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FABRÍCIO BRUNO MENDES

TECHNO-ECONOMIC FEASIBILITY OF BIOGAS PRODUCTION THROUGH CO-DIGESTION OF TYPICAL AGRO-INDUSTRIAL AND LIVESTOCK RESIDUES: CASE STUDY IN SAO PAULO STATE

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“I can see the promise.

I can see the future.

You’re the God of seasons.

I'm just in the winter.

If all I know of harvest

Is that it’s worth my patience.

Then if You’re not done working

God I'm not done waiting “

Song excerpt: Seasons
Ben Tan / Benjamin William Hastings / Chris Davenport
(Hillsong United)

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RESUMO

A energia renovável tem ganhado especial importância na agropecuária brasileira, este sendo um dos principais setores econômicos do Brasil. Elevada quantidade de resíduos é gerada anualmente com potencial de codigestão e posterior produção de bioenergia. Segundo o Atlas de Bioenergia do estado de São Paulo, um dos grandes centros agroindustriais do País, a rota biotecnológica impactaria positivamente a matriz energética estadual em pelo menos 24%. A integração energética da agropecuária paulista poderia desenvolver novos mercados e trazer soluções inovadoras com produção sustentável e viável economicamente. Ainda, o apoio promovido pela Política Nacional de Biocombustíveis, Renovabio, permite acessar uma abrangente rede de produtores, transportadores e consumidores. Portanto, este estudo visa avaliar cenários econômicos de integração energética no setor agropecuário paulista a partir da produção do biogás convertido a biometano e bioeletricidade de forma a incorporar coprodutos com valor agregado. Inicialmente, o trabalho se baseia na seleção dos potenciais municípios produtores da agroindústria paulista apresentados no Atlas, seguido pela análise e discussão da valoração dos co-produtos gerados, e finalizado com a avaliação técnico-econômica de um estudo de caso com dados reais de hipotética integração entre uma usina de cana-de-açúcar, uma fazenda de café e uma suinocultura. Entre os resultados destacam a compilação de custos de aquisição e transporte correlacionados com suas composições bioquímicas onde os co-substratos de milho e laranja são os mais elevados e os dejetos bovinos, suínos, e vinhaça são mais acessíveis; o calendário de disponibilidade de co-produtos das culturas energéticas cana-de-açúcar, milho, laranja, soja, café e da criação animal (bovino, suíno e avícola) indica necessidade de resíduos sólidos na entressafra, e evidencia a viabilidade em se produzir biometano ao invés de bioeletricidade. Neste estudo de caso, os créditos de descarbonização obtidos do biometano duplicaram a rentabilidade de plantas integradas em escala industrial. As informações detalhadas podem auxiliar na tomada de decisão de novos investimentos com este novo modelo de negócio, trazendo benefícios socio-econômicos para a futura expansão da bioenergia no País. Esta metodologia é aplicável para qualquer região onde há concentração de produção agroindustrial. O modelo de negócio de integração agropecuária traz uma sinergia econômica-social com antecipação de impactos ambientais no meio rural, com alternativa para destinação e valoração dos resíduos.

Palavras-chave: agroindústria, bioenergia, avaliação técnico-econômica, biorefinaria, política pública, co-digestão

ABSTRACT

Renewable energy has gained special importance in the Brazilian agro-industry, which is one of the main Brazilian economic sectors. A high quantity of residues is annually generated with the potential to co-digest into bioenergy. According to the Bioenergy Atlas of São Paulo, the biotechnological route would positively impact the state energy matrix by at least 24%. The energy integration of the São Paulo agribusiness would be able to develop new markets and promote innovative solutions for sustainable bioenergy production. The support of the National Biofuels Policy, Renovabio, would allow to access a comprehensive structure of producers, transporters, and consumers. Therefore, this study aims to evaluate scenarios of regional integration in the agricultural and livestock sectors through biogas production being converted into biomethane and bioelectricity in order to incorporate added-value co-products. Initially, the work selected the potential Sao Paulo municipalities presented in the Atlas, followed by the analysis and discussion of the co-products valuation, and finally the techno-economic assessment of a case study in a hypothetical integration between a sugarcane plant, a coffee farm, and a pig farm. Among the results, we highlighted the disclosure of acquisition and transportation costs correlated to the biochemical composition data where corn and orange residues are the most valuable and the vinasse and bovine/swine manure are the most accessible, the residue availability calendar from agricultural and livestock sectors sugarcane, corn, orange, soybean, coffee, and animal breeding (bovine, swine, poultry) followed the feasibility of biomethane instead of bioelectricity production. The decarbonization credits obtained from biomethane double the revenues of large-scale integrated plants. Detailed information can promote new investments by decision-makers through the new business model bringing socio-economic benefits for the expansion of bioenergy. The methodology can be applied to agricultural regions in the country and in the world. The integrative business model is synergic and anticipates environmental impacts in rural areas, as it contributes as an alternative to waste disposal and adds value.

Keywords: agro-industry, bioenergy, techno-economic assessment; biorefinery, public policy, co-digestion

SUMÁRIO

GENERAL INTRODUCTION

This introduction provides a general overview of the work. The thesis is composed of three articles formatted as chapters, followed by a general conclusion, then the final chapter with suggestions for future works. It must be highlighted that Chapter #2 was published (November 2022) and Chapters #1 and #3 were already submitted to scientific journals A1/A2.

Chapter #1 provided a São Paulo State context overview, representing the scope of the work. Its agricultural and livestock sectors have the most relevant productions in Brazil, where their residues are exploited as an alternative to integrating regional plants to produce bioenergy. The chapter also proposed a business model supported by organizations and public policies, which would be able to subside energy integration among the agricultural sectors here discussed – corn, sugarcane, orange, coffee, and soy crops, and animal breeding (poultry, bovine, and swine). The ultimate objective was to optimize and leverage biogas/biomethane production in a regional solution and diversify the energy matrix of the state. Through an analysis of the generation process, whether in the field or in the agro-industrial process, it was realized that certain residues have application or reuse within production chain. Consequently, the subsequent step could provide an assessment of the opportunity cost associated with residues and the estimation of their acquisition cost in relation to energy purposes.

Chapter #2 explored aspects of agricultural and livestock residues from an economic perspective. The so-called "waste" can assume a market value beyond its conventional reuse even though, until now, its costs remain hitherto unknown. In theory, the valuation cost can be related to the biochemical composition, which would allow a range of economic advantages to the source generators. Opportunely called co-products, the tables brought compilations of cost and biochemical composition – emphasizing the analytical data mainly from the Brazilian literature. This data has not previously been explored in the scientific literature and will improve techno-economic assessments of new biogas projects through co-digestion.

Chapter #3 wrapped up the hypothesis of waste integration. Accurate data was collected from ongoing sugarcane mill, coffee farm and swine creation all located in the state, to perform a biogas plant case study on an industrial scale. The choice of sectors was based on available production and geographical data. The techno-economic assessment compared the feasibility between biomethane or bioelectricity revenues with a sensitivity analysis of main economic indicators influencing the project, as well as the carbon credits contribution. Furthermore, a detailed fixed investment – CAPEX of a biogas plants operating annually – OPEX with all necessary inputs to the industrial process. From the cash flow, economic indicators were estimated, where the product cost was one of the novelties of the study. It will certainly motivate decision-makers to gain national and international perspectives.

The following chapter provided general conclusions, bringing together approaches related to the previous chapters. It pointed out whether is feasible or not within the scope of the proposed business model. It also brought statements arisen during the writing, some of them validating observations and others reporting the real issues to integrate an agro-industry process with energy purposes, under the light of interviews with local producers and experts. Finally, the last session suggested topics for future works that were based on the thesis's findings.

The methodology to compile data obtained from articles was through a systematic literature review. This approach involved a structured and comprehensive search of relevant scientific databases, expert interviews, and personal investigation to identify information that meet criteria of Brazilian biogas production. The references were critically evaluated and validated with experts to meet real conditions, identify trends, patterns, and key findings across the study. The economic assessment was simulated in Excel and synthesized to ensure an unbiased approach to gather data from a range of techno-economic studies, facilitating the generation of reliable insights into biogas research.

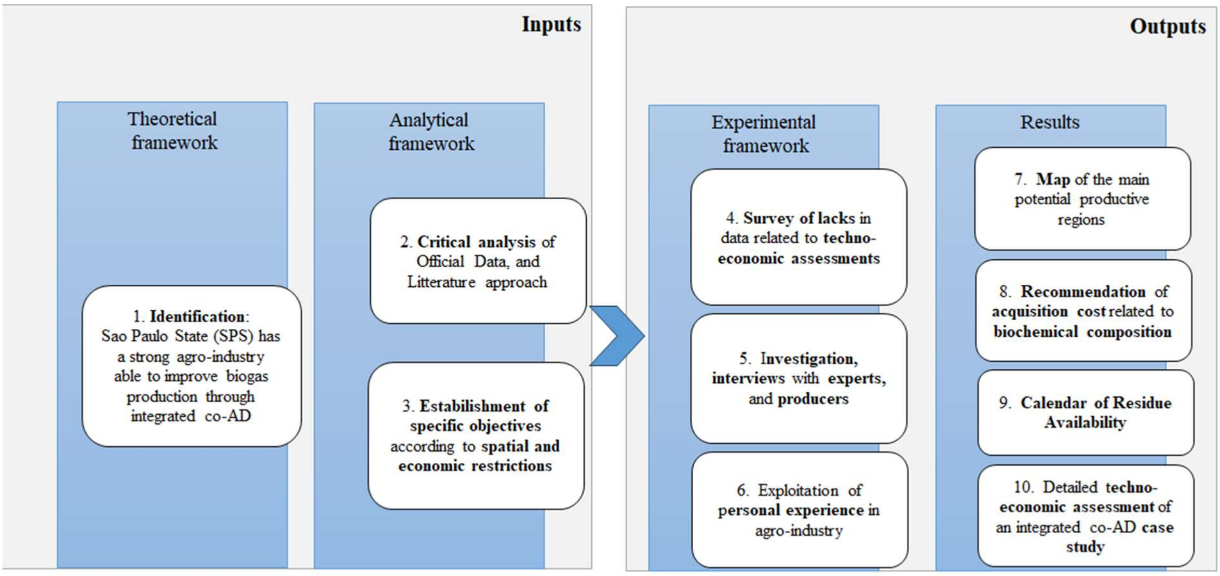

Figure 1: Process of methodology developed in the thesis

Hypothesis and Objectives

Climatic Conditions: São Paulo State benefits from a diverse and favorable climate, with regions that offer suitable conditions for a variety of increasing agricultural crops and livestock. The state experiences a well-distributed rainfall throughout the year, providing an ideal environment for plant growth and biomass production.

Land Resources: The state encompasses a diverse landscape which provides ample opportunities for the integration of energy crops and biomass feedstock. The availability of land resources enables the establishment of large-scale operations and encourages the expansion of bioenergy production.

Agricultural Industry: The state is recognized as a significant agricultural hub in Brazil and boasts a robust and well-developed agricultural industry. The state also has an established infrastructure, expertise, and technology for cultivating and processing various crops. This foundation provides a solid framework for implementing bioenergy projects, as it offers the necessary knowledge, resources, and support systems for efficient crop cultivation, harvesting, and conversion into bioenergy.

Combining these factors, I propose:

Hypothesis

The São Paulo State is the main hub of Brazilian agro-industry capable of integrating the agricultural and livestock sectors to expand bioenergy production as well as bringing regional development.

Objectives

- To study the scenario of São Paulo state (SPS) as an important agro-industrial producer and generator of different agricultural and livestock waste to produce bioenergy through an integrated co-digestion process.

- To evaluate the available residues under the economic and biochemical aspects, adopting a new meaning of co-products as alternative to reuse in biorefineries.
- To identify potential farms and agro-industry geographically close to conduct a case study with real data, evaluating the techno-economic feasibility in producing biomethane or bioelectricity as most profitable product of the business model proposed in this work.

CHAPTER 1

An Overview of the integrated biogas production through agro-industrial and livestock residues in the Brazilian São Paulo State

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Abstract

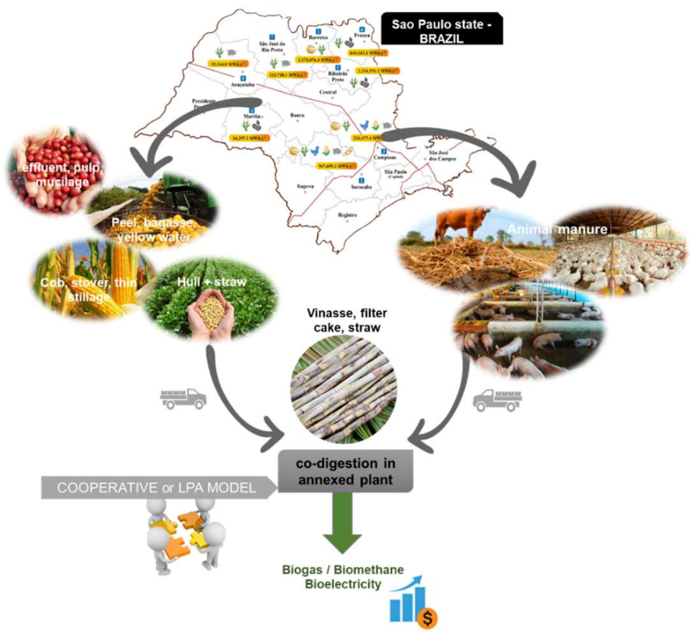
Recently, new solutions have arisen to promote bioenergy expansion, some of which meet the requirements of reliability, sustainability, and governance. In Brazil, the Sao Paulo state (SPS) is characterized by strong agro-industrial and livestock activities, which generates increasing residues in the last years with the potential to produce bioenergy and offer environmental and economic benefits. The Brazilian National Biofuel Policy (Renovabio) has been enhanced to seek sustainable development, encouraging new agribusiness research. Studies have shown that the sugarcane sector, a conventional ethanol and bioelectricity producer, has the greatest potential to produce biogas/biomethane, which can be maximized with the introduction of co-substrates regionally generated from corn, soy, orange, coffee, poultry, and swine. This overview, based on the main SPS agro-industrial and livestock residues, shows innovative alternatives for integrating anaerobic co-digestion (co-AD) processes through a regional strategy, by providing long-term revenues and greenhouse gas mitigation, which would also spread the discussion for National and International prospects. This study discusses logistical, political, and financial aspects, revealing a promising business model supported by public policies. However, its feasibility requires a real economic assessment with the inclusion of decarbonization credits, and political subsidies for biomethane as a biofuel under the Renovabio, which will facilitate its insertion into the agro-industry in the coming years.

