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ORIGINAL PAPER

Dry Anaerobic Digestion of Food Industry by-Products and Bioenergy Recovery: A Perspective to Promote the Circular Economy Transition

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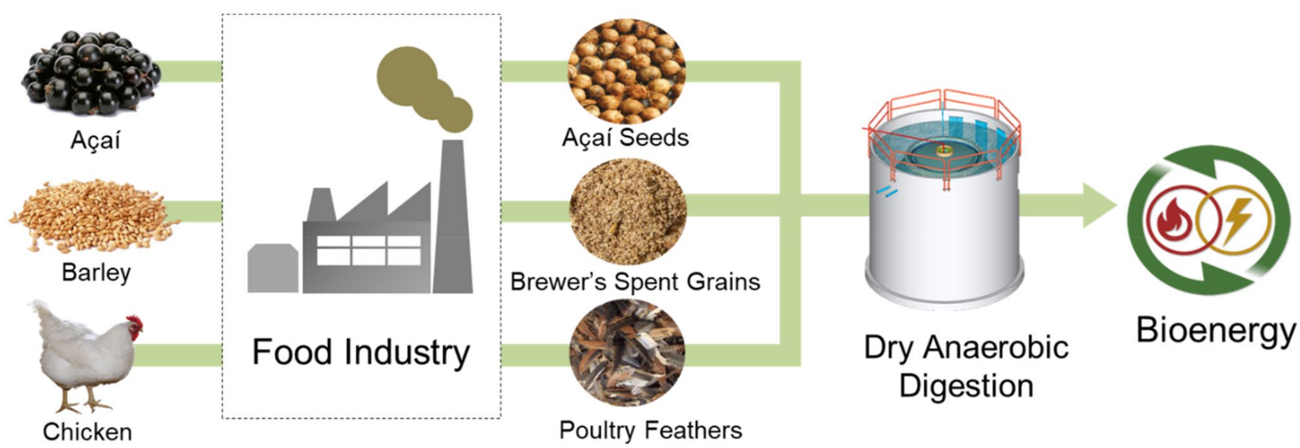
Abstract

Anaerobic digestion (AD) can be a suitable alternative for agro-industrial by-products energy recovery, contributing to reducing environmental side effects caused by incorrect disposal of these materials. In this study, dry AD reactors were started-up with açaí seeds, brewer's spent grains (BSG), and poultry feathers, all solid by-products generated from the food industry. The results demonstrated that during 22 days of dry AD, the BSG reactor presented the best operational performance, as follows: (i) highest solids biodegradation (up to 70%); (ii) accumulated biogas volume (up to 10 L); (iii) methane composition (57.49%); and (iv) methane yield (39.51 L CH_4 kg^{-1} total volatile solids). The biogas combustion in a combined heat and power engine could locally generate electric (0.101 MWh ton^{-1} BSG) and thermal energy (455.21 MJ ton^{-1} BSG), which could be used to self-supply the industrial facility, avoiding greenhouse gas emissions (0.03 ton CO_{2eq} ton^{-1} BSG) from the traditional energy sources. Based on the experimental dataset, the dry AD of agro-industrial by-products can be a promising approach to produce methane-rich biogas, being mainly of interest for the beer industry, as an alternative for energy recovery in a circular economy concept.

Graphical Abstract



Keywords Food waste · Food supply chain waste · Bioenergy · Biofuel · Methane · Biorefinery

Statement of Novelty

This study evaluated the dry anaerobic digestion of agro-industrial by-products for bioenergy recovery. The reactors were configured with 25% of by-products from the food

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industry and operated for 22 days in batch mode. The operational performance demonstrated that the reactor started up with brewer's spent grains presented better results when compared to açaí seeds and poultry feathers. The use of food industry by-products as a feedstock enables the dry anaerobic digestion technology application as a promising approach to produce methane-rich biogas, being an alternative for bioenergy recovery in a circular economy.

Introduction

Brazilian agro-industrial sector is responsible for the generation of a significant amount of solid by-products [1], as is the case of the açaí processing industry, beer production, and poultry slaughter. Figure 1 provides the flow diagrams of the generation of different by-products in their respective industrial processes. The generation of solid and liquid waste occurs daily in the food industry, from washing, cleaning, processing, and finishing operational steps. The most abundant renewable biomass is composed of lignocellulose and organic materials, making it a suitable feedstock for energy recovery [2–5]. Beyond, innovative solutions to improper disposal of waste in landfills are urgently necessary to mitigate greenhouse gas (GHG) emissions [6, 7]. Furthermore, the integration between waste treatment and bioenergy production can be a solution to reconcile energy renewability and environmental preservation [3, 8, 9]. Especially, the replacement of fossil energy by renewable ones is urging sustainable development goals [10]. The biogas obtained from anaerobic digestion (AD) can be converted into electrical and thermal energies, as well as biomethane as an alternative for vehicular fuel [11].

The edible part of açaí fruit (*Euterpe oleracea* Martius), which corresponds to only 10% of the total mass, is primarily used for pulp processing (Fig. 1a). The remaining biomass (90%, mainly composed of seeds) is a solid by-product with high energy recovery potential by AD [4, 9, 12]. Açaí seeds is a lignocellulosic material composed of cellulose (53%), lignin (22%), and hemicellulose (12%), being an excellent source for energy recovery [4, 9, 13].

In the brewing process, the most abundant final solid by-product is the brewer's spent grains (BSG), an insoluble biomass consisting mainly of barley husks (Fig. 1b) [14]. BSG represents about 85% of the solid waste generated in the process, and it is estimated that every 100 L of beer produced generates approximately 20 kg of dry spent grains [15]. In Brazil, the annual production of BSG is estimated at 2.8×10^6 tons year^{-1} (in wet basis) [14]. BSG is a lignocellulosic biomass rich in fibers, containing about 25% cellulose, 28% hemicellulose, 27% lignin, and 24% proteins, which can be used for biofuel production [16, 17].

In poultry processing (Fig. 1c), the carcass (heart, liver, gizmo, and feet) corresponds to approximately 83% of the live bird. The 17% inedible by-products, including head, feather, blood, viscera, skin, fat, and bones, could be converted into new products [18, 19]. Usually, the inedible poultry feathers undergo into feather flour processing. When not, it represents a major environmental issue [20]. The poultry feathers characterization demonstrates that this material has potential to be used for biogas production under anaerobic conditions [21–23].

Based on the composition of açaí seeds, BSG, and poultry feathers, a well-consolidated and environmentally friendly technology for waste management should be adopted. Then, AD could be a proper technology for the revaluation of those by-products [12, 24]. Likewise, the abundance and low cost of these by-products confirm the potential for new energy and materials recovery strategies, which can be profitable in a biorefinery concept [25, 26]. AD can be placed among renewable and sustainable green technologies for bioenergy production [27–29]. Nevertheless, the start-up phase of AD reactors with high solid content (called dry regime for 15 to 30% solids load) may present a challenge, since high solids and organic substrates could promote negatives effects to the microbiological conversion, decreasing the biogas production [30, 31].

