2), and solid residue obtained after separation of the fermented broth, also called vinasse (R3), which, in turn, can be used in the production of biogas through anaerobic digestion.

Anaerobic digestion is a fermentative and oxidative process, in the absence of molecular oxygen by the action of a consortium of microorganisms that occur interdependently, which promotes the transformation of complex organic compounds into simpler compounds, resulting mainly in methane and carbon dioxide gases (Amaral et al., 2019). In the anaerobic digestion process, it is possible to use the effluent as a biofertilizer, biogas as fuel, and economic energy production (Ji et al., 2017). However, economic, cultural, and operational limitations make implementing this technology in Brazil difficult, and it demands performance improvements that encourage its adoption (Regazi et al., 2021).

Thus, the present study aims to quantify and characterize the residues generated in the preparation of the substrate for bioethanol production from banana biomass (R1, R2, and R3) and evaluate the production of biogas and methane from them. In this way, it is expected that in addition to taking advantage of the solid residues generated in bioethanol production, there may be a positive contribution to the energy balance if a sequential process of production of bioethanol and biogas is used.

Material and Methods

The solid residues originating from the ethanol production process from banana biomass (banana pseudostem bagasse - R1, banana peels - R2, and the solid residues obtained after separating the fermented broth or vinasse - R3) were generated in the Biotechnology Laboratory of the University of the Joinville Region, in Joinville city, state of Santa Catarina, Brazil. The biogas production experiments were carried out in partnership with the laboratories of the Embrapa Swine & Poultry, in Concórdia city, state of Santa Catarina, Brazil, (27° 14′ 3″ S, 52° 1′ 43″ W, and an altitude of 478 m).

R1, R2, and R3 were quantified and characterized regarding moisture content, volatile, fixed, and total solids. The solid residues were quantified in wet mass by weighing on a semi-analytical balance. Moisture was determined using the Standard Test Method for Moisture Analysis of Particulate Wood Fuels - E871-82 (ASTM, 2019). The volatile solids (VS) content was determined by the Standard Test Method for Volatile Matter in the Analysis of Particulate Wood Fuels - E871-82 and E872-82 (ASTM, 2019). The determination of fixed solids (FS) (ash content) and total solids (TS) was conducted according to the Standard Test Method for Ash in Biomass - E1755-01 (ASTM, 2019).

Chemical oxygen demand (COD) determinations were conducted using the Hach COD Reagent Kit, ranging from 0 to 1500 $mgO_2\ L^{-1}$, using a colorimetric method with a HACH digester DRB200. The biochemical oxygen demand values (BOD5) were determined using the kit method in the BodTrac TM under the MOD.DBOTraK-HACH® apparatus. The chemical elemental characterization, carbon (C), hydrogen (H), and nitrogen (N), was determined using a Perkin Elmer CHN Analyser 2400 Series II elemental analyzer. For the analysis of sulfur (S), the samples were subjected to an acid digestion process by the Schöniger methodology in a SCP Science DigiPrep digester to eliminate organic compounds, and after being analyzed by spectro inductively coupled plasma optical atomic emission spectrometer, model Arcos with radial vision (SOP) with detection limit (LD:0.01 mg L^{-1}); quantification limit (LQ:0.10 mg L^{-1}). All these determinations were conducted in triplicate.

Biogas production experiments used the solid residues R1, R2, and R3 as substrates. The anaerobic inoculum was prepared from a mixture of equal parts (1:1:1) (mass/mass/mass) of the starter inoculums of anaerobic sludge from a UASB (Upflow Anaerobic Sludge Blanket) reactor fed with swine manure, anaerobic sludge from a gelatine industry UASB reactor and fresh dairy cattle manure. The cumulative biogas production was measured over time, and the data was used to determine the biochemical biogas potential (BBP) and the biochemical methane potential (BMP) for each substrate (VDI, 2006).

Treatments were conducted with different $VS_{substrate}:VS_{inoculum}$ ratios for each solid residue (0.5 for R1, 0.3 for R2, and 0.4 for R3) to ensure that the amount of substrate does not exceed the amount of inoculum (Steinmetz et al., 2016), which could cause damage (VDI, 2006). Each trial used 10 g of substrate and 190 g of inoculum. In addition to the tests with R1, R2, and R3, triplicate tests were also conducted with 200 g of inoculum (positive control) and 1 g of microcrystalline cellulose (CMC) with 199 g of inoculum (CMC control). The positive control was conducted to verify the viability of the inoculum's biological activity. In contrast, the CMC control was chosen due to the wide availability of data in the literature, which suggests biogas values in the range of 740-750 mL $g_{VSsubstrate}^{-1}$, with a recommended recovery of more than 85% of the reference values of 600 mL $g_{VSsubstrate}^{-1}$ (Holliger et al., 2021).