Keywords: co-digestion, crop residues, biogas, agroindustry, public policy, regional solution.

Resumo

Recentemente, novas soluções têm surgido para promover a expansão da bioenergia, e algumas delas devem atender aos requisitos de confiabilidade, sustentabilidade e governança. No Brasil, o estado de São Paulo (SPS) caracteriza-se por possuir forte desenvolvimento agropecuário, gerando nos últimos anos uma crescente quantidade de resíduos com potencial para geração de bioenergia e ainda oferecer benefícios econômicos e ambientais. A Política Nacional de Biocombustíveis do Brasil (Renovabio) impulsionou a busca pelo desenvolvimento sustentável, o que incentiva novos estudos do agronegócio. Estudos mostraram que o setor sucroenergético, um tradicional produtor de etanol e bioeletricidade, tem o maior potencial de produção de biogás/biometano, podendo ser maximizado com a introdução de outros resíduos regionais gerados de milho, soja, laranja, café, aves, suínos. Este levantamento, baseado nos principais resíduos agroindustriais e pecuários do SPS, apresentou novas alternativas para integrar os processos de codigestão anaeróbia (co-DA) sob uma perspectiva regional trazendo receitas a longo prazo, além de mitigação de gases de efeito estufa, o que também abre caminho para uma perspectiva nacional e internacional. O estudo discutiu aspectos logísticos, políticos e financeiros, revelando um modelo de negócios promissor, apoiado pelas políticas públicas. Entretanto, para sua viabilidade, é preciso realizar avaliação econômica incluindo receitas de crédito de carbono (CBIO), além de otimizar a cadeia do biometano dentro do Programa Renovabio, o que facilitará ainda mais sua inserção na agroindústria dos próximos anos.

Graphical/Visual Abstract and Caption



The diversified SPS agro-industry and livestock have the potential to co-digest its residues in an integrated process, with the participation of regional stakeholders, using the sugarcane mill as a co-processing hub, producing economically bioenergy.

1. INTRODUCTION

Energy demand keeps increasing worldwide and the new regime for energy security is based on renewables, especially in regions with biodiversity and available biomass. Bioenergy from different feedstocks can reduce greenhouse gas (GHG) emissions by reusing organic residues and ensuring reliable, timely, and cost-efficient delivery which can be considered an opportune regional solution that promotes sustainable benefits [1–3].

Brazil has geographical advantages to produce renewable energy, where the national policy mechanism, Renovabio recognizes the strategies of biofuels (ethanol, biodiesel, biomethane, biokerosene, and second-generation fuels) to diversify the energy matrix regarding energy security, predictability, and emission mitigation. However, there is still a lack of policies to disseminate sustainable markets with new arrangements in the agroindustry, while considering regional solutions. Such initiatives would play an important role in the establishment of mechanisms to commercialize decarbonization credits of different biofuels. Even though the sector appears to be resistant to change, the sugarcane sector of the future will be able to participate effectively in the energy matrix, which currently is in second place, with 19.1% of internal energy supply, just behind oil source, 33.1% [4]. The feasibility of new investments to maximize bioenergy through newly integrated processes via co-digestion requires a detailed study of co-product availability, operational costs, technology adaptation, and social impact assessment [5].

There are many technologies for biomass energy conversion suitable for small- and large-scale applications, such as: gasification, cogeneration (thermal and electric generation), energy recovery from solid residues, wastewater treatment, biobased products for chemical industries, and biorefineries [6]. Anaerobic Digestion (AD), a technology applied to residual biomass, has particular interest due to the use of low-cost (or even costless) substrates that convert into biogas [3]. This process is recognized as a clean technology that combines the suitability of residues with energy generation, fulfilling long-term sustainable requirements such as national targets and the COP26 Agreement [7]. Co-digestion (co-AD) consists of AD of two or more substrates, increasing the possibilities of integrating residual biomasses from different sources. Also, co-AD can optimize CH_4 production by providing and balancing macro and micronutrients, being a good option for recalcitrant substrates [8]. The sugarcane industry, the most representative agro-industrial sector in SPS, has been highlighted in literature for using vinasse and filter cake as available residues to economically produce biogas [9–11]. Some regional biogas plants have adopted the co-AD of vinasse, filter cake, and potentially bagasse to enhance bioenergy generation [12].

Biogas is a renewable source of electricity, heat, and biofuel, and leads to reduced negative impacts of pollution by waste disposal. In addition, the co-product originated from the AD process is a valuable organic fertilizer, which integrates the crop cycle [13]. On the other hand, biomethane, i.e., purified biogas similar to natural gas (NG), can be a suitable alternative to be injected into the NG grid and as fuel to replace diesel. If quality standards[1] are met, the transport sector promises to incorporate the use of biomethane, especially for light-duty vehicles and buses [14,15].

SPS contributes significantly to the Brazilian economy - 24% of the national GDP - particularly due to intense agricultural and livestock production [16]. Thus, solid and liquid residues are continuously generated in the fields and in agroindustry, particularly from monocultures – corn, soybean, orange – and concurrently from animal manure. Environmental issues are being faced such as the increase of particulate matter, erosion, loss of nutrients, imbalance in water consumption,

[1] The law specifies biomethane derived from agriculture, animal manure and commercial products in accordance with ANP Technical Regulation No. 1 - 2015 included in Resolution No. 685 of 2017 [110].

excess of pesticides, and contamination. During the crop seasons, the problems can intensify in the long-term if no treatment is implemented [17,18]. Among typical agro-industry corn, soybean, coffee, orange, and animal productions generate a relevant amount of residues, which are partially available to obtain biobased products through the biorefinery concept [19]. Sugarcane and orange crops have the largest national production concentrated in SPS: 53% and 77%, respectively. Soybeans, corn, and coffee have a smaller share but represent complementary crops in the interseason with annual growth of 11% in the period of 2010-2019 [20,21]. As for the national participation of livestock in SPS, poultry (13%), swine (3%), and cattle (5%) [20] occur in adjacent locations geographically favored for integration into the so-called "monocultures" mentioned above.

Given the context, this study aims to demonstrate the feasibility of integrating crop residues and animal manure produced in SPS, considering its seasonality as well as identifying geographic strategies that would assist in the decision-making of new co-AD projects for energy purposes. In this sense, biogas/biomethane expansion will play a positive role in the Brazilian energy matrix, given the considerable potential of the agro-industrial sector. Agroindustry in SPS certainly becomes an interesting field for assessing the environmental and economic impacts caused by energy crops, especially due to high productivity, data availability, and know-how compared to other Brazilian regions. Among the diversified agricultural and livestock concentrated in certain regions, the selected crops addressed are sugarcane, corn, orange, soybean, coffee, poultry, bovine and swine livestock. The combination of valuable solid and liquid residues can maximize biogas production in sugarcane facilities. Due to the large number of co-products generated in the sugarcane process, this sector is the hub [22,23], being a central player in this integration. The political and economic overview herein presented outlines a better regional solution anticipating future environmental legislation and promoting discussion with an international perspective.

2. GENERAL CONTEXT OF SPS AGROINDUSTRY

Agricultural residues as raw materials destined for value-added products are not a new concept. Interest in using crop residues in the manufacture of building panels dates to the early 1900s, along with a variety of other purposes, from fuel to a source of papermaking from fiber and animal feed, as occurs in China, India, Pakistan, Brazil, and Mexico [24]. This reuse is both socially and environmentally attractive if volumes removed from the land do not compromise soil conservation [25,26].

In 2017, according to the Energy Research Office (EPE, the Portuguese acronym), Brazilian agriculture and livestock together generated 706.3 million tonnes of residues, among which 394.5 million tonnes are classified as “energetics” ie, biomass [27]. The agro-industrial sector could be self-sufficient by supplying primary energy from crop residues and the amount generated will grow in the near future. Worldwide agricultural residues have increased by around 30-40% per decade, with corn and sugarcane crops being the most important for providing cellulosic ethanol and/or bioelectricity [25]. Brazilian agribusiness accounts for a large share of the national Gross Domestic Product - GDP, being 24.3% for the year 2020[28]. In 2021 there was a pointed increase of 1.5% to 2.0% for “Paulista” agribusiness, especially with the participation of corn, soy, and coffee, which represent the main commodities for agricultural GDP [29]. Another important fact concerns the cultivation of temporary crops. Short-lived crops – soy, corn in grains, and rice – and long-term (sugarcane) traditionally produce more waste and their harvesting can be done more straightforwardly and cost-effectively than perennials – orange, banana, and coffee in grain [30]. The livestock sector tends to intensify crops, with the increase in the animal herd as well as the geographic concentration (the clusters) which makes their residues and effluents increasingly available for energetic reuse [31].

2.1 Overview of SPS: a strong economic and agroindustry

SPS is in the southeast of the Federative Republic of Brazil. The state has 46.29 million inhabitants across a total area of 248,220 km² in 645 municipalities [31]. Historically, the rise of SPS began with the success of coffee in the 19th century, which quickly attracted relevant industrialization with specialized labor also the advantage of having diversified agriculture favored by the climate and soil. Currently, agricultural research boosted crop production helped by an infrastructure of transportation by railroads, waterways, and pipelines, connected to the main seaport in Latin America. In 2019, its GDP was US$ 2.38 billion, corresponding to 24% of the national GDP, with a 60% share of renewable energy, above the Brazilian average, which remained at 46% [32].

Among the renewables, the state has a predominant market share from sugarcane biomass, even though was evidenced in 2019 an imminent potential for solar energy (12 TWh/year) installed inside the planting areas as well as wind energy (13TWh/year). The sugarcane industry remains the most important sector with 206 sugarcane mills in operation in the state, producing 30% of the total electricity. However, SPS imports energy from other states (-69%) to meet its internal demand. Regarding transportation, the state has the largest fleet in the country, accounting for 28% of the national fleet. The fleet in use is estimated to be 15.4 million vehicles, of which 62.0% corresponds to flexible fuel light vehicles (ethanol and gasoline) while 12.5% are heavy vehicles currently powered by blended diesel B12 (12% in vol. of ester-based biodiesel and 88% in vol. of fossil diesel), and Natural Gas-based motorcycles and scooters account for the remaining 25% of vehicles [33]. The SPS is a pioneer in controlling atmospheric pollution and pollutant emissions from motor vehicles and industrial activities, in which environmental regulation supports federal legislation[34]. Currently, agribusiness is the most important sector in the country, with a market share ordered in Figure 1.

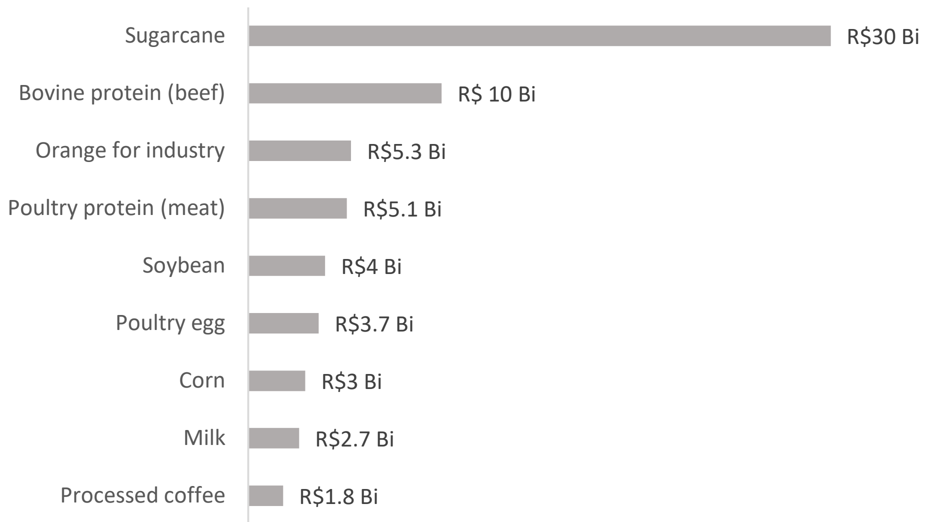


Fig. 1: Market value of main SPS agro products (R$ billion.year^{-1}) in 2019 [35]

With a production value of R$ 30 billion (around US$ 6 billion), the sugarcane industry accounts for 36% of all agribusiness in SPS. The second is bovine protein, which only represents a third of sugarcane participation. Bovine protein, oranges for juice production, chicken meat, soy, and corn collectively account for 37% of the agricultural market value in SPS. This list also covers milk and, lastly processed coffee sales. Agribusiness has been improving the labor force capability, reflecting modernization and concentration of production. Agribusiness currently employs over 20%

of the workforce in the country [36]. During the first year of the COVID-19 pandemic, the sector was resilient, with only a 5.2% reduction in job offers [37].