Considering the growing generation of solid by-products from the food industry [32], AD can be an alternative for biogas production. From an economic perspective, the global biogas market is expected to reach $50 billion by 2026 [33]. Moreover, AD could contribute to the economy decarbonization and country's state policies towards reducing environmental side effects caused by improper solid waste disposal [9, 27].

Based on the above, this study aimed to assess the start-up of dry AD reactors as an alternative for food industry waste management. For this, açaí seeds, BSG, and poultry feathers were treated for 22 days to obtain the reactor setup parameters, biogas production, and methane yields. Beyond, aiming to provide a more comprehensive assessment of the bioenergy recovery, the potential for electric and thermal energy generation was estimated from the biogas combustion in a combined heat and power engine, along with the corresponding GHG emissions avoidance to provide information over alternative strategies for the food industry towards the establishment of a circular economy.

Material and Methods

Solid Residues and Inoculum

The solid waste used in the dry AD were supplied by AmBev (Jaguariúna, SP, Brazil), Villa Roxa "*Açai e alimentação*"

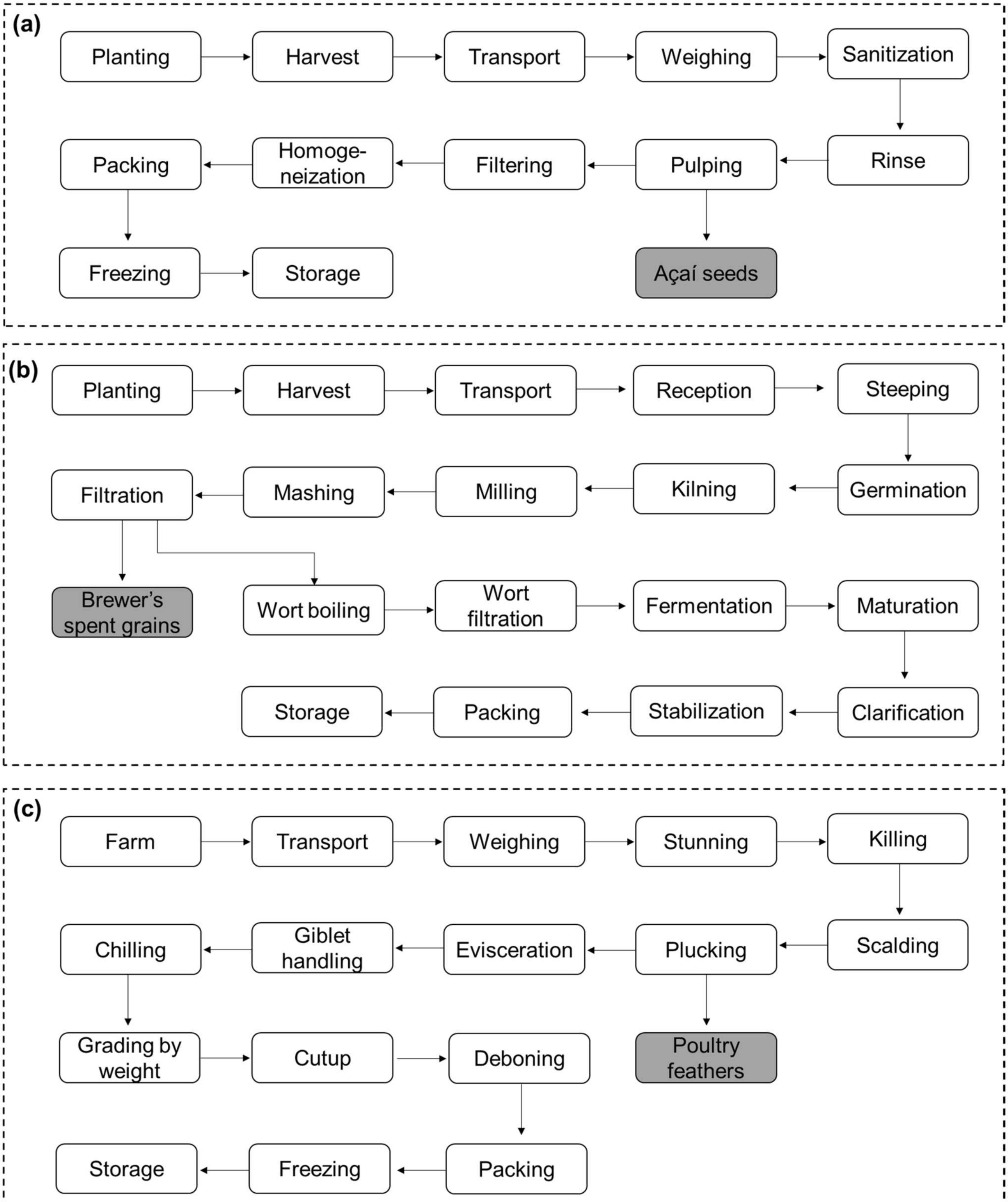

Fig. 1 Process flow diagram of the generation of different by-products in their respective industrial process. **a** açaí processing industry; **b** brewery industry; and **c** poultry slaughterhouse

(Bragança Paulista, SP, Brazil), and "*Empresa Oriente*" (Videira, SC, Brazil), respectively to BSG, açaí seeds, and poultry feathers. The solid industrial by-products (açaí seeds, BSG, and poultry feathers) were oven dried (Fenem, model 315 SE, São Paulo, SP, Brazil) (105 °C for 8 h), size reduced in a mill (Marconi, model MA 340, São Paulo, SP, Brazil) equipped with a 1 mm sieve, packed in a plastic bag, and stored at − 18 °C for later use in the experimental trials. The mesophilic inoculum was supplied by the company São Martinho S.A (Iracemápolis, SP, Brazil) and Coca Cola Femsa Company (Jundiai, SP, Brazil).

Experimental Configuration for Dry AD

Figure 2 shows the laboratory scale arrangement of the dry AD reactors. The stirred tank reactor fed with the solid by-products was kept in a batch regime. The total reactor volume of 6.8 L was configured for 40% (2.72 L) of headspace and 60% (4.08 L) of liquid phase for the substrate mixture [12, 34, 35]. The liquid phase was composed of 25% of solids (0.671 kg açaí seeds, 0.192 kg BSG or 0.368 kg poultry feathers), 45% of inoculum (1.87 kg), and 30% of water (1.2 L) (Fig. 1). During the reactor start-up, the system was kept under mesophilic temperature conditions (35 °C), adopting a heat exchanger (Tecnal, model TE-2005, São Paulo, SP, Brazil). In the first 10 days of AD, the pH of the substrate-reactor was not corrected to foster the hydrolysis and acidogenic reactions [36]. After the 10th day, the pH was kept from 7 to 8, with the addition of sodium hydroxide (6 mol L^{-1}) to support the methanogenic reactions [37]. The gases produced inside the reactor were collected in a Tedlar bag (Supelco Analytical) attached to the system and used to evaluate the biogas yield and composition. Substrate-reactor was analyzed to control the process efficiency.