Triplicate tests were conducted in reactors (500 mL) under mesophilic conditions at 37 ± 1°C, maintained with the help of temperature-controlled thermal baths, for 45 days, following the guidelines of VDI 4630 (VDI, 2006) and DIN 38414-8 (DIN, 1985). The reactors were purged with nitrogen gas before the tests to create anaerobic conditions. Biogas production was monitored by displacing a sealing liquid in an eudiometer tube containing a solution of sodium chloride (NaCl), citric acid ($C\,H\,O_{687}$), and methyl orange ($C\,H\,N_{14143}\,NaO_3\,S$) (DIN, 1985).

Biogas production was considered stabilized when the daily biogas value reached 1% or less of the total produced. All biogas volumes were corrected for normal temperature and pressure conditions (273.15 K and 1013 hPa, respectively). The biochemical biogas potential (BBP - mL g_{vs}^{-1}) for each solid residue was defined as the largest volume (mL) obtained during the test divided by the mass (g) of VS corresponding to each residue (VDI, 2006).

The composition of the biogas was analyzed using a Geotech BIOGAS 5000 portable gas analyzer, which measures the concentrations of CH_4 (%), CO_2 (%), and H_2S (%). The gases were collected using PET: Al: PE, Hermann Nawrot AG sampling package. Biogas was collected by following the displacement of the sealing liquid in the eudiometer tube. The sampling package was filled with the biogas resulting from the triplicates of each residue and was not evaluated separately. The biochemical methane potential (BMP - mL_{CH4} g_{vs}^{-1}) was calculated by multiplying the biochemical biogas potential (BBP - mL_{Biogas} g_{vs}^{-1}) by the percentage of CH_4 present in the biogas.

The observed data on biogas production as a function of time (days) were fitted to the non-linear Gompertz model (Eq. 1). This model is commonly used to model cumulative biogas production, evaluate the potential and maximum production rate, and determine the minimum time to start gas generation (lag phase) (Pellera & Gidarakos, 2016). The kinetic coefficients were determined using the GRG non-linear programming model, with the help of Solver in the Microsoft Excel® spreadsheet program.

$$M(days) = A \times exp^{\left(-exp\frac{r_m}{A}(\lambda - t)e+1\right)} \quad (1)$$

Where M - Accumulated biogas production (mL g_{vs}^{-1}) at time t (day); A - Maximum biogas production potential (mL g_{vs}^{-1}). A is equivalent to BBP, but in an estimated way; r_m - Maximum biogas production rate (mL (g_{vs}^{-1} per day)); λ - lag phase or adaptation phase (ln M(t) versus t) (day); t - total process time (day).

Eqs. 2 and 3, adapted from Aristarán et al. (2018), were used to estimate the volume (m^3) of biogas and CH_4 generation.

$$V_{Biogas} = BBP \times VS \times R \quad (2)$$

$$V_{CH_4} = BMP \times VS \times R \quad (3)$$

Where V_{Biogas} - Volume of biogas generation (m^3); V_{CH4} - Volume of CH_4 generation (m^3); BBP - Biochemical biogas potential (L_{Biogas} kg_{VS}^{-1}); BMP - Biochemical methane potential (L_{CH4} kg_{VS}^{-1}); VS - Concentration of volatile solids (kg_{VS} 100 kg_R^{-1}); R - Residue produced (kg).

The velocity value obtained from the Gompertz model (r_m) was used to calculate the daily volume of biogas and CH_4 (m^3 per day), according to Eqs. 4 and 5.

$$V_{Biogas} = r_m \times VS \times R \quad (4)$$

$$V_{CH_4} = r_m \times VS \times R \quad (5)$$

Where V_{Biogas} per day - Daily volume of biogas generation (m^3 per day); V_{CH4} per day - Daily volume of CH_4 generation (m^3 per day); r_m - Maximum biogas production rate (L kg_{vs}^{-1} per day); VS - Concentration of volatile solids (kg_{vs}100 kg_R^{-1}); R - Residue produced (kg).

The electricity generation potential (kWh per day) was calculated using Eq. 6 (Aristarán et al., 2018).

$$EE = V_{VCH_4N} \times \eta_c \times \rho_{CH_4} \times PCI_{CH_4} \times \eta_e \times f_{cap} \quad (6)$$

Where EE - Electricity generation potential (kWh per day); V_{CH4N} - Daily volume of CH_4 generation (m^3 per day); η_c - Biogas capture efficiency (85%); ρ_{CH4} - Density of CH_4 (0.656 kg m^{-3}); PCI_{CH4} - Lower calorific value of CH_4 (11,900 kcal kg^{-1}); η_e - Efficiency of thermal to electrical energy conversion (30%); f_{cap} - Capacity factor representing total system availability (90%); 1 kcal - 0.00116 kWh.