The rich biodiversity and climate favor the cultivation of a variety of energy-based crops, making it a major agro-industrial hub in the Southeast region. Although the metropolitan region of the capital is considered the most Brazilian industrialized area, the municipality of Campinas – 100 km from the capital – has a strong influence from the agro-industrial sector. From this city towards the northwest region that borders the states of Mato Grosso, Paraná, and Minas Gerais, monocultures are cultivated, such as sugarcane, orange, soybean, corn, coffee, as well as the widespread presence of poultry, swine, and bovine cattle. Table 1 presents the scenario of the main Sao Paulo agribusinesses and their national market share.

Table 1: Scenario of agroindustry in SPS – 2019 [19,20,38]

Culture	Production in the state (10^6t.year^{-1})	Market share State/Brazil (%)	GP² (residue/ crop)
Sugarcane	342.61	53.2	0.22
Orange	13.64	77.5	0.50
Corn (1st and 2nd crops)	4.60	8.0	1.42
Soybean	3.30	3.0	2.05
Coffee	0.34	7.7	--
Animal manure	***Cattle (10^6 units)***		
Poultry	0.18	13.0	1.58
Swine	1.21	3.1	0.06
Bovine	8.33	4.8	0.07

²GP – generating potential index (tonne residue/tonne culture).

SPS agribusiness expanded in 2019, increasing 5.44% of its GDP, helped by the external demand for animal protein, due to the African Swine Fever (PSA) outbreak in Asia. Production expanded by 0.6% in the same year, mainly due to the performance of sugarcane, orange, and corn. The state is characterized by a large predominance of plant-based activities, being a major supplier of raw materials used in the whole country [15]. Regarding biofuels, the sugarcane industry accounts for 47% of bioethanol production in the country. Biogas plays an important role in SPS, accounting for 35% of national production, but predominantly generated from landfills. The overview of main fuel production and raw materials is summarized in Table 2.

Table 2: Comparative SPS fuels production – 2019

	SPS – volume (m^3)	National participation (%)	Main raw material (in SPS)
Bioethanol (Anhydrous + hydrated)	16,680,340	47%	Sugarcane
Biodiesel	231,090	4%	Soybean
NG – x1,000	6,694,188	15%	Oil industry

Biogas – x1,000	---	35.3%	Landfill, and scarcely from food industry, sugarcane waste, swine manure

Source: adapted from [39,40].

Currently, the SPS has only three biodiesel plants in operation: in the municipality of Lins, the JBS company produces biofuel from a bovine fat substrate; in Catanduva, Fertibom generates biodiesel from oils; and in the municipality of Orlândia, Brejeiro food industry produces biofuel from food waste and cooking oil. Soybeans are the main source of biodiesel in Brazil, and their productivity has been increasing in recent years [41]. For the remaining biofuels, the SPS market share is more than a third of the whole country.

2.2 Agricultural residues as feedstocks for biofuels

The Brazilian agricultural residues have increased by 40% from 2005 to 2014 in recent years, specifically due to developments in technology, such as the mechanization of harvesting, monitoring, and area expansion [42,43] For example, only the sugarcane industry expects an expansion of 3 million hectares projected by Renovabio [44]. For second-generation biofuels and bioelectricity via direct combustion, straw from soybean and corn crops, as well as sugarcane bagasse were found to be the most suitable residues that can be used as lignocellulosic feedstock [23,42]. Crop residue harvesting for renewable energy has been recently proposed in Brazil. Management for bioenergy purposes is becoming a new strategy and does not disregard the long-term effects on soil and plant growth. Agricultural residues play a variety of roles in the soil, affecting ecosystem services both directly and indirectly [45]. Adequate management incorporates good practices, such as agricultural rotation and cover crops, as well as monitoring nutrient levels and organic matter to mitigate the negative effects of crop residue harvesting [25]. As indicated, optimizing the removal of above-ground biomass is compulsory to maintain yields and soil fertility. Studies reveal that 20 to 25% of the residues can be removed from the fields without the need for additional nitrogen or phosphorous applications [43,46]. In other cases, however, a small additional amount of potassium may be profitable [47]. Given the relevance of the theme, in 2019 the Brazilian government established the Agricultural Module of Energy (SIEnergia), a business information service designed to enable studies evaluating regionally agricultural residues for bioenergy purposes [32]. SIEnergia defined "energetics" as a useful biomass capable of generating bioenergy. Figure 2 shows a survey between total residue and energetic amounts from agriculture and livestock in SPS during the 2016-2019 period.

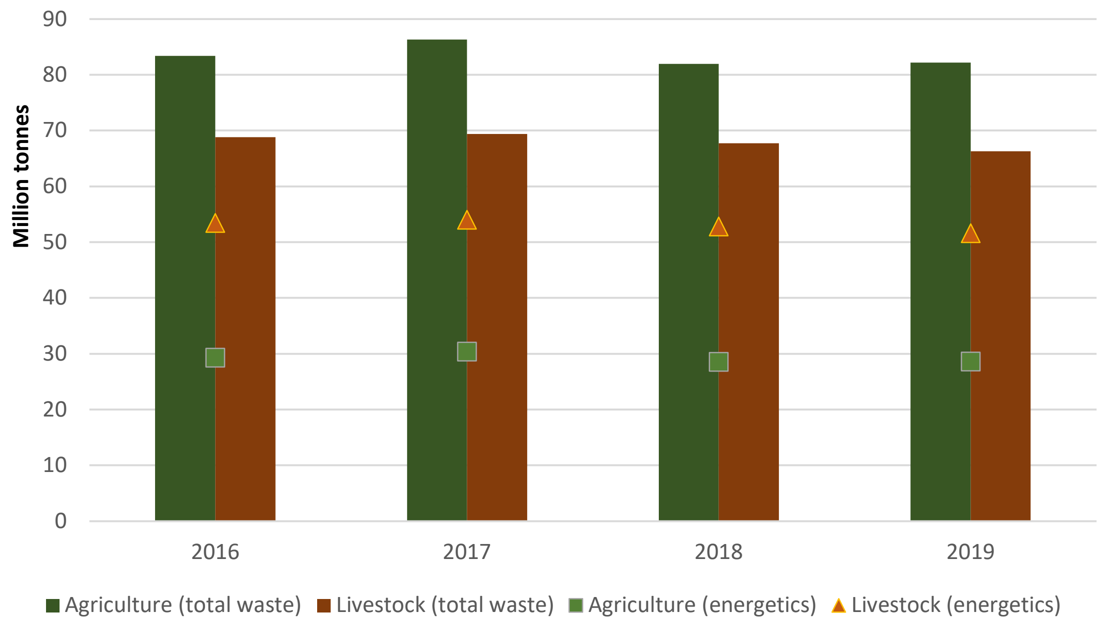


Fig. 2: Total waste and energetics generated from livestock and agriculture in SPS, 2016-2019
Source: Adapted from SIEnergia [48]

For this survey, the approach uses collection parameters to estimate energy from crop residues. Field collection factors are 0.40 for agriculture; 1.0 for poultry and swine, and 0.8 for bovine cattle [43,48]. Other relevant literature also reported these factors [27,49]. These values hypothetically represent the fractions of organic matter that can be collected and converted into bioenergy via the biodigestion route. However, there are technical, environmental, and cultural variations, meaning that estimates are rough when applicable to official studies [42,48]. The emphasis on energetics is necessary to evaluate bioenergy generation in two modalities: biogas (electricity or heat) and biomethane (biofuel).

3. SCENARIO-BASED

3.1 Assessment Overview

The main agricultural and livestock productions in SPS were selected based on the amount of solid and liquid residues generated during rural and agro-industrial activities. It observed the biochemical potential required for the co-AD process to maximize biogas production. A focus was given to prominent agricultural and livestock production, mainly due to the larger supply of residues and the better logistical radius in the integration areas. The interactive Bioenergy Atlas of SPS was an important tool to evaluate municipalities with energy potential based on their geographic location combined with the variety of production [50]. Among the crops and livestock existing in SPS, the six selected were sugarcane, coffee, corn, soybeans, and orange, as well as swine, poultry, and bovine. The residues are generated in three stages: harvesting, agroindustry, and livestock; and lignocellulosic residues (such as straw, leaves are partly left in the field for soil conservation and replanting. Thus, vinasse, filter cake, and straw are residues in sugarcane agroindustry; cobs, thin stillage, and stover are residues in the corn process; residual water, pulp, and mucilage are generated in coffee production;

hull and straw from soybean; finally peel and yellow water from the citrus industry. The selected residues considered in this study are summarized in Table 3.

Table 3: Selected residues generated from agriculture and livestock in SPS

Agriculture / Livestock	Selected Residues	Estimated bioenergy ($GWh.y^{-1}$)
sugarcane	*Vinasse, filter cake, straw*	31,895.0
corn	*cobs, thin stillage, straw*	1,548.3[1]
orange	*Peel, bagasse, and yellow water*	1,046.0[1]
soybean	*hull and straw*	1,071.3
swine, poultry, and bovine	*Liquid manure*	818.0
coffee	*wastewater, pulp, and mucilage*	71.2[1]

Estimate refers to the ten largest producing municipalities [49]
[1]Do not include orange bagasse, yellow water, thin stillage, and coffee wastewater

The residues are listed in order of importance. Specifically, it is highlighted that animal manure is generated in confined areas. The next subsection explains each stage of the agro-industrial generation for each sector analyzed. Figure 3 illustrates the scope of the methodology and its stages.

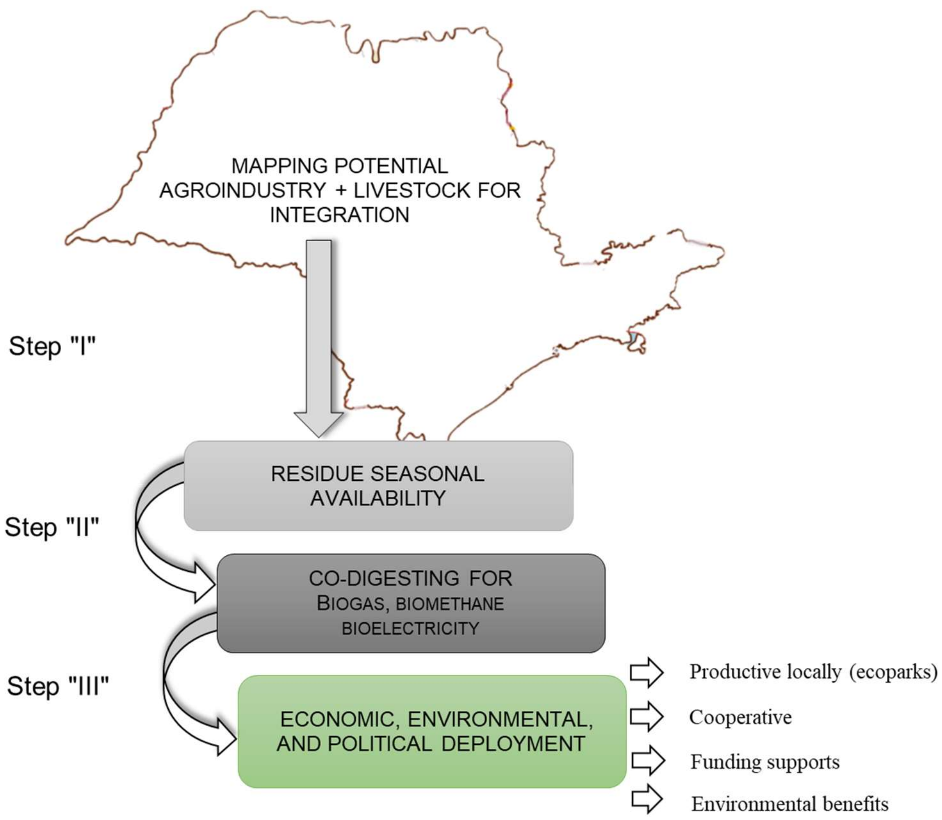


Fig. 3: Flowchart of the procedure performed in this work

Step "I": Identification of prominent regions and municipalities with major potential to generate agro-industrial and livestock residues in activities related to sugarcane, corn, soybean, coffee, and orange crops as well as animal manure from swine, poultry, and cattle. This step uses the bioelectricity theoretical capacity according to research data from Bioenergy Atlas. For the proposed waste integration, the logistical factor is relevant because it is related to the economic feasibility, and the sugarcane facilities (distillery and sugar factory) are the hub of operation. In most sugarcane mills, loaded sugarcane trucks travel around 33km from the field to the mill, which is technically feasible. In biomass transportation for reuse purposes, studies considered up to 50km [23,54], however, it depends on the quantity transported and the type of truck. In this overview, this parameter was adopted for large waste availability between two productive units. A ranked list was created to design the map and identify the main municipalities. Figure 10 and Table 5 resulted from this analysis.

Step "II": Creation of a residue seasonal availability calendar that reflects geographically the integration between different agricultural and livestock companies in the SPS. In this way, we show the spike periods of bioenergy production throughout the year, resulting in the innovative Figure 11.

Step "III": Discussion of political, environmental, and economic aspects related to the integration model. This discussion identifies alternatives for specific regional solutions, whether through cooperatives, or local productive arrangements supported by recent public policies. Funding programs and financial conditions to promote new investments in biogas projects in SPS are also identified. The political outlook is a driving force to support the model of waste integration in the agribusiness sector. Section 5 looks at techno-economic assessments for future implementations.

The next section offers a comprehensive description of waste generation processes for each agroindustry selected in this work.