Analytical Methods

Substrate-Reactor Characterization

Substrate-reactor was analyzed according to the Standard Methods for Examination of Water and Wastewater [38] for the following parameters: pH (method 4500-H^+ B); solids (total, volatile, and fixed) (method 2540B); alkalinity (method 2320 B); ammonia nitrogen (method 45,000-NH_3 C); and soluble chemical oxygen demand (COD) (method 5220 D). To perform the alkalinity, ammonia nitrogen, and COD analyses, the samples were diluted in deionized water and stirred (150 rpm) for 2 h; while for analysis of solids, the samples were not diluted. Solid biodegradation (SB) was calculated based on Eq. 1.

$$SB\,(\%) = \frac{\text{Solids before AD} - \text{Solids after AD}}{\text{Solids before AD}} \times 100 \quad (1)$$

Biogas Volume and Composition

Biogas was collected daily and measured. The accumulated biogas volume Eq. 2 was applied, where V is the biogas volume, and *n* is the number of days analyzed.

$$\text{Accumulated biogas volume(L)} = \sum_{n=1}^{n_i} V_n \quad (2)$$

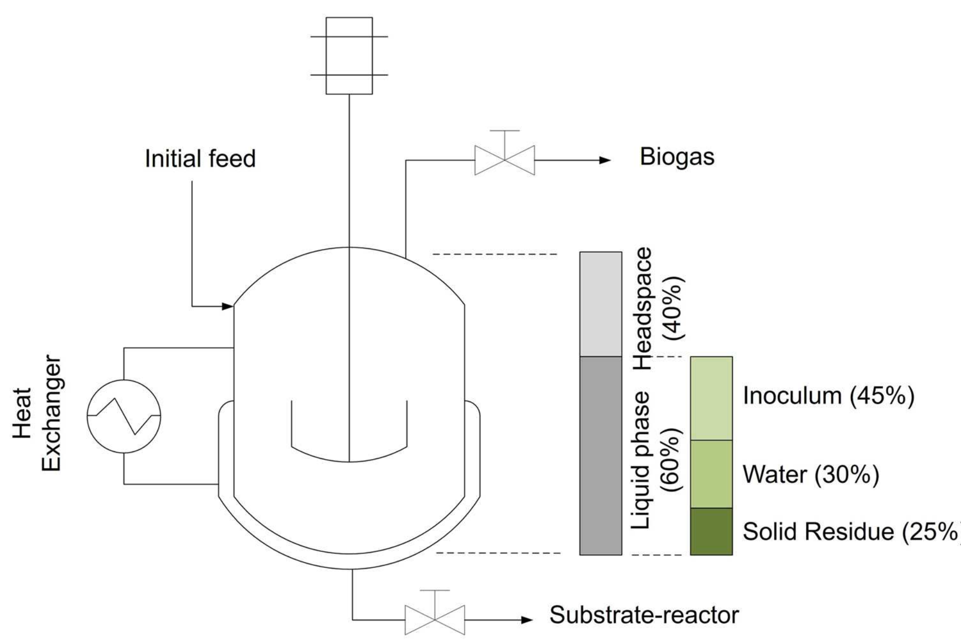

Fig. 2 Scheme of dry AD reactor operated in batch mode and its start-up conditions

The biogas composition was determined using a gas chromatograph (Shimadzu®, model GC 2014, Kyoto, Japan) equipped with a thermal conductivity detector. The determination of O_2, H_2, CH_4, and CO_2 was accomplished with a micro-packed column (length of 6 m and an internal diameter of 3 mm) (ShinCarbon, ST 50/80 mesh). The following chromatographic conditions were applied: injection port and detector temperatures were set to 200 °C; GC column initial temperature was 50 °C (held for 3 min), and then, increased by 5 °C min^{-1} to 180 °C (held for 5 min); the sample volume injected was 0.5 mL; and N_2 was used as carrier gas (35 mL min^{-1}, 5 bar).

The accumulated methane yield was determined according to the Eq. 3, where V is the biogas volume, *n* is the number of days analyzed, M is the methane content (%), and TVS is the content of total volatile solids in the reactor.

$$\text{Accumulated methane yield}\left(\text{L CH}_4\text{kg}^{-1}\ \text{TVS}\right) = \sum_{n=1}^{n_i} \frac{V_n \times M}{TVS} \quad (3)$$

Potential for Electricity and Heat Generation

The potential of electrical (Eq. 4) and thermal energy (Eq. 5) that could be generated from the biogas produced by AD in a combined heat and power engine was estimated for the different by-products [39]. For both estimations (EG_{CH_4} and HG_{CH_4}), it was assumed that the generation was accomplished on site:

$$EG_{CH_4} = Q_{biogas} \times LCV_{CH_4} \times C_m \times \eta_e \times CF \quad (4)$$

$$HG_{CH_4} = Q_{biogas} \times LCV_{CH_4} \times C_m \times \eta_e \quad (5)$$

where: EG_{CH_4} is the potential electricity generation from experimental biogas yield (MWh ton^{-1} of solid waste); HG_{CH_4} is the potential heat generation from experimental biogas yield (MJ ton^{-1} of solid waste); Q_{biogas} is the biogas volume (m^3 of biogas per mass fed in the reactor); LCV_{CH_4} is the lower calorific value of methane (35.59 MJ m^{-3}); C_m is the percentage of methane in biogas (%); η_e is the engine efficiency (%), assumed as 40% for electric energy and 50% for thermal energy; and CF is the conversion factor from MJ to MWh.

Avoided GHG Emissions

The replacement of the electricity obtained from the national grid for a local more renewable source implies in avoided GHG emissions ($A_{GHG\text{-}EG}$), calculated according to Eq. 6. The same model was adopted to estimate the avoided GHG emissions due to heat generation ($A_{GHG\text{-}HG}$), assuming that the total volume of biogas generated was burned in co-generator (Eq. 7) [7].

$$A_{GHG-EG} = EF_{CO_2-EG} \times EG_{CH_4} \quad (6)$$

$$A_{GHG-HG} = EF_{CO_2-HG} \times HG_{CH_4} \quad (7)$$

where: EG_{CH_4} is the electricity generated (MWh ton^{-1}); HG_{CH_4} is the heat generated (MJ ton^{-1}); EF_{CO_2-EG} is the emission factor of CO_{2eq} for 2019 national electric energy generation; and EF_{CO_2-HG} is the emission factor of heat energy.

The emission factor for the grid (EF_{CO_2-EG}) was the annual mean value (from January 2019 to December 2019), reported from official data of the Ministry of Science, Technology, Innovation, and Communication [40], 0.075 tons of CO_{2eq} per MWh of electricity. The emission factor of heat energy (EF_{CO_2-HG}) was assumed as 0.056 tCO_{2eq} GJ^{-1} [41], for the replacement of natural gas for biogas in the boiler.

Industrial Energy Balance

For the technological transfer of dry AD and to support the implementation of a biorefinery, a global industrial energy balance was assessed. In the scenario proposed, batch reactors operated with açaí seeds, BSG, and poultry feathers were integrated for bioenergy recovery. All the calculations accomplished for the industrial energy balance were based on the laboratory dataset obtained in this study.