The characterization results of solid residues R1, R2, and R3 and the results from the production of biogas (BBP) and methane (BMP) were submitted to the analysis of variance, and the means were compared by the Tukey test at $p \leq 0.05$. The software used was OriginPro 9.0®.

Results and Discussion

The solid residues used for biogas production were generated when obtaining the substrate and after bioethanol production. To obtain 7.7 L of substrate containing 165 g L^{-1} of reducing sugars, 7.5 L of pseudostem broth was prepared, generating 3.8 kg of solid residue R1 (wet mass) and 4.1 L of peel broth generating 2.7 kg of solid residue R2 (wet mass). The mass obtained by filtering the fermented broth (solid residue R3) was 1.2 kg (wet mass). The total solid residues generated after preparing 7.7 L of substrate for bioethanol production was 7.7 kg.

The residues were characterized in terms of moisture, total solids, volatile solids, fixed solids, VS:TS ratio, COD, BOD5, C, N, S, C:N ratio, and C:N:S ratio according to Table 1.

The results (Table 1) showed high moisture content in the residue, with R2 presenting the highest value (84.17%). Santos et al. (2020) determined values for agro-industrial fruit waste of 81.49, 80.77, and 70.96% for passion fruit peel, orange bagasse, and cashew bagasse, respectively, corroborating the values found in this study.

Table 1. Physical and chemical characterization of solid residues R1, R2, and R3. Means ± SD (standard deviation) with the same letters in the lines are equal by the Tukey test at p ≤ 0.05

Variables	Unit	R1	R2	R3
Moisture	%	75.49 ± 2.97 a	84.17 ± 0.85 b	77.89 ± 2.02 a
Total Solids (TS)	%	24.51 ± 2.97 a	15.83 ± 0.85 b	22.11 ± 2.02 a
Volatile Solids (VS)	%	23.49 ± 2.83 a	14.41 ± 0.84 b	20.25 ± 2.01 a
Fixed Solids (FS)	%	1.02 ± 0.15 a	1.42 ± 0.03 b	1.86 ± 0.03 c
VS:TS	-	0.959 ± 0.13 a	0.910 ± 0.43 b	0,915 ± 0.69 b
COD	(mg_{O2} L^{-1})	346.00 ± 4.00 a	349.50 ± 2.50 a	1,111.00 ± 2.83 b
BOD_5	(mg_{O2} L^{-1})	206.50 ± 10.50 a	174.50 ± 4.50 b	865.50 ± 0.50 c
BOD_5:COD	%	59.73 ± 3.72 a	49.92 ± 0.93 b	77.90 ± 0.18 c
C (total carbon)	%	21.21 ± 0.08 a	9.73 ± 0.16 b	11.07 ± 0.07 c
N (nitrogen)	%	0.26 ± 0.01 a	0.48 ± 0.00 b	1.01 ± 0.07 c
C:N ratio	-	81.6:1	20.3:1	11.0:1
S (sulfur)	%	0.0528 ± 0.0013 a	0.0466 ± 0.0004 b	0.1287 ± 0.0016 c
C:N:S ratio	-	1,206:15:3	627:30:3	258:24:3

R1 (banana pseudostem bagasse), R2 (banana peels), R3 (vinasse)

The VS:TS ratio indicates the proportion of organic matter that can be transformed into biogas during anaerobic digestion. Varol & Ugurlu (2016), using the microalga *Spirulina platensis* as a renewable energy source, observed that the conversion of VS into biogas decreased when TS content increased. Table 1 shows that the VS:TS ratio was similar in all residues, with R1 standing at 0.959. However, since the TS value for R1 was the highest at 24.51%, this could disadvantage this residue in biogas production.

The BOD5:COD ratios reflect the quality of the organic matter, with R3 showing the highest value (77.9%). According to Jouanneau et al. (2014), based on the relationship between BOD5 and COD, the higher this value is, the greater the probability that this waste will be biodegradable.

Analysis of the elements revealed variations in carbon and nitrogen content between the residues. Residue R1 had the highest amount of C (21.21%), while R2 and R3 had 9.73 and 11.07% values, respectively. The highest amount of nitrogen was found in R3, with 1.01%.