3.2 General aspects of co-substrates generated in SPS agribusiness

The following topics give the characteristics of waste generation, the productivity of the selected crops and livestock, and briefly report reuses in the conventional processes.

a) Sugarcane sector

According to the National Supply Company – CONAB, 630 million tonnes of sugarcane were processed in 2019. Productivity was 3.6% higher than the 2018/19 harvest, while the planted area remained around 8.41 million hectares. Data collected up to December 2019, showed that processed sugarcane produced 29.03 million tonnes of sugar and 35.5 billion liters of ethanol [38]. The SPS remains the main producer, accounting for 53.7% of the Brazilian sugarcane production in the 2019/20 harvest and producing 46.2% of ethanol (16.4 billion liters) and 62.6% of sugar (18.8 million tons). Several studies explored the potential for reusing coproducts associated with the process – straw, filter cake, vinasse, and carbon dioxide from fermentation – to add value while mitigating environmental concerns[9,51,52]. Conventionally, sugarcane straw, filter cake, and vinasse have been reused as co-products for energy generation, and fertirrigation, respectively, despite many studies demonstrating that the best technical alternatives are still being incorporated by decision-makers in sugar-energy plants [53,54]. Figure 4 highlights the process of the sugarcane industry from the fields, until sugar, ethanol, and electricity production, as well as the solid and liquid residues generated throughout the stages.

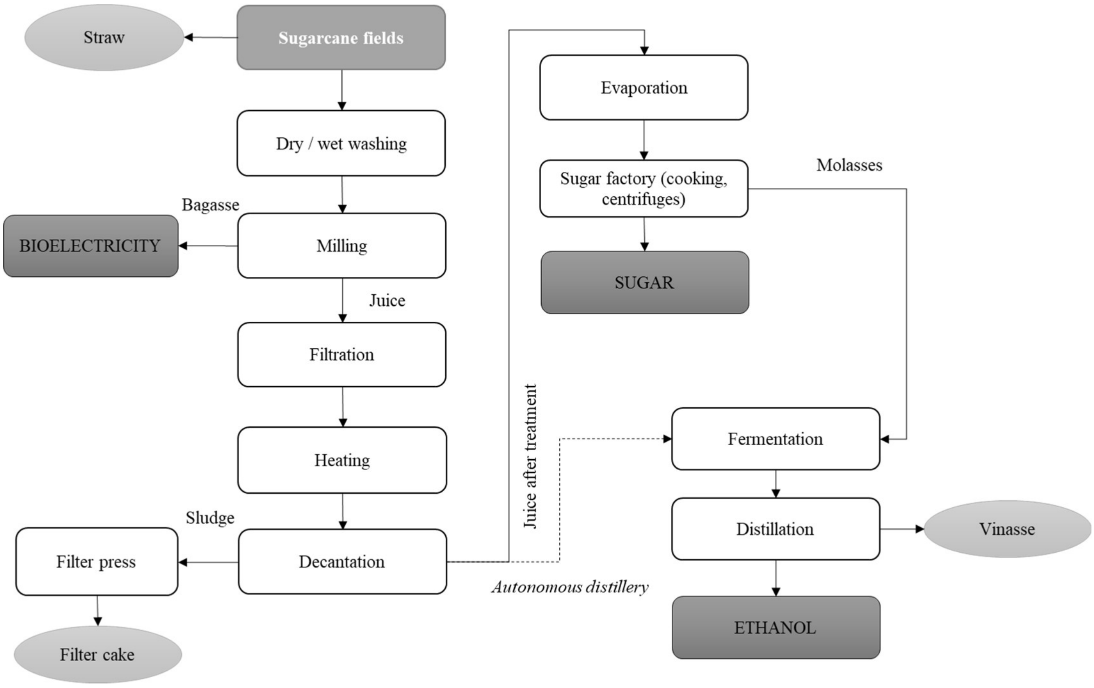


Fig. 4: Sugarcane agroindustry generating products and co-products

Vinasse, the liquid fraction generated from the rectification and distillation operations of ethanol, is a sulfur-rich, low pH, dark-colored, and odorous effluent, producing up to 10-12 fold the ethanol volume [9,11]. To quote, the application of vinasse for irrigation is only considered because it contains inorganic compounds, particularly potassium (K), an important nutrient for soil fertilization [54]. The high organic matter content indicates its potential AD substrate [9,55]. The literature cites the large volume of vinasse that is generated but does not deeply discuss the correct control of the applied organic load rate (OLR) when feeding a biodigester, since the large water volume in the composition can change the organic content fed into the reactor at each batch. Authors [9,56] also mentioned that vinasse generated from first (1G) and second (2G) generation ethanol present different compositions. Due to the type of pre-treatment adopted for the lignocellulosic material, liquid streams (such as 2G vinasse and pentoses liquor) are not recommended for fertirrigation because of the high organic matter content, in addition, there is the lack of regulation concerning its disposal. In contrast, the reuse as co-substrates for co-AD would make it a promising alternative for energy reuse.

Currently, most agricultural managers adopt sugarcane straw for soil conservation in the fields. Therefore, in conservative terms, 40% of the available straw could be reused, with the largest portion destined for soil protection [27,49]. In addition to the environmental impacts, the cost of removal, baling, and transportation to the plant must be considered. The cost of removing sugarcane straw from the fields depends on the collection system applied and the amount recovered per hectare. According to [57,58] the cost varies between US$ 12 - 37 per ton collected and its economic and environmental feasibility is mainly driven by industrial scale and electricity price [59,60].

Many biogas projects in the sector have been recently launched, and some of them started with additional investments. The ongoing projects from the companies Cocal, GasBrasiliano, Raízen, and GeoEnergetica are the most representative in terms of integration with the sugarcane industry. GasBrasiliano is a gas distribution company in the northwest of SPS, which is in partnership with the Cocal mill and has been implementing a project in July-2022 to commercialize biomethane in the municipality of Presidente Prudente. The production unit can achieve 24,000 m^3/day of biomethane (8.9 million m^3/year) from vinasse, straw, and filter cake and the biofuel is distributed in a 68 km gas grid [61]. Similarly, the Bonfim mill, located in Guariba in the northwest region of SPS, a joint venture between the Raízen and Geoenergética companies, started its operation in 2020 using vinasse and filter cake to produce 135,000 MWh annually. The general data concerning the technological arrangement for biogas production is presented in Table 4.

Table 4: General data for Bonfim biogas plant at Guariba

Electric energy production	135,000	$MWh.y^{-1}$
Biogas production	11,500	$Nm^3.h^{-1}$
Installed capacity	21	MW
Content methane in biogas	53	%
Co-AD approach (500 $tonnes.day^{-1}$)	Vinasse	70%
	Filter cake	30%
Bacterial consortium	A Mix of swine, orange residues, vinasse	

Source: adapted from [61]

Regarding the 10 largest sugarcane-producing municipalities in the SPS, the estimated biogas from straw, filter cake, and vinasse are 14,726 million $Nm^3.y^{-1}$ [49]. According to the International Center for Renewable Energies - CIBIOGAS, there are 30 biogas plants in operation or under construction in SPS that uses co-substrates from agriculture, livestock, and landfills [40].

b) The Citrus belt

SPS is the largest producer, accounting for 77.5% of national production, with 13.7 million tonnes in 2019, or 334.6 million boxes of 40.8 kg each: an increase of 8.5% compared to the season in 2018. Boxes of 27 kg and 40.8 kg are used for commercializing oranges for local consumers and industry, respectively. The citrus belt stands out for the high technological level of the orchards, with most of the orange cultivation destined for juice production, an important export product for Brazil [62]. The orange crop is an 18-year-cycle perennial cultivation. Falling leaves and small branches are marginal residues absorbed by the soil. Usually, adverse weather conditions have negative impacts on oranges in SPS, especially in dry seasons, which causes unevenly patterned fruit, small size, and fruit drop [63]. During the orange industrialization for juice production, large amounts of residues are generated, equal to 50% of the fruit weight and 82% moisture [64]. For every 1,000 kg of oranges processed, around 500 kg are bagasse, oils, pellets, and animal feed [19]. As pointed out by [65], conflict of interest and pricing issues cause difficulties in coordinating plans between rural farmers and the citrus industry. Traditionally, there is competition for planting areas between the orange and sugarcane belts, a fact that occurs mainly in the SPS central-west. The authors [66,67] discussed the potential to share bioenergy produced through co-AD technology between two agro-industry.

Figure 5 shows the stages of the citrus industry. Oranges are graded, washed, and stored in bins after being inspected. The juice is extracted using a rotary reamer or a finger crusher. The aim is to obtain juice recovery as quickly as possible without getting excessive peel oil in the juice to avoid spoiling the flavor. The peel is washed at the extractor with water to collect the oil, which is separated from the water-oil emulsion using centrifuges. The rotary extractor slices the fruit and presses the cut side against revolving burrs, crushing the liquid [68].

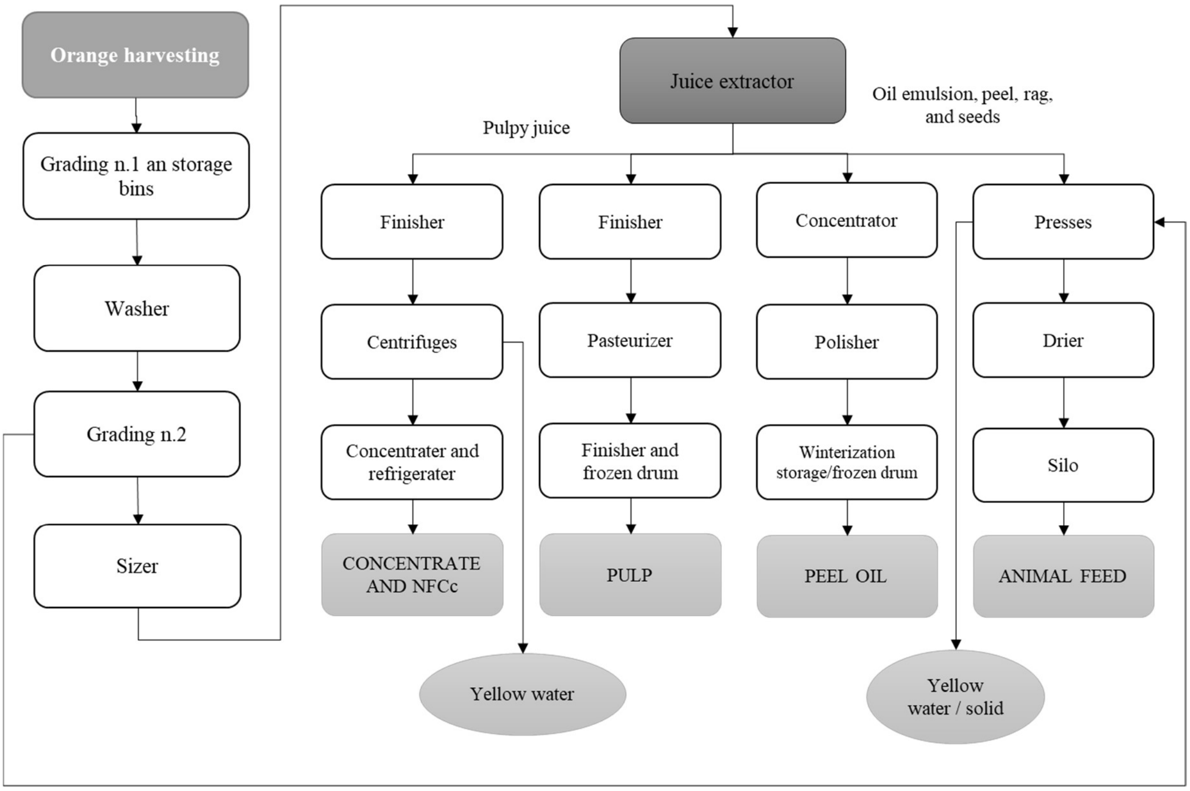


Fig. 5: Schematic process flow diagram for orange juice and its co-products. Adapted from [68]

The juice is squeezed out from a perforated tube and the peel is discharged onto a conveyor. After pasteurization, the juice is concentrated by multi-effect evaporation. Flavors from peel oil are a product collected in the first stage of evaporation. The wastewater from the oil recovery can be evaporated to make citrus molasses, which is a co-product used in animal feed [73]. As observed in the diagram, yellow water, peel, and solid residues are generated mostly in intermediary equipment, such as centrifuges and filter presses. Currently, orange peels are used as pellets for animal feed, a protein supplement for bovines. However, this fiber needs to be well conditioned because the solid waste produces mycotoxins capable of intoxicating animals. In addition, as a source of pectin – a soluble fiber used in the food industry – around 342 tonnes of pectin can be obtained from 8,000 tonnes.day^{-1} of residues after drying, milling, enzymatic inactivation, and extraction by heat treatment [64]. Pectin, terpenes, pellets, hesperidin, and nanocellulose can also be present with value-adding potential [69]. Reuses, such as energy sharing with the sugarcane industry, require additional discussion, such as the feasibility of both agroindustry´ proximity. To summarize, peel and yellow water are promising residues for co-AD operations.

c) Corn crops

The corn crop usually has two harvests throughout the year, which is determined by the climatic conditions of regions. In the first harvest, planting takes place between September and December, and the harvest takes place from January to April of the following year. The second harvest, known as the "safrinha" in Brazil, is planted at the beginning of the year and harvested between May and June.

In SPS, corn production from the first and second crops together accounted for 26.4% of total grain production in 2019. Between 2010 and 2019, the second crop plantation grew 87.1% while production increased 141.3%, demonstrating technological advances in productivity growth. Annual rates were 7.85% and 11.19% per year, respectively. After soybean, second-crop corn is the most cultivated grain, with 474,296 hectares with a market share of 20.0% among the crop types [63]. In the Cerrado biome, sorghum is sometimes cultivated during the “safrinha”, occurring in areas designated to the sugarcane inter-season. The first harvest has prices indexed to the international market, associated with animal protein demand. Productivity in the two periods 2014/15 and 2019/20 demonstrated an increase in the planted area despite typical oscillations, caused by climate adversities, rainy, and drought periods, during the cycles, which occurred in the last six years of the corn “safrinha”. Between 2019/2020, the mesoregion formed by the cities of Assis, Itapeva, and Ourinhos accounted for approximately 60% of the total production of the second crop [63].