Results and Discussion

Dry AD Performance Under Batch Operation

pH and Alkalinity

In the AD process, the microbiological community involved in the reactions requires different optimal pH values for growth [42]. In the present study, the pH was adjusted just after the 10th day of digestion, and during the first 10 days, the pH was not controlled to favor hydrolysis and acidogenesis reactions [36]. In the initial digestion period, the reactors fed with açaí seeds and BSG presented pH lower than 7, and after the correction, the pH was maintained between 7 and 8 (Fig. 3a). Otherwise, the poultry feather reactor was stable during all the digestion period. Hence, after the 10th day of AD, the pH was stabilized between 7 and 8 to develop the methanogenic microbiota, responsible for the methane production [43].

Depending on the substrate and AD technique employed, the pH can vary until it reaches stabilization, and the

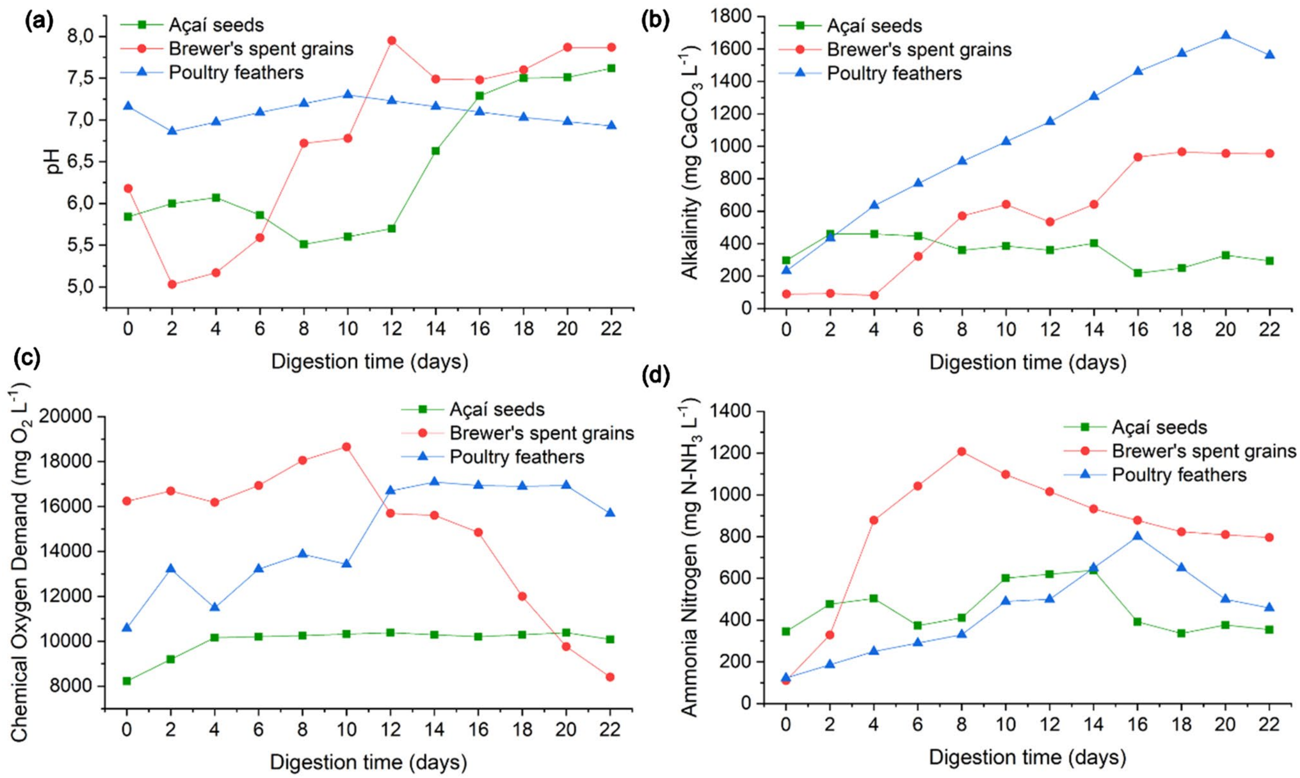

Fig. 3 Main operating parameters evaluated in the dry anaerobic reactors operated in batch mode with açaí seeds, brewer's spent grains, and poultry feathers. **a** pH; **b** alkalinity; **c** chemical oxygen demand; and **d** ammonia nitrogen

oscillation is commonly observed in reactors start-up [44, 45]. Alkaline pH levels (approximately 8) can disintegrate microbial granules, and pH below 6.6 can reduce the growth rate of the methanogenic bacteria, which is not an advantage for methane production [46]. Acetogenic and methanogenic bacteria are more difficult to adapt to pH changes than other microorganisms, as they produce volatile organic acids that are converted into acetic acid, hydrogen, and carbon dioxide, which results in acidification of the environment that negatively influences the methanogenic bacteria activity [29, 46, 47].

The concentration of alkalinity can be associated with pH levels, representing the ability of a system to neutralize weak acids. Therefore, it can be related to the buffering capacity of the AD reactor. High-alkalinity solution does not report a significant change in pH since the free ions neutralize the weak acid. In contrast, a low-alkalinity solution shows a reduction in pH by a weak acid [48, 49]. Figure 3b presents the alkalinity evolution in the dry batch AD reactors. The reactor fed with açaí seeds presented relatively constant alkalinity along the digestion period. However, for the reactors fed with poultry feather and BSG, a continuous increase was obtained. This alkalinity increase may be related to accelerated bicarbonates and carbonates production as a consequence of the pH [48]. For AD reactors, stable systems operate with total alkalinity values between 1000 and 3000 mg $CaCO_3$ L^{-1} [49], while açaí seeds and BSG batch reactor presented alkalinity lower than 1000 mg $CaCO_3$ L^{-1}. It is worth observing that after the 16th day of AD, the alkalinity value was stabilized, demonstrating the buffering capacity, and corroborating with the pH data (Fig. 3a), indicating a positive operational performance.

Chemical Oxygen Demand

The AD efficiency should be evaluated by its organic matter contents, and soluble chemical oxygen demand (COD) is widely used for this purpose [50]. From Fig. 3c, it is notable that the COD of AD reactors fed with BSG and poultry feather increased from the initial digestion day until the 10th and 12th days, respectively. This result can be associated with the pH conditions established for the reactor's start-up focused on the hydrolysis and acidogenesis AD phases. Besides, the soluble COD increase was related to increasing organic matter solubilization. After this increase in the hydrolysis and acidogenesis phase, different features can be observed for each solid waste. For the BSG reactor, an expressive reduction (48%) was obtained after the 12th day of AD, which can be attributed to the consumption of organic matter for biogas production. For poultry feather and açaí seeds reactors, a stable COD was observed until the end of digestion (22 days), demonstrating that the feedstock presents a complex composition to degradation by methanogenic bacteria. For the AD reactor operated with açaí seeds, the large amount of lignocellulosic material can be complex to degradation [4, 35, 51, 52], with a lower elimination of organic matter when compared to the initial and final digestion times. Maciel-Silva et al. [4] reported that a long time during the hydrolysis and acidogenesis phase could be an alternative to reduce the COD content in the reactor. Therefore, for a complete reduction of COD for waste management of solid substrates, different operational conditions should be assayed to promote different degradability rates and remove all the organic content.