The C:N ratios differed, with R2 and R3 around the ideal range for methane production in anaerobic digestion at 20.3:1 and 11.0:1, respectively. According to Amaral et al. (2019), the best C:N ratio to anaerobic digestion is 10 - 30:1. The residue R2 (banana peels) is a food residue and presented C:N among the best values, just like R3. However, the residue R1, which showed a higher value (81.6:1), is less favorable for anaerobic digestion, as the methane yield may not reach its maximum peak due to the reduction in the metabolic activity of the microorganisms and, as a result, the carbon is not wholly degraded (FNR, 2010). The disadvantage to anaerobic digestion was already observed by the higher ST value presented by R1 (Table 1).

The minimum environmental requirement of macronutrients in the literature is 600:15:3 (C:N:S) (Amaral et al., 2019). The C:N:S ratio of R1 was 1,206:15:3, and R2 was 627:30:3, in line with the literature, but with R3, the 258:24:3 diverged from the optimum value due to its higher sulfur content (0.1287%). According to Amaral et al. (2019), excess sulfur in the medium can cause the precipitation of some trace nutrients and some metals essential to anaerobic digestion.

The biogas generated from CMC, R1, R2, and R3 were characterized by methane (CH_4), carbon dioxide (CO_2), and hydrogen sulfide (H_2S) (Table 2).

Notably, residues R2 and R3, composed of banana fruits and peels originally rich in starch and cellulose, had the highest CH_4 content (58 and 57%, respectively), similar to the CMC control (53%). The approximate composition of CH_4 expected in biogas production when carbohydrates are used as a substrate is 50% (VDI, 2006). It should be noted that these percentages are in line with expectations for biogas production from carbohydrates. On the other hand, R1 showed the lowest production due to its characteristics. It may contain fibers and lignin that are difficult for bacteria to degrade during anaerobic digestion, resulting in lower biogas production (Ji et al., 2017). Table 2 also shows that similar percentages of CO_2 were also found between the CMC control and the R2 and R3 residues.

Regarding H_2S, R3 had a much higher content than the others (0.0783%). H_2S is considered an impurity in biogas; however, it is commonly produced. The combustion of H_2S and biogas produces sulfur dioxide (SO_2), which causes severe environmental problems and requires filtration (Amaral et al., 2019). A desulphurization process can also be used before combustion).

Furthermore, according to Colturato et al. (2016), high concentrations of sulfur can be found in vinasse and can result in biogas with H_2S values that can exceed 3%. Generally, it should be removed at concentrations below 0.02%. Thus, although R3 had 0.1287% of S, which resulted in 0.0783% of H_2S, this value is well below that found in the literature. About the biogas obtained from residues R1 and R2, these would not need to undergo a desulphurization process.

Figure 1 illustrates the kinetics of biogas (BBP) and methane (BMP) production per gram of accumulated volatile

Table 2. Biogas composition after anaerobic digestion in terms of methane (CH_4), carbon dioxide (CO_2), and hydrogen sulfide (H_2S) for the CMC control and the residues R1, R2, and R3

Variables	Unit	CMC control	R1	R2	R3
CH_4	%	53	44	58	57
CO_2	%	45	32	40	40
H_2S	%	0.0172	0.0115	0.0151	0.0783

CMC (microcrystalline cellulose), R1 (banana pseudostem bagasse), R2 (banana peels), and R3 (vinasse)