The typical residues found after corn harvesting are stem, straw, bark, and corn cob. They have low nutritional value and if crushed, can ultimately be used as animal feed. Corn straw can be burned in rural areas, discharged, or used as soil cover after the mechanized harvest, but the surplus can cause problems for disease proliferation. Presently, corn straw has been designated for cigarette production, packaging, and handicrafts such as basketry. Recently, it has been extensively used in studies of enzyme production, via solid-state fermentation [19]. The main co-products from the agro-industrial process are DDG (distiller-dried grains) and thin stillage – a partial liquid waste, which is obtained from starch grain fermentation by yeasts [70]. The dry grind is the conventional method consisting of six steps: grinding, slurrying, cooking, liquefaction, saccharification, fermentation, and distillation. The final products include ethanol, carbon dioxide, and DDG [71]. Figure 6 shows the flowchart of the process for a corn ethanol production unit generating thin stillage, or corn vinasse, useful wastewater to be used as a substrate for co-AD with other agro-industrial residues.

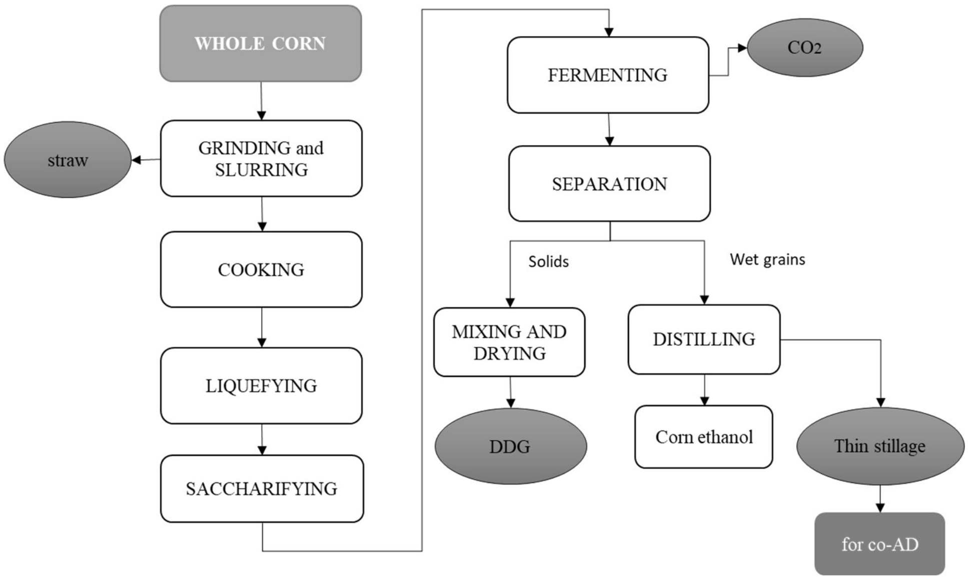


Fig. 6: Schema of traditional dry-grind corn ethanol and thin stillage generation
Adapted from [71]

The liquid generated is sent to a set of centrifuges, where the thin part (which can be recirculated in the process) is separated and the remaining part goes to evaporators. The syrup obtained contains 50% moisture which is mixed with the solids removed from the centrifugal process and dried, resulting in DDG. The subsequent stage is distillation, which is similar to obtaining ethanol from sugarcane [72]. Every 2.54 kg of fermented corn produces 1.02 L of ethanol, 0.28 kg of carbon dioxide, and 0.82 kg of DDGS [70]. DDGS is commonly destined for animal feed, due to its high protein and fat contents, however, these factors vary considerably according to plant operation. In Brazil, DDG and thin stillage are recommended substrates for co-AD in sugarcane facilities [73], especially if corn crops are adjacent to sugarcane mills. In SPS, only a few mills produce corn ethanol during the off-season. This method is most widespread in Mato Grosso, a neighboring state.

d) Soybean crops

Brazil is the world's largest soybean producer, where cultivation occurs in October and November, while harvest takes place in January and February of the subsequent year. Grain is essential to supply animal feed, as well as human nutrition. Most of the extracted oil is used to produce biodiesel [74]. The SPS remains the 8th state in soybean production [20]. Between 2010 and 2019 soybean cultivation grew by 120.4%, while the annual rate reached 11.68% per year [63]. Mechanized harvesting keeps straw in the fields while the rest of the residues are generated in the industrial process. Straw corresponds to 120% of the grain´s weight, so it is recommended that 70% of the total amount remains on the field, with 30% of available waste to be reused [49]. Soybean hulls, which account for roughly 8% of the whole seed, are the primary co-product. Figure 7 gives a general overview of the stages in the agro-industrial process.

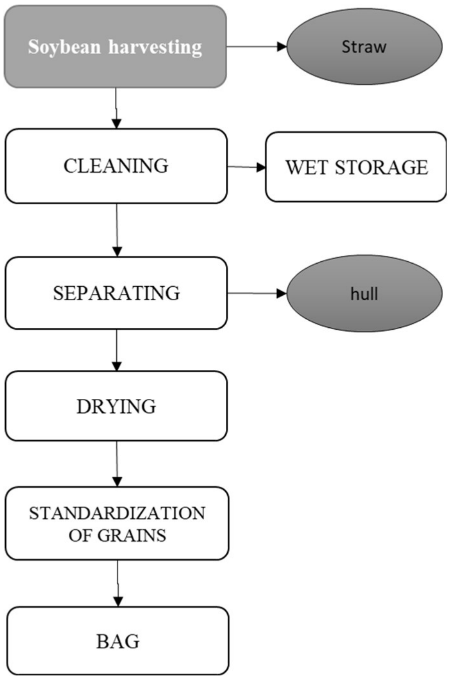


Fig. 7: Simplified soybean process and waste generation

Soybean straw, a recalcitrant lignocellulosic material, has high levels of glucan and lignin compared to soybean hulls and the carbohydrate content is attractive for bioethanol production [75]. In addition, the chemical composition of the soybean hull depends on the efficiency of the dehulling process, because a high-protein meal is desired, thus the dehulling process is intensified to avoid contamination with hull fragments. The final biomass is currently destined for animal feed, however, its low lignin level represents a potential source of fermentable sugars for cellulosic ethanol generation [76]. For biogas production, the main residues to be considered are hull and straw. Until the present research, no revealing studies were found that considered co-AD from soybean waste. However, because of the recent development in biodiesel production in SPS, possibly new arrangements of integration with other crops can emerge. Moreover, biodigestible residues generated in the food industry and their co-products were not examined in this study.

e) Coffee crops

Brazil is also the largest coffee producer in the world. Solid and liquid fractions of biomass with high organic content remain as residues after grain processing, which makes the coffee industry an important sector to be exploited for bioenergy purposes. According to Rotta et al. [77] only 2.6%

(m/m) of the total coffee harvested is for human consumption and the rest remains as waste. Typical Brazilian coffee production generates pulp and husk of around 420kg per 1 tonne of processed coffee grain, while the wastewater ranges from 5.0 m³ to 15.0 m³ per tonne of processed coffee [78]. In SPS, coffee production remains stable in the last few years. A long-standing work by [79] historically analyzed the spatial distribution of coffee culture in this region. Production keeps concentrated in small municipalities. Coffee trees are planted in the west of Ribeirão Preto, Franca, and Campinas mesoregions, near the Minas Gerais state border. Positive clusters can also be observed in the Assis, Marília, Araçatuba, and Presidente Prudente mesoregions.

The coffee industrial process can be carried out by two different methods: dry and wet. The wet method is preferred by producers because it enhances grain quality by eliminating the pulp and mucilage, however, this technique generates more residues [77]. Extra pulping, fermenting, washing, and drying stages are included in the wet processing. After harvest, the pulp and husk from red and green coffee fruits are easily removed during the pulping stage, while mucilage is then removed from the grains by fermentation. Then, wastewater, husk, and pulp are the most common residues [80]. Figure 8 shows both stages of processing of coffee residue generation.

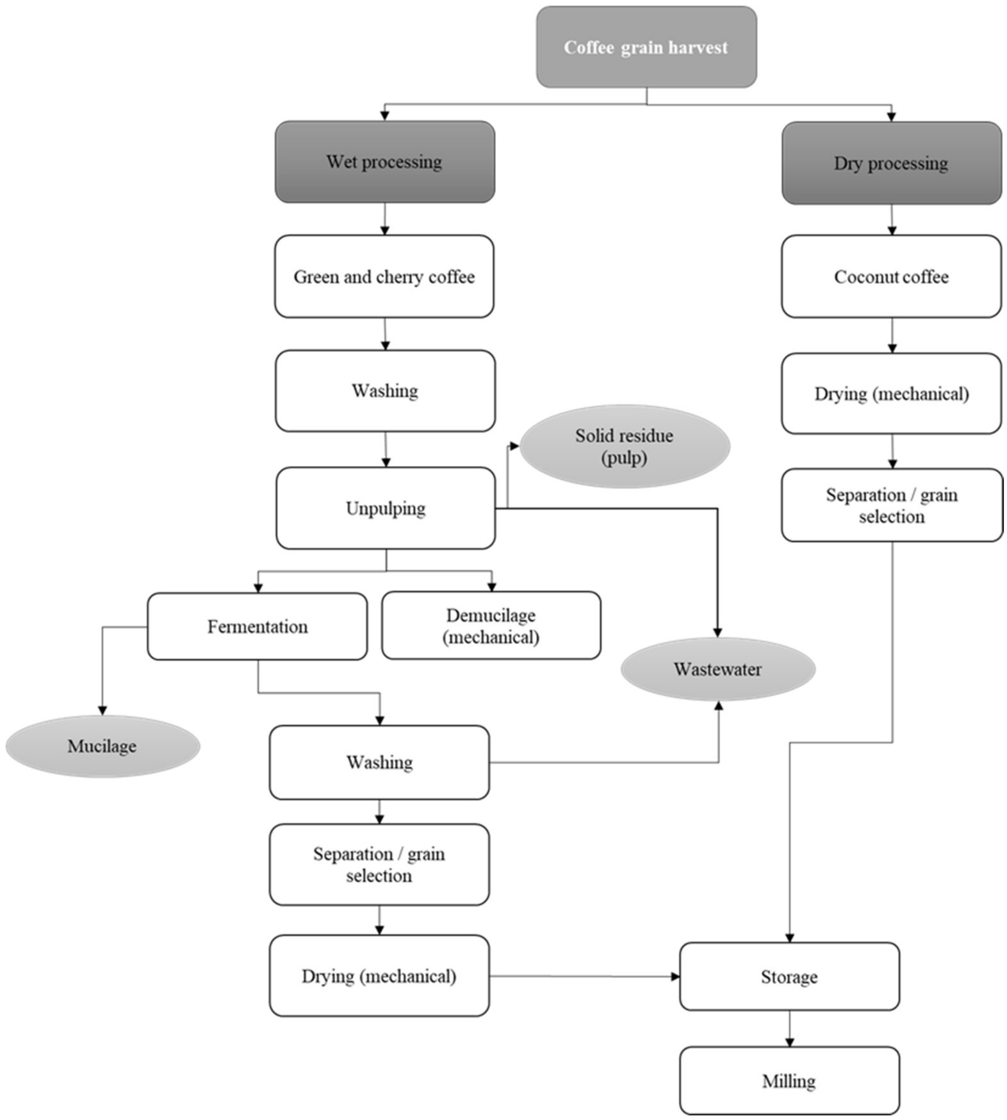


Fig. 8: Wet and dry methods for coffee processing
Adapted from [80]

Mucilage, one of the coffee residues, is rich in carbohydrates and has been used as a substrate for methane production, in similar conditions (pH 6-8; temperature 32-38ºC) as those used for biogas production from vinasse and filter cake [81]. Another study has found hydrogen, alcohols, and organic acids produced from the co-AD process when using mucilage as a co-substrate [82], as well as from ethanol production by mucilage fermentation in specific circumstances [83]. Mono-digestion of coffee residues does not have good stability in the long-term due to the lack of nutrients, such as nitrogen, that inhibit microbial growth. It has been demonstrated that co-digesting coffee residues improve the yields by increasing the C/N ratio, also providing adequate alkalinity amortization, and diluting toxic components such as tannins and phenols [84]. Another successful reuse of coffee mucilage by co-AD with swine manure was reported by [85]. Nevertheless, there is a scarcity of coffee residue recovery in Brazil because producers have conventional practices to incorporate part of residues on the soil.

f) Animal residue

Land use for pasture remains an important component of the Brazilian economy. According to the IBGE, there were 188,620 agricultural establishments in 2017, covering over 16.5 million hectares, with 49% allocated for farming, 29% for pastures, and 18% for forestry [86]. Technical developments in animal confinement have brought significant advantages to livestock production, but also induced environmental difficulties such as high organic load, pathogens, contaminated rivers, underground water and soil – mainly due to residue concentration on a large scale [87]. New solutions are currently required to reduce the negative impacts as well as provide new perspectives to the supply chain [88]. In the Census 2017, the 645 municipalities in the SPS produced 10.4 million tonnes of manure from cattle, swine, and poultry farming, which if collected and biodigested, would be possible to annually generate 374.5 million $Nm^3.y^{-1}$ biogas corresponding to 818 $GWh.y^{-1}$ [49]. Animal manure from confined livestock, particularly poultry, pigs, and cattle, has the largest biogas potential. The carbon content can be converted into liquid fractions with high added value, such as amino acids, according to the concept of biorefinery [19].