Ammonia Nitrogen

Ammonia is the final product of AD, and optimal ammonia nitrogen concentrations are necessary for methane production. Low (500 mg $N\text{-}NH_3$ L^{-1}) and high (4000 mg $N\text{-}NH_3$ L^{-1}) concentrations of ammonia nitrogen inhibit methane production, which is not favorable for AD methanogenic regime [53, 54]. In general, for the reactors evaluated in this study, after the methanogenic phase, high concentrations of ammonia nitrogen were not observed, and the AD process was not inhibited. The evolution of the ammonia nitrogen during the AD process (Fig. 3d) was evaluated in association with methane production. The ammonia nitrogen in the reactors varied from 200 to 1200 mg $N\text{-}NH_3$ L^{-1}. The BSG reactor presented a significant increase in the ammonia nitrogen content, which can be related to the degradation of nitrogen compounds (proteins) during the hydrolysis phase since BSG presents an expressive proteins content [21, 47, 54]. The mentioned reactor suggests a better digestion performance, which corroborates the COD reduction and the biogas yield [29]. Besides, when comparing ammonia nitrogen with pH, alkalinity, and COD, it can be inferred that the reactors fed with açaí seeds and poultry feather should be optimized to control the operational conditions for a better methane yield.

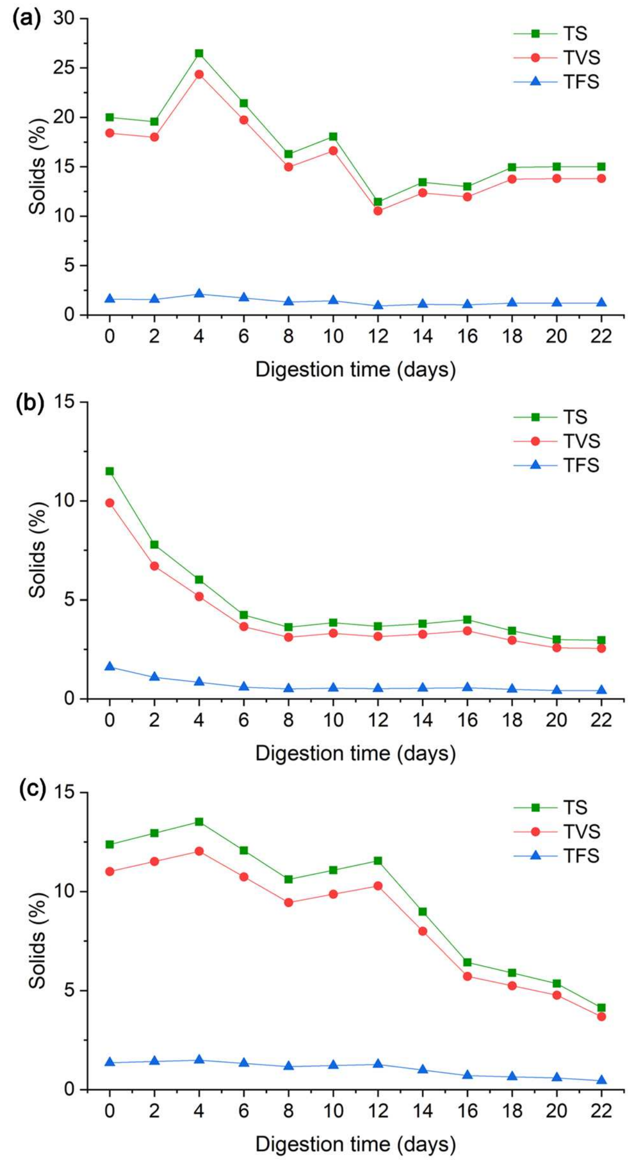

Fig. 4 Evolution of total solids (TS), total volatile solids (TVS), and total fixed solids (TFS) in the dry anaerobic reactors operated with food industry by-products. **a** açaí seeds; **b** brewer's spent grains; and **c** poultry feathers

Solids and Solids Biodegradation

Total solids content is the most critical parameter to evaluate the microbial activity efficiency in the degradation of solid substrates. After the 22nd day of AD, the total solids significantly reduced in all the reactors (Fig. 4). In the BSG reactor, the solid's content decreased rapidly during the initial days of AD. The reactors fed with açaí seeds and poultry feathers presented an initial solid content of around 13%, and after the digestion, lower than 5%. To express the efficiency of waste reduction for methane production, solids reduction is widely applied [55]. The solids biodegradation after 22 days revealed a decrease of 74.2% (BSG), 66.6% (poultry feather), and 25% (açaí seeds) (Fig. 5), indicating high levels of microbial activity, especially for the reactors operated with BSG and poultry feather. Beyond, the dry batch AD reactors evaluated in this study presented higher solids biodegradation when compared with the literature [28, 56], which demonstrates that the start-up phase was positive to the organic matter biodegradation [57]. In the hydrolysis and acidogenesis reactions (initial days of AD), the microbiological community hydrolyzed the compounds

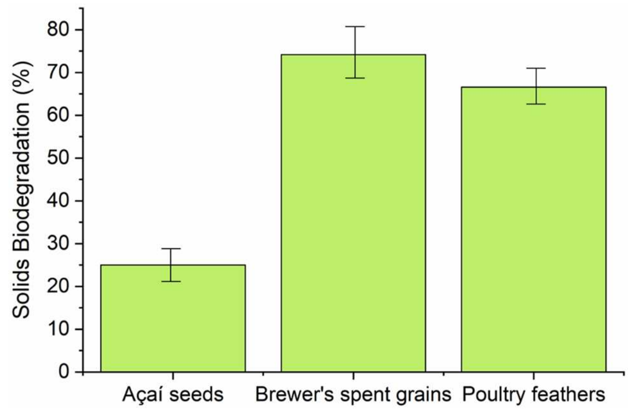

Fig. 5 Solid biodegradation (%) in the dry anaerobic reactor operated in batch mode with açaí seeds, brewer's spent grains, and poultry feathers

with complex chemical structures (lignocellulose, proteins, and lipids) into simple compounds, reducing the solids in the system [29, 58, 59].

Biogas Production and Composition

The biogas volume produced from the dry AD reactors was regularly measured (Fig. 6). Daily biogas volume (Fig. 6a), accumulated biogas volume (Fig. 6b), and accumulated methane yield (Fig. 6c) were evaluated. In general, the BSG reactor presented the highest daily biogas productivity, approximately 500 mL per day. For açaí seeds and poultry feathers, the daily volume obtained was lower than 250 mL, half of that obtained for BSG. For the accumulated biogas volume after 22 days of AD, the BSG reactor presented 10,949 mL, followed by poultry feather (4760 mL), and açaí seeds (5080 mL). From the accumulated methane yield (Fig. 5c), BSG seems to be the most appropriate feedstock for dry AD (39.5 L CH_4 kg^{-1} TVS). This value was around 2-fold higher than açaí seeds (19.82 L CH_4 kg^{-1} TVS) and 4-fold higher than poultry feathers (10.1 L CH_4 kg^{-1} TVS).