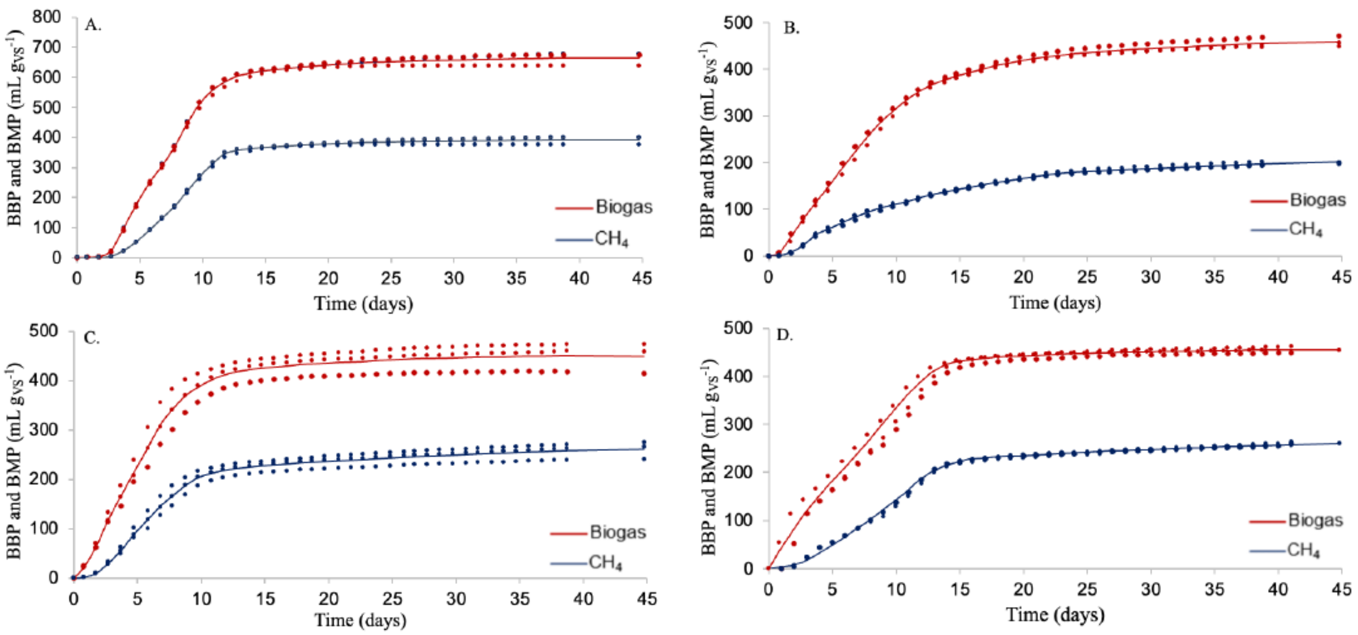

Figure 1. Profile of biogas (BBP) and methane (BMP) production per gram of accumulated volatile solids for the CMC (microcrystalline cellulose) control (A) and the residues R1 (banana pseudostem bagasse) (B), R2 (banana peels) (C), and R3 (vinasse) (D)

solids for each residue. It can be seen that R2 and R3 reached stabilization more quickly compared to R1, indicating the greater ease of degradation of residue rich in banana peels and pulp caused by the greater ease of bacteria in degrading these types of residues (Cesar Neto et al., 2020).

Table 3 shows the biochemical potential of biogas (BBP) and methane (BMP). The assay that used only the inoculum (positive control) in anaerobic digestion produced 23 $mL_{Biogas}\ g_{vs}^{-1}$, a value lower than that obtained in the other assays. It is observed, then, that the inoculum, as it presents BBP corresponding to only 3.5% of the BBP of the CMC Control and 5.0% of the BBP of residues R1, R2, and R3, did not influence the biochemical potential of biogas and methane.

Based on the BBP values of the CMC control and the residues R1, R2, and R3, it can be seen that the CMC control (Table 3) was statistically superior to the R1, R2, and R3 residues, which in turn showed no statistically significant difference between them, remaining at around 454 mL g_{vs}^{-1}. This behavior may be related to the fact that microcrystalline cellulose (CMC), considered a standard in biogas production (VDI, 2006), is more readily available to the inoculum since the cellulose present in residues R1, R2, and R3 has not been treated to reduce its crystallization. To verify the satisfactory activity of the mesophilic inoculum, the BBP value of the CMC control must be higher than 85% of the standard value of 750 $mL_{Biogas}\ g_{vs}^{-1}$, i.e., above 634 $mL_{Biogas}\ g_{vs}^{-1}$ (VDI, 2006). Thus, the biological activity of the inoculum was satisfactory because the CMC control had a BBP value of 664 $mL_{Biogas}\ g_{vs}^{-1}$.

It can be seen that R2 and R3 had the same BMP (260 $mL_{CH4}\ g_{vs}^{-1}$) (Table 3), indicating adequate anaerobic decomposition of these residues. Values of up to 750 mL g_{vs}^{-1} and a composition of approximately 50% CH_4 are expected in terms of biogas production when carbohydrates are used as a substrate (VDI, 2006). Thus, as the biogas from residues R2 and R3 have 58 and 57% CH_4, respectively, in their composition, this residue complies with the VDI 4630 standard (VDI, 2006). As for R1, its higher TS value (24.51%) and C:N ratio (81.6:1) (Table 1) were expected to lower its methane performance.

In this study, the value of 260 $mLCH_4\ g_{vs}^{-1}$ was found for the R2 residue (Table 3), which corresponds to banana peels without the juice, i.e., 42% higher than that obtained by Serna-Jiménez et al. (2021) (182 $mL_{CH4}\ g_{vs}^{-1}$) who used banana peels as a substrate. In these two studies, the inoculum contained anaerobic sludge. The study by Rempel et al. (2019), who used the same type of inoculum as in this study but *Spirulina platenses* as a substrate, found a BMP value of 326 $mL_{CH4}\ g_{vs}^{-1}$, 25% higher than the highest BMP (260 $mL_{CH4}\ g_{vs}^{-1}$) value obtained in this study, with R2 and R3. When the same substrate, *Spirulina platenses*, was used with another inoculum (Varol & Ugurlu, 2016), a BBP value of 640 $mL_{CH4}\ g_{vs}^{-1}$ was found, which was around 40% higher than the BBP of the residues R1, R2, and R3. Using vinasse from sugarcane ethanol production, Volpi et al. (2022) obtained BMP values of 507 $mL_{CH4}\ g_{vs}^{-1}$, practically double that obtained in R3 (260 $mL_{CH4}\ g_{vs}^{-1}$), proving the influence of the type of substrate on the BMP values obtained.