Swine farming is a polluting activity that generates unpleasant odors and GHG [89]. Swine manure is very useful as a substrate for biogas plants due to its low dry matter, which facilitates its transport and storage in tanks. Similarly, bovine manure is recommended as a co-substrate mixed with silage, especially due to the presence of methanogenic archaea that stabilizes biodigestion [90]. Figure 9 shows the general flowchart of manure generation in confined livestock.

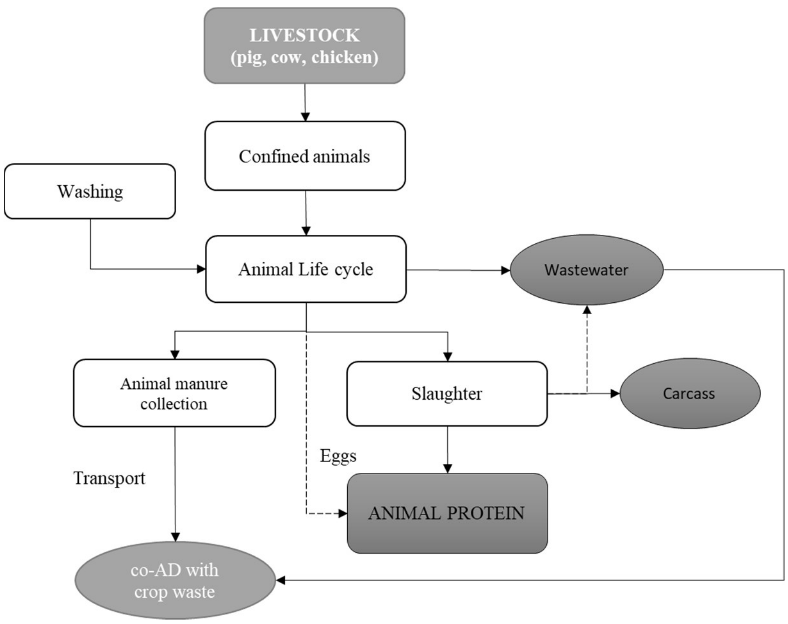


Fig. 9: Simplified schema of animal manure generation in confined areas

Poultry manure – bedding, dust, odor, washing water, and carcasses -- are collected in commercial farms through a productive cycle. The total amount of swine manure varies individually by weight. For bovine manure, the authors consider the whole production system during confinement, ie, from animal growth, water, and feed supply to slaughter and carcass generation [19]. Similarly, Coelho et al [49] considered only the confined cattle system and specific confinement periods. Thus, to estimate the manure generation, it is considered the average of the cattle´s initial mass, the final mass, and the time of stay in confinement. Then, the growth rate is calculated and represents the weight acquired by the animal during the confinement. The poultry industry is the fourth agro-economic activity in SPS (see Fig. 1). The number of matrices determines the production capacity. Swine farmers, meanwhile, are made up of a diverse range of producers, most of them are self-employed, while some are associated with slaughterhouses. However, issues concerning swine production, such as high costs, competition with other animal proteins, and lack of cooperative assistance are challenges for the sector [49]. In the SPS, bovine cattle are positioned in the western areas, where one-third of the total herd is distributed among five regions. Presidente Prudente reports having 7.5% of the total herd; Presidente Venceslau, 7.3%; Andradina, 5.3%; General Salgado 4.7%; and São José do Rio Preto, 4.2%. The pasture area is estimated at 9,186 thousand hectares, where the administrative regions of Marília, Presidente Prudente, Araçatuba, and São José do Rio Preto together account for 50.6% [63].

4. INTEGRATION THROUGH CO-DA TO PRODUCE BIOENERGY IN SPS

4.1 Mapping the regional solutions (step I)

Biomass – a geographically dispersed energy source- – can be strategically exploited for bioenergy to contribute in the medium-term to the SPS' energy matrix diversification. The state is divided into 15 administrative regions (ADM region), for political and economic administration. From the municipal bioenergy potentials indicated by Bioenergy Official Atlas [50] , we aggregated the highest values by region. Figure 10 highlights the ADM regions with the largest bioenergy potential (MWh.y^{-1}) generated from the selected co-substrates.

Fig. 10: Mapping SPS potential to produce bioenergy through co-AD with the selected crop residues.

Bioelectricity was determined by using the concept of "energetics", under a biodigestion process, where biogas can be converted into electricity or heat. The studies resulted in 8 main ADM regions where bioenergy production is feasible through co-AD. Barretos, Sorocaba, Campinas, Ribeirão Preto, Marília, Franca, São Jose do Rio Preto, and Araçatuba represents together the key regional hubs. These cities also host the largest sugarcane plants with considerable waste availability, and therefore can offer central co-AD processing. Co-substrates from neighboring areas can be mixed with sugarcane residue in a favorable logistics network, using a centralized sugarcane facility. Table 5 describes the information contained in the map, highlighting the municipalities and their respective energy potentials from the aforementioned residues based on official estimates.

Table 5: Municipalities in SPS with the largest capacity to produce bioenergy from agricultural and livestock residues

	Municipality	**Crop / livestock residue**	**Bioelectricity Potential (MWh.y^{-1})**
Region 1 (ADM Barretos)	Colômbia	orange bagasse, yellow water, tree pruning	55,163
	Guaíra	vinasse, straw, filter cake	1,086,000
	Barretos	vinasse, filter cake	31,913
Region 2 (ADM Sorocaba)	Itapetininga	orange bagasse, yellow water, tree pruning	41,696
		corn stover, leaf, stalks	44,267

		corn stover / cob	32,697
		poultry and swine manure	3,524
	Botucatu	orange bagasse, yellow water / tree pruning	41,351
	Itu	poultry and swine manure	3,088
	Tatuí	poultry and swine manure	1,911
	Tietê	poultry and swine manure	1,576
	Conchas	poultry and swine manure	1,132
		corn / stover, leaf, stalks	134,870
	Itapeva	soybean straw	147,754
		corn stover / cob	99,619
	Sorocaba	vinasse, filter cake	14,210
Region 3 (ADM Campinas)	Casa Branca	orange bagasse, yellow water, tree pruning	40,331
		corn stover, leaf, stalks	75,027
		corn stover / cob	55,417
	Rio Claro	poultry and swine manure	4,879
	Mococa	poultry and swine manure	1,615
	Amparo	poultry and swine manure	1,011
	Campinas	vinasse, filter cake	46,197
Region 4 (ADM Marília)	Garça	coffee husk	4,557
	Paraguaçu Paulista	vinasse, straw, filter cake	65
	Quatá	vinasse, straw, filter cake	39
	Marília	vinasse, filter cake	29,636
Region 5 (ADM Ribeirão Preto)	Altinopolis	coffee husk	4,177
	Sertãozinho	vinasse, straw, filter cake	1,008,000
	Pradópolis	vinasse, straw, filter cake	602,000
	Pitangueiras	vinasse, straw, filter cake	634,000
	Ribeirão Preto	vinasse, filter cake	66,774
Region 6 (ADM Franca)	Pedregulho	coffee husk	3,863
	Franca	bovine and swine manure	3,863
	Morro Agudo	vinasse, straw, filter cake	766,000
	Franca	vinasse, filter cake	32,924
Region 7 (ADM S.J. Rio Preto)	Riolândia	bovine and swine manure	23,622
	São José do Rio Preto	vinasse, filter cake	32,924
Region 8 (ADM Araçatuba)	Araçatuba, Buritama, Guararapes, Mirandópolis	bovine and swine manure	0.06
	Araçatuba	vinasse, filter cake	55,565

Note: Bioelectricity was estimated from residues generated during the season of 2018/2019.

Bioelectricity produced from residues was based on the interactive map and data from the SPS Bioenergy Atlas [49,50]. One of the criteria established in our study was choosing municipalities with a larger potential of energy that can be converted into biogas or bioelectricity through the biodigestion process. There is still no theoretical value for methane in the literature for the co-AD process using a mix of the residues mentioned in this work, despite the conversion depending on the biochemical composition as well as factors related to the bioreactor operation [3]. Concerning biomethane production, the model of annexed facilities proposed herein can be a profitable strategy because, among the 201 sugarcane plants in the SPS, 66 of them are up to 20 km from gas distribution networks. The potential capacity is approximately 3.0 million Nm^3 /day [91]. The logistical factor might be an important factor for the feasibility of the integrated process, similar to ethanol life cycle assessments, in which the displacement of inputs and outputs requires a substantial amount of fossil fuel [9,11]. On the map, the NG network is crossing the SPS, where, for example, Presidente Prudente and Campinas are city gates capable of injecting biomethane into the NG pipeline to attend to the energy demands. According to Energy Research Office [92], the proximity between gas pipelines and agro-industries (~50km, an example of Bonfim mill), enables connections to the biomethane supply. Recently, there has been the government initiative of mapping data by satellite to better understand the impact of agro-industrial residues in SPS as well as to monitor regional reuses and dispositions [93].

4.2 Co-substrates seasonality and alternatives of integration (step II)

With an understanding of the seasonal availability of the residues used for this investigation, appropriate substrate combinations can be better predicted, leading to the co-digestion process in a bioreactor performing effectively. The continuous operation of a co-AD process must be adapted so as to avoid interruptions of biomass supply (input) during the process. Figure 11 summarizes the harvest periods of each co-substrate investigated including the prominent combinations throughout the year based on the map-identified regions.

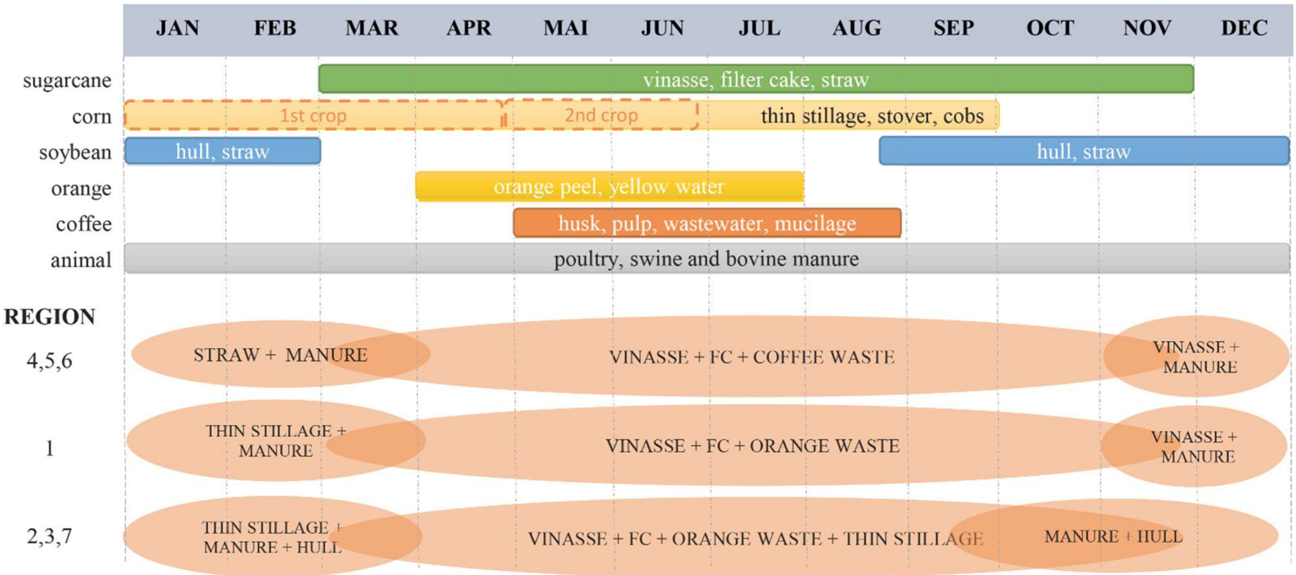


Fig. 11: Annual calendar of residue seasonal availability and the recommended combinations for each region

Note: "FC" means filter cake. Region 8 is not included because no feasible co-AD was evidenced.

It is economically feasible to maintain a biogas plant operating for the whole year. Therefore, the equalization of solid and liquid contents in the co-AD process is part of the operational planning. Animal manure is continuously generated throughout the year, having peak periods in the Easter (April) and Christmas (December) for swine and poultry manure that coincides with some crop interseasons. The strategy is to match each seasonal availability with each rural property that is geographically close. It should be noted that in some localities – Araçatuba, Presidente Prudente (Region 8) – the bioenergy potential from animal manure is not significant, given the fact that breeding is not performed in constrained areas, despite a large number of animals. The proximity of

Regions 5 and 6 benefit residue integration and transportation. In addition, these regions together generate the largest amount of sugarcane co-products. Due to soybean residues, Region 4 is the only where production is maintained throughout the sugarcane interseason. Regions 1, 2, and 3 allow for the mixing of many distinct co-substrates, demanding a comprehensive review of substrate composition, nutritional content, theoretical methane production, and OLR.

5. OPPORTUNITIES AND PUBLIC POLICY (step III)

5.1 Public Policies on the Agenda

As discussed so far, the diversity of biomass generated in the Brazilian agricultural / livestock activities would maximize renewable energy and consequently the energy matrix, as well as promote environmental benefits. However, despite the recent implementations of biogas projects, some configurations still require an appropriate business model due to their unique characteristics, particularly when multiple economic sectors are involved. Initially, a techno-economic study is recommended to define the type of investment and its technical limitations. Subsequently, effective public policies are equally important so as to enable favorable regulations, assure profitable stakeholders, and encourage small and medium rural producers. Beyond Renovabio, proposals are emerging to expand the implementation of new projects. For example, the Brazilian Program of Incentives for Production and Use of Biogas, Biomethane, and Associated Co-products (in Portuguese, PIBB), was recently established by Bill 3865/2021, in November 2021. One of the goals (item XIII) assists the logistical infrastructure needed for biomass transportation, as well as the interiorization of biogas / biomethane consumption. Tax incentives individually favor legal companies who participate in the supply chain, including co-products, as the digestate originated from the co-digestion. In addition, article 20 requires the guaranteed purchase of 10% of electricity from plants powered by biogas in reserve auctions for at least 15 years [94]. This mechanism is essential to encourage new investors in the reuse of agricultural /livestock feedstocks.