The biogas production can be associated with the operational performance related to the substrate-reactor characterization (Table 1). The significant decrease in COD (Fig. 3c) and solids (Fig. 4) for the BSG reactor were the most critical factors for the higher biogas yield. The reduction in the total solids and COD were strongly related to the increase in biogas production, corroborating with the literature [60]. Beyond, the water activity in the mixture and its relationship with the microorganisms present, involving extrinsic factors (temperature, irradiation, oxygen, and chemical treatments) and intrinsic factors (pH, nutritional potential, and antimicrobial components) [61], affects the biogas production. Another inference for the lower biogas productivity for açaí seeds and poultry feathers could be associated with the harder degradation. The applied time would not be enough for the medium adaptation to the substrate, affecting the organic load conversion into biogas [60]. Accordingly, as previously suggested, a longer digestion time can promote a better stabilization of the reactor, improving the organic matter biodegradability and, consequently, raising the biogas volume.

For the biogas composition, at the end of 22 days of AD, methane was obtained in more significant proportions in all the reactors evaluated. This is strongly related to the operational conditions since pH was kept between 7 and 8 to favor the acetogenesis and methanogenesis phases [29].

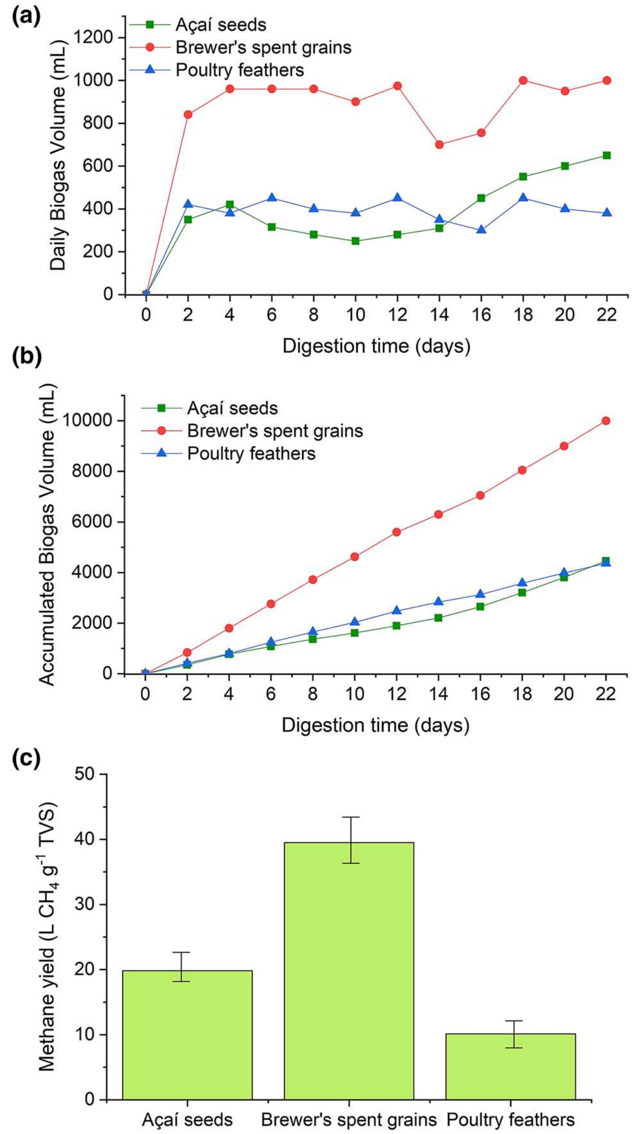

Fig. 6 Biogas produced in the dry anaerobic reactor operated in batch mode with açaí seeds, brewer's spent grains, and poultry feathers. **a** Daily biogas volume; **b** accumulated biogas volume; and **c** methane yield

Table 1 General parameters recorded to dry AD operated in batch mode with food industry by-products

Parameters	Unit	Digestion time	Dry AD operated in batch mode		
			Açaí seeds	BSG	Poultry feathers
pH	–	Initial	5.84	6.18	7.16
		Final	7.62	7.87	6.93
Alkalinity	mg $CaCO_3$ L^{-1}	Initial	298.11	89.67	232.67
		Final	293.72	955	1560.83
Chemical oxygen demand	mg O_2 L^{-1}	Initial	8221.3	16,239.6	10,584.5
		Final	10,082.7	8407.1	15,695.25
Ammonium nitrogen	mg N-NH_3 L^{-1}	Initial	345.3	109.76	122.5
		Final	354.667	795.76	458.0
Total solids (TS)	%	Initial	20.0	11.5	12.4
		Final	15.0	3.0	4.1
Total volatile solids (TVS)	%	Initial	18.40	9.89	11.01
		Final	13.80	2.55	3.68
Total fixed solids (TS)	%	Initial	1.60	1.61	1.36
		Final	1.20	0.42	0.46
Accumulated biogas volume	mL	Initial	0	0	0
		Final	5080	10,949	4760
Methane yield	L CH_4 kg^{-1} TVS	Initial	0	0	0
		Final	19.82	39.51	10.14
CH_4 composition in biogas	%	Initial	0	0	0
		Final	66.58	57.49	58.54
CO_2 composition in biogas	%	Initial	0	0	0
		Final	33.42	42.51	41.17

In addition, the presence of hydrogen was not observed during digestion, which is associated with the inhibition of acidogenic bacteria. In neutral pH levels (from 7 to 8), the acidogenic microbiota is not able to develop, causing the absence of hydrogen.

A stable methane profile in AD reactors requires stable operational conditions. The reactors composed by açaí seeds (Fig. 7a) and BSG (Fig. 7b) presented a methane stabilization after the 15th day of AD, with a final methane composition of 66.58% and 57.49%, respectively. On the other hand, the reactor fed with poultry feather presented, until the 16th day of AD, 10% of methane; and after this, the methane content increased to 58.54%. The conditions established for poultry feathers were not favorable, and only after 20 days of AD, the methane content was superior to the CO_2, indicating that the reactor stabilization was not reached. Poultry feathers contain a high crude protein content (around 80%), and this macronutrient can act as a digestion inhibitor [21–23]. Furthermore, during the AD process, the sulfetogenesis step (sulfate reduction) can occur for substrates rich in proteins [62]. The bacterium responsible for the decrease in sulfate ends up as competitors of acetogenic and methanogenic bacteria for substrate, generating a lower efficiency in the process, and consequently, lower levels of methane [21].