Table 3. Biochemical potential of biogas (BBP) and methane (BMP) for the positive control, CMC control, and the residues R1, R2, and R3. Means ± SD (standard deviation) with the same letters in the lines are equal by the Tukey test at $p \leq 0.05$

Variable	Positive control	CMC control	R1	R2	R3
BBP ($mL_{Biogas}\ g_{vs}^{-1}$)	23 ± 2 c	664± 23 a	459 ± 12 b	449 ± 30 b	455 ± 7 b
BMP ($mL_{CH4}\ g_{vs}^{-1}$)	-	352 ± 12 a	201 ± 5 b	260 ± 18 c	260 ± 4 c

CMC (microcrystalline cellulose); R1 (banana pseudostem bagasse); R2 (banana peels); R3 (vinasse)

The Gompertz model was applied to the biogas kinetics, as shown in Table 4. The kinetic parameters and coefficient of determination (R^2) were determined for residues R1, R2, and R3.

All three residues showed rapid adaptation ($\lambda < 1$ day), with R3 having no "lag" phase. R2 had the highest r_m (53 mL.g_{vs}^{-1} per day). This result confirms what was previously evaluated (Table 1) in terms of TS, where R2 presented the lowest value (15.33%) and the C:N ratio (20.3:1) within the ideal range for anaerobic digestion 10-30:1 (Amaral et al., 2019). However, all three residues (R1, R2, and R3) showed a higher maximum velocity than that obtained by Santos et al. (2020), who studied the potential for generating biogas from orange bagasse agro-industrial waste (29.02 mL.g_{vs}^{-1} per day) and passion fruit peel (17.3 mL g_{vs}^{-1} per day) and, by Sonwai et al. (2019) obtained r_m of 25.8 mL g_{vs}^{-1} per day when using fresh grass as a substrate.

The maximum biogas potentials (A) were statistically similar for R1, R2, and R3 (448 mL g_{vs}^{-1}), indicating that the Gompertz model can adjust the biogas curves for these substrates. The fit was confirmed by high correlation values ($R^2 > 0.99$). These values were statistically equal to the experimental values (454 mL g_{vs}^{-1}).

Figure 2 shows a graphical profile of the cumulative biogas production of residues R1, R2, and R3, comparing experimental data with estimated data using the Gompertz mathematical model.

Table 4. Kinetic parameters obtained with the Gompertz model: "lag" phase (λ), maximum production speed (r_m), maximum biochemical potential of biogas (estimated) (A), and coefficient of determination (R^2) for residues R1, R2, and R3. Means ± SD (standard deviation) with the same letters in the lines are equal by the Tukey test at $p \leq 0.05$

Parameters	R1	R2	R3
λ (day)	0.60 ± 0.25 a	0.62 ± 0.07 a	0.00 ± 0.00 b
r_m (mL g_{vs}^{-1} per day)	35 ± 1 a	53 ± 7 b	40 ± 1 c
A (mL g_{vs}^{-1})	446 ± 10 a	443 ± 24 a	454 ± 6 a
R^2	0.997	0.998	0.992

R1 (banana pseudostem bagasse), R2 (banana peels), and R3 (vinasse)

Figures 2A and B show adequate fit for practically the entire period (45 days). Figure 2C does not show a good fit for the initial period. For this reason, the Gompertz model is indicated for modeling curves of this type. It allows for simple and straightforward interpretation and has been widely studied (Arreola-Vargas et al., 2016; Gaspareto et al., 2020).

To project the volume (m^3) and speed (m^3 per day) of biogas and methane generated and the potential for generating electrical energy (EE) from residues R1, R2, and R3, the mass of 3.8 kg of R1 + 2.7 kg of R2 + 1.2 kg of R3 generated when obtaining the substrate for bioethanol production (7.7 L), were used as the base. It can then be said that bioethanol production generated solid residues R1, R2, and R3 in the wet mass ratio of 3.2:2.3:1.0, respectively, equivalent to 0.49 kg_{R1} L_{Cc}^{-1}, 0.35 kg_{R2} $L_{Cc}^{-1,}$ and 0.16 kg_{R3} L_{Cc}^{-1}.