Concurrently, the Research Center for Greenhouse Gas Innovation – RCGI has been looking at new ways to assist in the strengthening of energy policies, particularly enhancing biomethane and NG supply to the SPS energy matrix [95]. Meanwhile, public policies are often designed in different instances that can result in challenging waste integration. At the federal level, three organizations are concerned: the Energy Research Office (EPE), the Ministry of Agriculture and Livestock (MAPA), and the Ministry of Mining and Energy (MME). At state and municipal levels, projects and partnerships can be handled by cooperatives by following local regulations and interests. Ongoing facilities may not obstruct regional solutions if public policies anticipate the new model.

Currently, it is allowed to capitalize the calorific potential of biomethane produced in landfills. This business model has been applied in various Brazilian regions – CTR Santa Rosa in Rio de Janeiro; GNR Fortaleza in Ceará - having an infrastructure to supply commercial fuel in gas stations, specifically in GNR Dois Arcos, Rio de Janeiro state [96]. Furthermore, after national regulation for authorized purchasing and sales (the year 2017), SPS has become a pioneer in establishing conditions for biomethane commercialization and insertion into the gas network. The ARSESP - State Regulatory Agency for Public Services is responsible for delegating the requirements for purchase and sale contracts, as well as the duties of suppliers and concessionaires. It also specifies the maximum volume that can be injected into the natural gas grid. Two modalities are authorized: the free market and the controlled market [97]. For commercialization, the option of monetizing by auctioning must adhere to standards by ANEEL[2] - The National Agency of Electrical Energy. In this case, the mentioned program PIBB (Bill 3865/2021) must benefit the producers. These initiatives allow for the fulfillment of contracts as well as the implementation of bioenergy projects, particularly those involving crop residues. Economically, the profitability of the chosen alternative is related to different forms of biogas uses, whether by thermal, power, or fuel applications, as schematized in Figure 12.

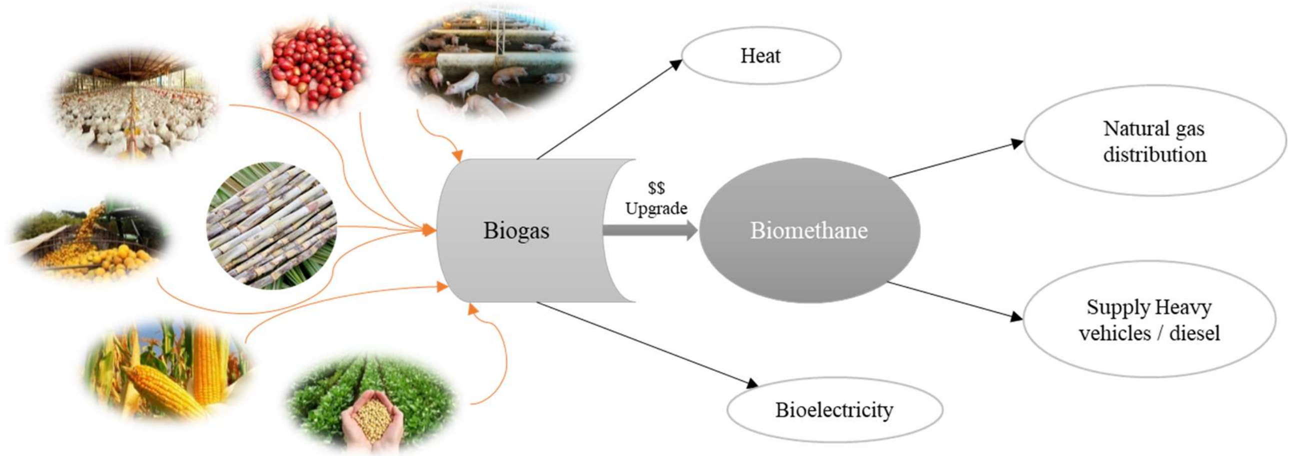


Fig. 12: Schema of biogas/biomethane applications through co-AD technology

To summarize, the political discussion must address co-AD technology from the perspective of incorporating more residues into biogas production, especially in a hypothetical integrated sugarcane facility. The development of a new business model is based on the regional integration of agricultural and animal co-substrates. Co-AD implementation is already predicted by Renovabio in terms of types of residues. Therefore, political deployments must predict that sectors may present different capacities and different local needs, depending on the availability. The regulatory implications can proportionally benefit the sectors to consolidate the proposed business model. In the following sections, the authors investigated existing mechanisms, little known by stakeholders, which can legitimize this Brazilian framework. The arrangements presented can contribute positively to the creation of partnerships as regional solutions, disseminating similar discussions internationally.

5.2 Arrangements and financial funding to enable waste integration in SPS

I - Model of Local Productive Arrangement – LPA

Local Productive Arrangement – LPA, developed in the late 1990s, is a Brazilian public program focused on collaborative bioenergy production. LPA was widely disseminated and institutionalized by the Federal government under the consent of the National Science, Technology, and Innovation Plan, the Productive Development Policy coordinated by the Ministry of Development, Industry, and Foreign Trade (MDIC) [98]. LPAs are agglomerations of companies and enterprises located in the same territory that have a productive specialization, a particular governance to maintain interaction and cooperation among members, as well as with industrial associations

[2] The distributed electricity is regulated by Resolution ANEEL nº482/2012, modified by Resolution nº687/2015.

(National Confederation of Industry – CNI), credit institutions (Bank of Brazil, Micro and Small Business Support Service – SEBRAE), and research centers (public universities, SENAI). Currently, there are 839 LPAs scattered among 2,580 municipalities in all parts of the country, representing 40 different production sectors [99]. Table 6 gives three arrangements that operate with bioenergy activities in SPS.

Table 6: Current agribusiness LPAs operating in SPS

The Formal name of LPA	Region / main municipalities	Acting in
"Energias Renováveis de Sorocaba"	Campinas; Indiana; Itapevi; Salto	Manufacturing and technological innovation in **renewable energy**
"Agronegócio de Jaboticabal"	Bebedouro; Guariba; Jaboticabal; Monte Alto; Monte Azul Paulista; Pitangueiras; Taquaritinga; Terra Roxa; Viradouro and others.	**Ethanol, sugar, and peanuts** cooperation
Bioenergia de Piracicaba (APLA)	Matão; Piracicaba; Sertãozinho	**Ethanol, sugar, and bioelectricity** dissemination

Adapted from *Observatório Brasileiro APL* [100].

APLA is focused on energy production in the agro-industry, especially in assisting the Brazilian sugarcane sector and in developing integrated sustainable solutions ranging and promoting commercialization of ethanol, biodiesel, and biomass [101]. The LPA outlines joint actions of economic interest, such as manufacturing, process development, commercialization, and acquisitions of equipment, raw materials, and inputs [102] being a challenging approach for long-term investments. Nevertheless, it was noticed that leadership is not well defined by the local arrangements, the actions are sparse and undisclosed, although the members seem to have autonomy in their decision-making.

II - Model of Agricultural Cooperatives

Cooperatives are autonomous organizations made up of people who voluntarily share mutual aspirations and meet economic, social, and cultural needs. Members can be collectively owned companies managed democratically. Agricultural cooperatives provide important support for rural producers, contributing to income generation by adding value to the supply chain and offering benefits such as access to the worldwide market and embracing new technologies to boost productivity. The organizational structure allows rural producers to assume self-management of agro-businesses, being able to define commodity prices and facilitate the market of inputs [103]. However, governance problems can emerge, mainly because participants usually are both rural producers and users of their businesses. Thence, contracts are not properly established, and activities are poorly managed. As a result, conflicts and expensive costs are typical occurrences within the organization [104]. On the other hand, cooperatives can provide some benefits to the members while assisting economic growth. For example, the generation of electricity can be distributed among members and reduces operational expenses. Table 7 lists the benefits and drawbacks:

Table 7: Advantages and disadvantages of agricultural cooperatives

Advantages	Disadvantages
● Revenues from joint exploitation ● Energy self-sufficiency ● Competitiveness by using benchmarking. ● Sustainable development in regional communities. ● Ongoing professional development	● High cost for maintaining human resources. ● Investment in training is required. ● Disarticulation of rural producers´ income. ● Environmental liabilities, such as crop residue destination ● Low renewal of cooperatives in SPS and closure of organizations

Adapted from [105]

According to the *Brazilian Cooperatives Organization* – OCB [105], the biogas model can be a competitive opportunity for sharing energy in the cooperativism. Bioelectricity and biofuel could be primary energy sources for many agricultural cooperatives, where, nowadays represents around 8% of the energy consumed in Brazil, either directly or indirectly [40]. The Association for biogas promotion (CIBIOGAS) suggests creating a business model of cooperatives dedicated to power generation involving civil organisms, associates, and cooperatives following a compensation system, encompassed by Normative Resolution nº482/2012 of ANEEL [103]. In this context, biogas becomes a versatile biofuel for cooperatives, providing opportunities for energy self-sufficiency, environmental impact mitigation, and improving the competitiveness of affiliated producers for sustainable development. Brazil's biodiesel production is a successful example of a collaborative approach that has proven effective in energy operations. Small cooperatives (processing castor, soybean, palm oil, and cotton) have played an essential role in the development of family farmers in the Northern region, particularly supporting social sustainability in rural areas [74]. Table 8 lists the qualified cooperatives operating in SPS to assist in new integrated initiatives.

Table 8: Largest agricultural cooperatives operating in SPS (in volume and revenue)

Official name	Description
Copersucar	**Sugarcane Cooperative** began operation in 1959 and globally consolidated in 1979 by supporting the Formula 1 team. The association generates around R$ 28.6 billion in revenues.
Coplacana	The Cooperative of **Sugarcane producers** was first created in SPS, in 1948. Cooperative offers inputs and technical assistance to rural producers in the surrounding region of Piracicaba – SP, accounting for 27 stores spread throughout SPS, Goiás, Minas Gerais, Mato Grosso do Sul, and Paraná. It also has a Feed Factory; Central pesticide packing; Cattle Containment, and Grain Storage units.

Coopercitrus	Founded in the mid-1970s, the Cooperative of Rural Producers has a portfolio of over 35,000 farmers operating in SPS, Minas Gerais, and Goiás. They cultivate **coffee**, **sugarcane, soybeans, corn, livestock, horticulture,** and, especially, **citrus**. Recently, it was recognized as the largest financial organization for agricultural inputs and machinery. In 2018 its net revenue was R$ 3.6 billion.
Integrada Cooperativa Agroindustrial	It is 22 years old. It is one of the largest agricultural cooperatives in the South and Southeast regions. The company commercializes **soybeans, corn, wheat, coffee,** and **citrus**. There are 80 units in Paraná and Sao Paulo states.

Agricultural and livestock cooperatives together can be an interesting case to demonstrate the potential of integration. Social issues have been frequently discussed among the associations and may expand productive activity while also addressing environmental concerns [106,107]. Federal law 10406/2002 regulates cooperatives and associations across the Brazilian territory, in article 50, paragraph 5 provides that: "the expansion or alteration of the objective of any economic activity does not constitute a diversion of purpose". Thus, cooperatives that acquire inputs used in the processes, operations, storage, and product industrialization, could also subsidize agricultural residue (such as the digestate, a biofertilizer) as a substrate with added value for profitable reuse. Additionally, a business model could be designated between a grain or poultry/swine cooperative and a sugarcane mill to produce bioenergy and biofertilizer as exchangeable products. In this hypothetical value chain, agro-industrial or animal manure would acquire economic value as raw material. Biofertilizers can be reused by the associated producers in their supply chain. The shared energy generated through biogas would be implemented in the production cycle. For now, the cooperative model for bioenergy projects based on residue integration from different crops seems to be common in other Brazilian regions. The "Consórcio Verde" project operating in Rio Grande do Sul, in the South, includes a citrus cooperative, a livestock farm, and a gas distribution company. The three stakeholders are producing biogas and sharing their demands [108]. The plausible reason for this good example in Southern cooperatives is due to the robust rural economy based on cultural pillars, particularly among traditional families who have lived in the countryside for generations.

III - *Sustainable funding for rural projects*

Most producers are individuals (small and medium properties), accounting for 76.7% of rural businesses. Half of them rely on government subsidies to fulfill their production costs [109]. This topic provides recent financial conditions supported by the Federal government to enable new investments in the agricultural sector, especially for projects involving bioenergy and sustainability. Table 9 gives the modalities.