Bioenergy Recovery and GHG Mitigation

Açaí processing, brewery, and poultry slaughterhouse are consolidated industrial sectors in Brazil, which yearly generate a large number of solid by-products. The açaí industry produced 960,347 tons of açaí seeds in 2019 [63]. The beer industry was responsible for the production of 221,850 tons of dry BSG in 2019 [64]. Finally, poultry feathers generation was estimated at 650,000 tons in 2019 [65]. Table 2 summarizes the potential for bioenergy recovery and GHG emissions avoidance for the three by-products. The estimations were done considering the on-site use of heat and power by the industry, while eventual energy surplus could be sold back to the grid.

Based on the experimental data, the electric energy produced by dry AD of BSG was superior to the açaí seeds (7-fold higher) and poultry feathers (4-fold higher). From BSG, 0.101 MWh ton^{-1} could be recovered, which represents 2.24×10^4 MWh $year^{-1}$. This positive performance of BSG can be attributed to the operational performance and higher biogas yield compared to the other feedstock. Poultry feathers and açaí seeds could produce, respectively, 0.0236 MWh ton^{-1} and 0.0143 MWh ton^{-1}, under the operational conditions established in the lab-scale experimental trials. Usually, the scientific literature related to continuous AD reactors reported the potential to produce more energy.

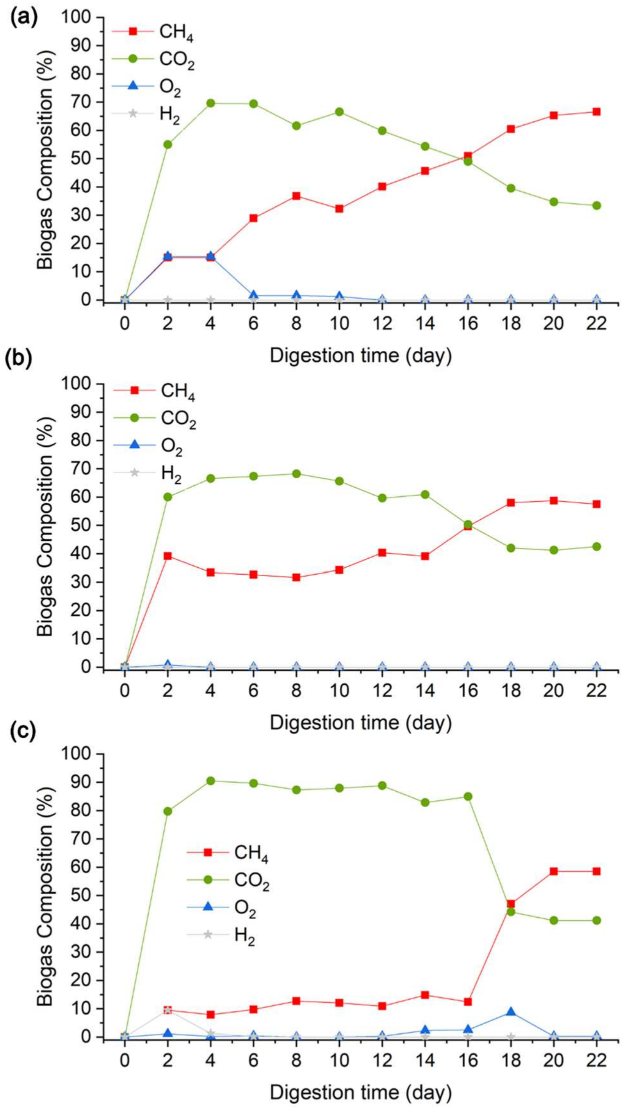

Fig. 7 Biogas composition (CH_4, CO_2, O_2, and H_2) in the dry anaerobic reactor operated in batch mode. **a** Açaí seeds; **b** Brewer's spent grains; and **c** Poultry feathers

Notwithstanding, dry batch AD could be a preliminary step for high COD and solids substrates treatment, previously to a continuous reactor. A more in-depth discussion related to this possible application was addressed in "Dry AD in Batch Mode: A Perspective Approach for a Biorefinery Implementation" section. The adoption of solid AD still requires additional research for a real implementation by the food industry, and the present study provides a mandatory initial assessment for the reactor operational parameters and start-up.

From the environmental perspective, a waste management technology associated with energy recovery is a promising strategy for GHG mitigation coping with food industry carbon footprint reduction. From BSG, GHG mitigation could reach 0.00758 ton CO_{2eq} ton^{-1} of feedstock and 1.68×10^3 ton CO_{2eq} $year^{-1}$. This value is 1.5-fold higher than the obtained for açaí seeds (3.46×10^3 ton CO_{2eq} $year^{-1}$) and poultry feathers (3.87×10^3 ton CO_{2eq} $year^{-1}$).

Dry AD in Batch Mode: A Perspective Approach for a Biorefinery Implementation

Agro-industrial wastes are interesting feedstocks to leverage sustainable development based on the circular economy concept [10]. The adoption of dry AD for bioenergy recovery from the food industry solid by-products can be a possible approach to the transition from the common linear economy to a circular one (Fig. 8) [66]. The circular economy plays an essential role in materials reinsertion in a productive chain, and is a supportive way to achieve economic growth. The main benefits of a circular economy are related to the principles of green chemistry [67]. For instance, the sixth and seventh principles of green chemistry are associated with the improvement of energy efficiency and the use of renewable feedstocks, respectively [67]. Bioenergy recovery from by-products acts in the mitigation of environmental side effects, likewise: water eutrophication (due to organic

Table 2 Potential of electric energy, heat, and avoided GHG emissions using dry anaerobic reactor in batch mode with food industry by-products

Parameters	Unit	Dry AD operated in batch mode		
		Açaí seeds	BSG	Poultry feathers
Electricity generation	MWh ton^{-1}	0.0143	0.101	0.0236
	MWh $year^{-1}$	1.37×10^4	2.24×10^4	1.53×10^4
Heat generation	MJ ton^{-1}	64.49	455.21	106.32
	MJ $year^{-1}$	6.19×10^7	10.09×10^7	6.91×10^7
Avoided GHG emissions electricity generation	tCO_{2eq} ton^{-1}	0.00107	0.00758	0.00177
	tCO_{2eq} $year^{-1}$	1.03×10^3	1.68×10^3	1.15×10^3
Avoided GHG emissions heat generation	tCO_{2eq} ton^{-1}	0.00361	0.025	0.006
	tCO_{2eq} $year^{-1}$	3.46×10^3	5.65×10^3	3.87×10^3

Fig. 8 Circular economy approach to bioenergy recovery using dry anaerobic reactor in batch mode with food industry by-products