This substrate volume (7.7 L) can generate 308.0 g of bioethanol considering an average concentration of 40.0 g L^{-1} (5 °INPM or 6.3 °GL at 20 °C). It can be estimated that to produce 1 m^3 of fermented broth, around 1000 kg (1 ton) of wet disposal will be generated (Ûchoa et al., 2021) and 40,000 g of bioethanol.

As quantified above, 23,000 kg of residues will be generated to produce 1 m^3 of bioethanol and 23 m^3 of substrate will be needed to produce 1 m^3 of bioethanol. Taking the ratio between the residue mass and substrate volume, 11270 kg of R1, 8050 kg of R2, and 3680 kg of R3 will be generated by producing 1 m^3 of bioethanol. Considering these values, Table 5 shows the projected volume and potential for generating electricity from the biogas and methane generated based on the VS, BBP, BMP, and rm values obtained for R1, R2, and R3 residues.

The potential for generating electricity and methane was projected considering VS, BBP, BMP, and r_m, with R1 standing out with daily CH_4 production of 40.6 m^3 per day and the higher potential for generating electricity of 84.4 kWh per day and R2 with daily CH_4 production of 35.6 m^3 per day and potential for generating electricity of 74 kWh per day, similar

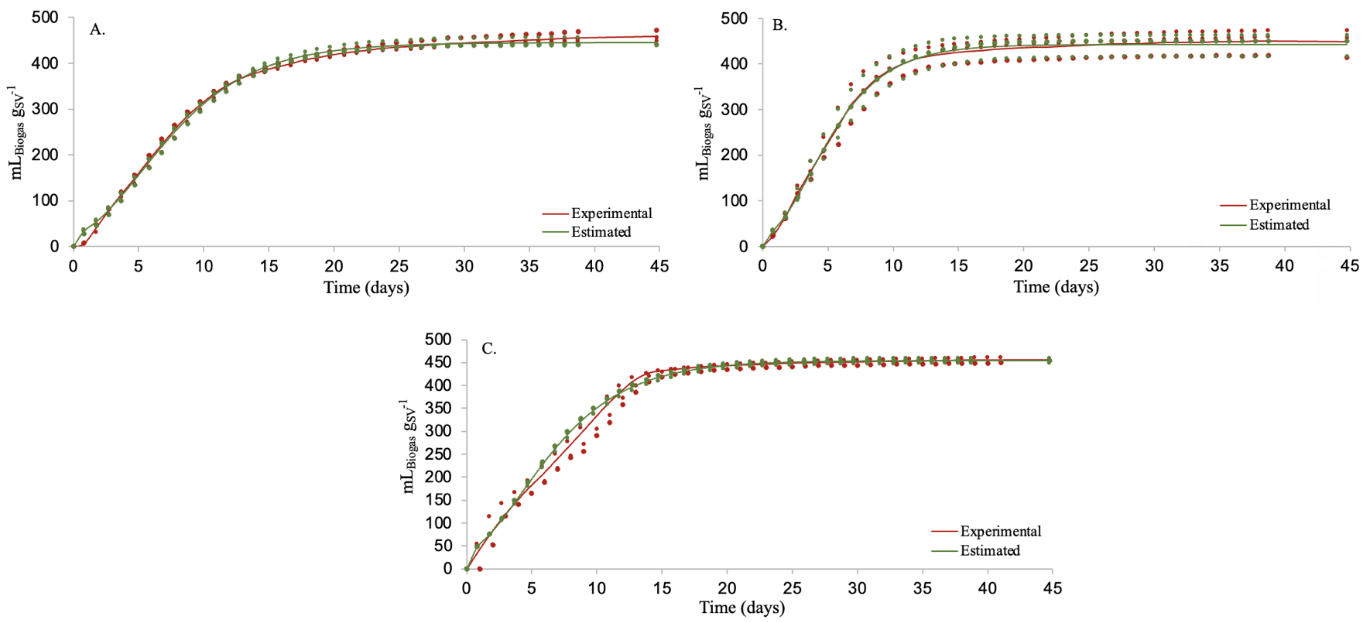

Figure 2. Experimental and estimated biogas accumulation profile for R1 (banana pseudostem bagasse) (A), R2 (banana peels) (B), and R3 (vinasse) (C)

Table 5. Estimate of the volume (m³) and speed (v - m³ per day) of biogas (V_{Biogas}) and methane (V_{CH4}) generated and the potential for generating electricity (EE) from residues R1, R2, and R3, predicting the production of 1 m³ of bioethanol