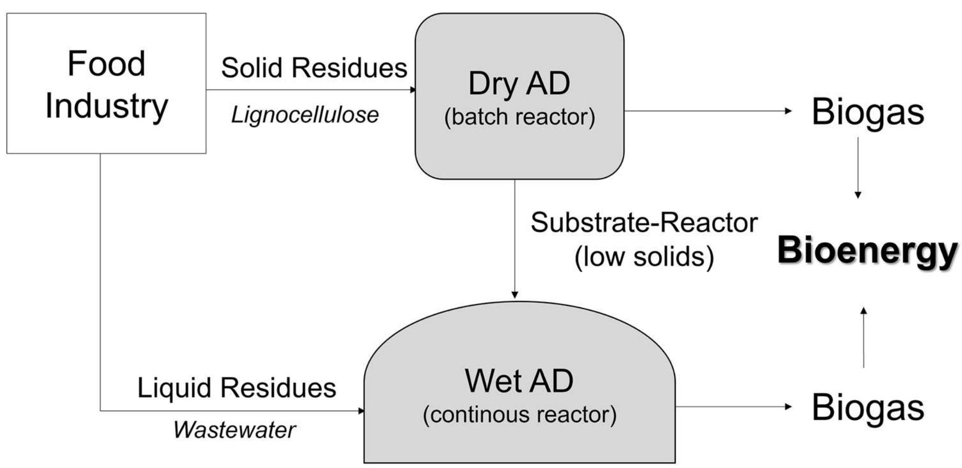

Fig. 9 Anaerobic reactors integration for bioenergy recovery from food industry by-products

matter decomposition and possible leaching in improper waste disposal systems) and climate change (due to fossil fuel combustion).

Hence, for the complete development of supporting technologies and infrastructure for the circular economy flourishing, a biorefinery for solid waste management would be designed. The food industry could adopt the practice of attaching high solids batch AD reactors as a pretreatment step to the existing liquid treatment systems for methane production. Figure 9 presents a proposal of an integration of dry and liquid AD for bioenergy recovery. Such an integrated system presents benefits like reversing production costs, increasing efficiency, and competitiveness while reducing environmental side effects. Depending on the operational condition of dry batch AD reactors, bioenergy could be directly recovered from the biogas produced, and the substrate-reactor after AD (with low solids contents) could be fed to liquid digesters for new digestion (Fig. 9). In

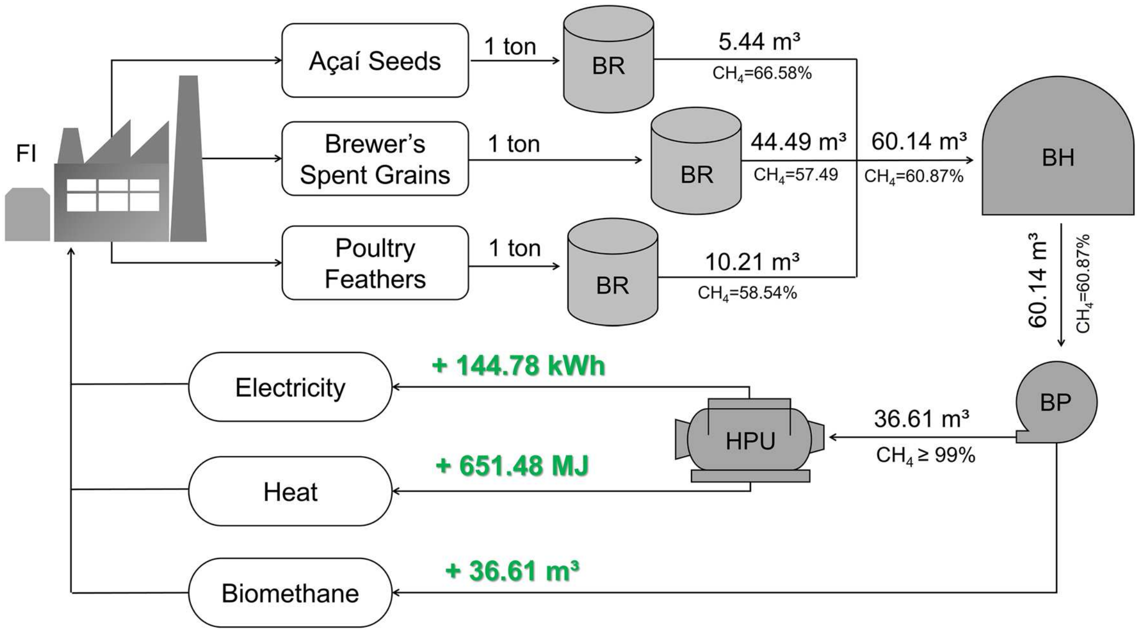

Fig. 10 Industrial balance approach to bioenergy recovery using dry anaerobic reactors operated in batch mode with food industry by-products. *FI* food industry, *BR* batch reactor, *BH* biogas holder, *BP* biogas purifier, *HPU* heat and power unit

addition, the biogas produced could be applied to heat and electricity generation for facilities self-consumption, while any eventual energy surplus could be sold to the grid. Otherwise, biogas can undergo a purification process to eliminate of sulphur compounds (i.e., H_2S) and carbon dioxide for the production of biomethane [68, 69]. The biomethane can be injected directly into existing natural gas networks for the use as gas oven, light, and heavy-duty vehicles, which are additional routes to mitigate greenhouse gas emissions [11, 68]. Hence, taking advantage of the potential energy of waste at a local level, a biogas economy could diversify and contribute to a country's energy matrix renewability without the need to deploy new transmission lines and pipes [70, 71].

Thereby, to support a biorefinery implementation using biomethane, electricity, and heat, a general industrial balance was assessed for the dry AD in batch mode (Fig. 10). The biogas produced can be collected by adopting a simple pipeline to the gasholder, where the biogas produced is mixed and stored. This gasholder can be used by a group of industries, with the implementation of a single biogas purification step and further conversion into electric and thermal energies. The use of biogas can be an alternative to the decentralized production of electric energy, which supports the diversification of energy resources, improved supply, reliability, and efficiency. Nonetheless, the production of decentralized energy can be a promising substitute for hydroelectric and petroleum-based energy since the adoption of the AD system can reduce GHG emissions, supporting the biorefinery concept. From the data presented in this study and taking into account one (01) ton of each solid feedstock subjected to dry AD, a total of 60.14 m^3 of biogas could be obtained, with an average methane composition of 60.87% (Fig. 10). After the purification, biomethane is obtained (36.61 m^3), which could be injected directly into natural gas existing networks or used as vehicular fuels in the own facility [11]. In Fig. 10, a theoretical co-generator was applied to produce electric and thermal energy; 144.67 kWh and 651.48 MJ, according to the proposed scenario. A combined co-generation process could be an advantage for a group of industries since the implementation costs of an engine could reach up to 200 thousand USD. Therefore, the innovative route proposed with dry AD could be an alternative route for energy recovery, especially in a biorefinery, supporting the circular economy transition.

Conclusion

Dry AD operated in batch mode with açaí seeds, BSG, and poultry feathers were evaluated. From the reactor start-up and operational parameters with 25% of solid by-products, it was possible to obtain a high biogas yield, with high methane content, especially for BSG, a residue from the brewing industry. The biogas produced can be an alternative source for electrical and thermal energy generation. Therefore, the treatment of solid waste through AD can be an ecological alternative for food industry waste management. Beyond, for the innovative route proposed with dry AD for energy recovery, a circular economy transition could be achieved. Eventually, the technological approach could support the establishment of biorefineries especially designed for solid by-products conversion and local industries renewable energy and biomaterials supply.

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