Variables	R1	R2	R3	Total
VS (%)	23.49	14.41	20.25	-
BBP (L_{Biogas} kg_{vs}^{-1})	459	449	455	-
BMP (L_{CH4} kg_{vs}^{-1})	201	260	260	-
r_m (L kg_{vs}^{-1} per day)	35	53	40	-
Residues produced (kg)	11,270	8,050	3,680	23,000
V_{Biogas} (m³)	1,215.1	520.8	339.1	2,075
v (m³ per day)	92.6	61.5	29.8	183.9
V_{CH4} (m³)	532.1	301.6	193.7	1,027.4
v (m³ per day)	40.6	35.6	17.0	93.2
EE (kWh per day)	84.4	74	35.3	193.7

R1 (banana pseudostem bagasse); R2 (banana peels); R3 (vinasse); VS - volatile solids; BBP - biochemical biogas potential; BMP - biochemical methane potential; r_m - maximum production speed (L kg_{vs}^{-1} per day)

to those obtained with R1. On the other hand, R3, the residue with the lowest mass (3,680 kg), consequently had the lowest daily production of biogas and CH_4 and the lowest potential for generating electricity among the three residues.

However, according to Uchôa et al. (2021), the pre-treatment of wet pseudostem bagasse to produce pseudostem juice is costly and energy-intensive, accounting for 97% of total costs, such as pressing, crushing, and filtering, in addition to the costs of acid hydrolysis, neutralization, and enzymatic hydrolysis. R2, on the other hand, stood out due to its low generation costs and lack of chemical treatments, requiring only the crushing and filtering of the banana peels, i.e., R2 has lower generation costs. It should be remembered that banana peels do not undergo chemical or enzymatic treatment. The residue R3 had a high content of H_2S, 0.0783%, above 0.02%, and should undergo a desulphurization process (Colturato et al., 2016) so that methane gas can be used safely and efficiently.

Therefore, if the residues are used separately to generate methane gas, it is suggested to use residue R2, the solid part in the production of banana peel juice. In addition to having daily methane and energy values similar to R1 and higher than R3, this residue requires the least cost to generate. However, R1, R2, and R3 are generated in the bioethanol production process from banana biomass. If the three residues were concomitantly used in biogas generation, there could be a daily production of CH_4 of 93.2 m³ per day and an electrical energy generation potential of 193.7 kWh per day, although confirmatory tests are needed. It is important to note that the experimental tests were conducted in batches, so the projected values could be lower on a real scale.

Considering the production of bananas in Santa Catarina in 2022 (714,252,000 kg) according to EPAGRI/CEPA (2022) and using the values obtained in this study, it can be estimated a biogas production of 64,437,952.2 m³, CH_4 production of 31,905,326.3 m³, and electricity generation potential of 6,015,244 kWh per day. In the Joinville micro-region, which is the leading banana producer in Santa Catarina, production in 2022 was around 354,000,000 kg (EPAGRI/CEPA, 2022), which would result in an estimated biogas production of 31,936,956.5 m³, CH_4 production of 15,813,026.1 m³, and electricity generation potential of 2,981,295.6 kWh per day.

Estimated values for CH_4 production and electricity are crucial for assessing the performance of methane gas production systems. The estimate for banana production in Santa Catarina suggests significant potential for generating biogas and electricity. However, factors such as residue availability, treatment, and technology influence the choice.

Conclusions

1. In the bioethanol production from banana biomass, 3.8 kg of solid residue from banana pseudostem bagasse, 2.7 kg of solid residue from banana peels, and 1.2 kg of vinasse totaled 7.7 kg. The three residues met the optimum macronutrient ratios for biogas production. However, in the case of vinasse, the excessive presence of sulfur generated H2S (0.0783%), which requires treatment of the biogas before.

2. The residues from banana peels and vinasse proved to be more suitable, with higher CH_4 (260 mL_{CH4} g_{vs}^{-1}) than the residue from banana pseudostem bagasse (201 mL_{CH4} g_{vs}^{-1}), promoting a better response in terms of anaerobic digestion.

3. The non-linear Gompertz model showed an excellent descriptive capacity of the biogas production kinetics for the three solid residues: banana pseudostem bagasse, banana peels, and vinasse, with R^2 greater than 0.99.

4. Considering the estimation of bioethanol production, for 1 m³, 23,000 kg of residue would be generated, 11,300 kg of which would be banana pseudostem bagasse, 8,000 kg of banana peels, and 3,700 kg of vinasse, in turn, could produce 40.6, 35.6 and 17.0 m³ per day of methane and, consequently, 84.4, 74.0, and 35.4 kWh per day of electricity, respectively.

5. The three residues, banana pseudostem bagasse, banana peels, and vinasse, have enormous potential for producing biogas and methane due to the high degradation rate of their compounds. In addition, the composition of the biogas meets the criteria for use, with adequate percentages of CH_4 and CO_2.

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