Table 9: Financing for agricultural and climate change investments in Brazil

Funding support	Indicators and interest rates
"PRONAF" (Implementation, expansion, or modernization of productive structure in rural establishments)	4.0% per year (fixed rate) Financeable amount up to 100%

	Deadline from 2 to 10 years
"BNDES FINEM" (Investments in production, storage, and food processing. Conventional or 1G biofuels also included)	Financial cost: TLP[1] (long-term rate) BNDES spreads (remuneration): 1.3% per year. Financeable amount up to 100% Deadline up to 20 years
"FUNDO CLIMA" (projects focusing on GHG emission reduction and climate change adaptation)	DIRECT OPERATION Financial cost: 0.1% per year BNDES spreads (remuneration): 0.9% per year. INDIRECT OPERATION Financial cost: 0.1% per year BNDES spreads (remuneration): a) 0.9% per year (micro and small business) b) 1.4% per year (medium and large business) Financial agent fee limited to 3.0% per year Financeable amount up to 80% (annual limit: R$30 MM) Deadline up to 12 years
"BNDES Renovabio" (Direct support for certified biofuels production through ESG credit)	1.5% per year (remuneration) which can be decreased if the company improves its CBIO efficiency factor[2] Financeable amount up to 100% R$ 20 M up to R$100 M Deadline up to 8 years

[1] the final interest rate of the contracts will consist of TLP, added to BNDES' accredited financial agent's spreads (in the case of indirect operations) and the credit risk rate.
[2] CBIO emission factor known as NEAA - energetic-environmental efficiency score.
Source: adapted from [109]

PRONAF offers a higher interest rate among the options cited and can be financeable up to 100% of the project value for short periods corresponding to the 6-8 year payback for ongoing biogas projects in the Brazilian sugarcane sector. Companies regularly request FINEM for new equipment purchases or technological retrofits. The modality offers a low-interest rate, is 100% financeable, and may be paid off in 20 years. FUNDO CLIMA presents a lower interest rate compared to other modalities; it is focused on environmental issues; thus, it is recommended for projects that offer medium- and long-term GHG reductions. The recently announced BNDES Renovabio, is a financial support based on ESG – Environmental, Social, and Governance, and encourages the biofuel industry to improve energy-environmental efficiency within the Renovabio framework. Certified companies that have headquarters in Brazil must be registered as biofuel and/or ethanol facilities [116]. The Santa Adélia sugarcane plant located in the Ribeirão Preto was the first to sign up for Renovabio funding. The focus has not been on biomethane so far, although the program can meet this demand. This financial incentive can boost new investments in biomethane facilities, an alternative capable of replacing NG as part of the program's scope. Ultimately, these financial parameters must be considered for the techno-economic assessments, particularly for the business model of integration discussed throughout this work.

6. CONCLUSION AND FURTHER DIRECTIONS

It is still necessary to carry out practical studies to better elucidate waste integration in the agroindustry. Techno-economic assessments on an industrial scale including operational costs should be performed to clarify aspects of an integrated biogas production via an anaerobic co-digestion route. Analysis of social impacts involving the agricultural and livestock sectors is also recommended for debate. The biofuel industry is currently the subject of several social debates if crops either affect directly or indirectly the natural resources. Thus, governments and researchers must promote the incorporation of social impact assessment of local projects, especially in the case of bioenergy produced from various crops in SPS, which can be complex.

Moreover, the significance of biomethane requires a better decarbonization credits calculation method by the Renovabio program, which is still limited to lowering GHG emissions. If bioenergy can be generated using different residues from agriculture and livestock, the producer may also receive additional benefits. Small producers are part of a cooperative and may receive financial incentives. In this regard, public policy would serve as a primary inducement mechanism for biogas innovation in SPS.

Finally, faced with the externalities of the future, particularly the demand for new regulations, the sugarcane sector, in particular, will discover new challenges. A sugarcane biorefinery in partnership with agricultural sectors could provide a regional solution for making biogas/biomethane feasible and boosting agribusiness for the future. The new alternatives herein identified, can promote an international discussion of integrative processes for potential agricultural regions in many countries.

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CHAPTER 2

Brazilian agricultural and livestock substrates with potential co-digestion for energetic purposes: analysis of technical and economic aspects

Substratos da agropecuária brasileira com potencial de co-digestão para fins energéticos: análise de aspectos técnicos e econômicos

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Review

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Brazilian agricultural and livestock substrates used in co-digestion for energy purposes: Composition analysis and valuation aspects

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Abstract: Brazil's agriculture and livestock annually generates enormous amounts of biomass, which varies in its biochemical composition. Many studies have pointed out the benefits of using this biomass as a substrate for biogas production through anaerobic digestion (AD), mostly via the co-digestion (co-AD) pathway. The agriculture and livestock of southeastern Brazil – sugarcane, orange, corn, soybean, coffee, cattle, swine, and poultry – have together demonstrated their potential for producing biomass that can be used for maximizing methane production. Filter cake, vinasse, straws, bagasse, mucilage, pulp, washing water, thin stillage, and manures also have specific organic matter and nutrient content that can be evaluated from an economic perspective as co-products of biorefineries. Some are costless but others have acquisition costs in the agricultural market. Comparing the recent biochemical compositions cited in scientific literature (technical parameter) and to know the costs (valuation parameter) is crucial for farmers and investors make decisions in large-scale. This study conducted a bibliographical survey of biomass generated in Brazilian agroindustry as a co-substrate for energy production. The analysis summarized two tables: 1- a compilation of biochemical composition of the main co-substrates, and 2- the acquisition or opportunity costs, discussing innovative aspects in the context of biogas production. © 2022 Society of Chemical Industry and John Wiley & Sons, Ltd.

Key words: residues; co-products; biogas; biochemical composition; cost of acquisition

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Introduction

The transition to sustainable energy sources poses environmental and economic challenges. Brazilian biogas expansion is facing different alternatives, especially regarding techniques to facilitate usage of biomass resources in the productive regions, and compliance with new public regulations.[1]

Short-lived crops typically generate greater quantities of agricultural waste with lower harvesting costs than long-cycle (perennial) crops. Traditionally, some of the agricultural waste is incinerated, composted, and used as fertilizer or as animal feed. However, these procedures demand energy and have a significant environmental impact. Similarly, the livestock sector has a tendency to boost productivity, which is reflected in an increase in liquid manure.[2]

As an alternative, anaerobic co-digestion - co-AD has been proposed as a potential solution for the reuse of biomass and subsequent production of clean bioenergy (mostly biogas) to satisfy sustainable development goals.[3] Bagasse, straw, bran, and processed grains – a typical biomass destined for animal nutrition, particularly for bovine, swine, and poultry – have added value and can be commercialized. Eventually, to maximize the efficiency of biogas production, pretreatment of lignocellulosic wastes, notably for corn and sugarcane straws, orange bagasse, as well as soybean meal, may be necessary.[4] In addition, the valuation of raw materials for bioenergy (biogas/biomethane/bioelectricity) purposes seems to be a necessary strategy to the productive cycle, recognizing the biochemical composition of wastes, and in parallel, predicting its value-based pricing.

Thus, our objective was to conduct a survey of Brazilian agricultural and livestock wastes to provide technical information for biogas plants operation while also introducing a new discussion concerning aspects of the valuation of co-substrates. This study presents technical parameters such as organic load, pH, nutrient content (Ca, Mg, N, S, P, K), total and volatile solids, lignocellulosic composition of substrates such as sugarcane products (filter cake, straw and vinasse), corn (straw, thin stillage from corn ethanol), orange (yellow water, bagasse and fibers), soybean (straw and bran), coffee (mucilage, bark and wastewater), and animal manures (bovine, poultry and swine). The information related to the acquisition and opportunity costs of co-substrates is based on current market quotations and data obtained from experts.

Background of co-substrates for energy purposes

Brazilian agriculture is geographically delineated into green belts. Sugarcane, soybeans, and corn are the main energy crops, especially in Sao Paulo state (SPS), a leading agro-industrial producer. Citrus, coffee, and livestock, notably cattle, poultry, and pigs, are prominent in certain regions of the state.[5] These productive regions are geographically close to each other, which is particularly advantageous for cooperative partnerships. The sugarcane agroindustry is one of the largest biomass sources. The economic benefits extend beyond biogas. It produces fuel for trucks, contributes to the reduction of bagasse consumption, and, finally, is used to produce surpluses of lignocellulosic ethanol (2G) and bioelectricity.[6] Production of energy for rural producers' own use would also increase their energy autonomy, enabling entrepreneurs to supply their own fleet, as is the case with biomethane, which can be used to fuel medium and heavy vehicles during cultivation.[7] With this approach, biomass can be economically valuable if exploited in biodigestion processes for bioenergy purposes, such as sugarcane biomass (filter cake, straw, and vinasse), soybean biomass (soybean straw), corn biomass (straw and thin stillage from corn ethanol), coffee biomass (pulp, processing waste, and effluents), orange biomass (bagasse and yellow water), and animal manure (cattle, poultry, and swine). Biomass is seen as a resource for earning profits in Brazil, whether for energy or non-energy purposes. Recycling and biodegradable packaging, animal feed, soil cover, and fertilizing are all examples of its multiple reuses.[2] The versatility of this organic material, and its added value and environmental acceptability, encourage its reuse on a large scale.

Anaerobic Codigestion (co-AD) combines the anaerobic digestion (AD) of two or more substrates, allowing for the integration of residual biomass from agroindustry. The mix of co-substrates also improves CH_4 synthesis by supplying and balancing macro and micronutrients during the microbiological process. It may also be an alternative to difficult-to-biodegrade substrates,[8] and it can be transformed into by-products with fertilizing potential, which can be partially reused for agricultural purposes. In general, no harmful effects were observed on soil ecosystem when biofertilizer was added. Digestates also showed agronomic properties intermediate between fertilizers and amendments, being able to improve biochemical soil properties.[9] However, some aspects still need to be evaluated – mainly the demand for biofertilizer in agricultural areas, digestate quality, and the logistic costs. The increasing number of biogas plants

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associated with the amount of digestate produced, and the diverse material fed into different biogas processes, and differences in operational management, produce fertilizers with different qualities, varying in macro- and micronutrient content and also in chemical contaminants.[10-12]

Recent operational conditions and productivity using the co-AD approach

The biodigestion process conducted by microorganisms in a bioreactor involves the parameterization of the co-substrate feed stream – that is, the balance of the content of organic matter or available carbon, in addition to the nutrient and micronutrient content.[13] Under the appropriate operational conditions, co-AD technology boosts biogas production while addressing a part of the problem of accumulating solid residues and effluent.[14] The design of industrial facilities for the biogas plant is a significant aspect. Some of the elements that affect productivity are the appropriateness of the equipment, the modeling of biodigesters, the ability to combine co-substrates with variable total and volatile solids, and biodigestion kinetics. These elements must always be observed in new initiatives in commercial-scale plants.

According to the literature, the upflow anaerobic sludge blanket (UASB) bioreactor was the most frequently recommended model in continuous-flow operation for monodigestion of vinasse, the most frequently employed substrate in AD in Brazil. The continuous stirred tank reactor (CSTR) is the recommended bioreactor model for co-AD processes because it mixes solids and liquids better and may be operated in a continuous or semi-continuous mode.[8,15,16] Table 1 shows the operational and technical parameters adopted in recent tests, combining agro-industrial wastes and animal manure, as well as the survey with the most prominent productivity reached.

In the experiments, the adopted combination between co-substrates reveals a trend, particularly the necessary adjustments of C/N, feed rate, and productivity in a co-AD approach. The CSTR was found to be the most frequently employed model, corroborating the fact that solid waste is better utilized in mixed bioreactors. The productivity varies depending on the composition of the co-substrate as well as the percentage of organic matter in the feeding bioreactor. It was noted that there is no consensus in the scientific literature regarding the standardization of the biogas unit, which makes productivity comparisons challenging.

Some combinations of different co-substrates are highlighted. The mixture of conventional ethanol vinasse (1G), cellulosic ethanol vinasse (2G), and pentose liquor is new, and represents a breakthrough. The results showed that the mixture mentioned boosted CH_4 generation (568 Nl $CH_{4}.g\ VS^{-1}$) compared to isolated substrates. The main gains achieved with pentose liquor and vinasse 1G were 12.7% and 15.4% higher than individually, respectively.[18]

Other survey showed that combining swine manure and sugarcane vinasse in different proportions of total solids (TS) resulted in higher yield compared to vinasse-straw. The hydrogenotrophic methanogenesis pathway is not carried out appropriately in some unknown proportions of swine manure, most likely due to the high nitrogen content in the form of ammonia, which can inhibit CH_4 conversion.[14]

Retention time is also one important parameter in the conversion of volatile solids (*VS*) into CH_4, and for controlling the microbial growth rate. For batch tests, the methane production rate increased during the initial stage, and gradually decreased afterwards. Similarly, solid retention time (SRT) – a measure of the time length for microbes (or solid wastes) to stay in a bioreactor – is a common parameter in the biological process.[3] For the co-AD process, the SRT is usually equal to the hydraulic retention time (HRT) as there is no recirculation of microbes in the effluent back to the digestor. The HRT of a digester varies from a few days to months, depending on the substrate types and process configurations. A longer retention time commonly yields a higher cumulative CH_4 production, leading to a greater reduction in the total *VS*. For an engineering design, the HRT of a co-AD process is usually determined by the feedstock content, mixing, temperature, the nature of the inoculum, the weather, and even the recirculation of digestates.[3]

Criteria for data compilation

A review of biochemical composition was conducted to assemble detailed technical parameters regarding the main Brazilian agricultural and livestock wastes. The acquisition and opportunity costs of substrates were based on a bibliometric analysis methodology using available publications containing prices and quotations as well as consultations with experts and leaders from agroindustry. The valuation and discussion addressed here are also unprecedented in the literature.

The following topics were considered:

- Recent interdisciplinary journal articles referring to the substrates generated in the Brazilian climate and with Brazilian soil conditions .
- Relevant technical parameters monitored by the main researchers to provide better co-AD performance for biogas production.

Table 1. Recent biogas productivity and operational characteristics of co-AD using agricultural and livestock co-substrates.

Substrates	Feeding features	Operational parameters	Biogas/CH_4 productivity	Comparative productivity* (L biogas. Kg VS^{-1})	Reference
Poultry droppings (PD) with wheat straw (WS)	70:30 (PD:WS)	pH 7.7; operating 8–9%TS	BMP 330 NL/kg *VS*	600	17
Poultry droppings, meadow grass (MS)	50:50 (PD:MS)	pH 7.7; operating 8–9%TS	BMP 340 NL/kg *VS*	618.2	17
Vinasse 1G, vinasse 2G; pentose liquor	15.4% (v1G); 12.7% (liquor); 71.9 (v2G)	-	BMP 568.2 NL CH_4.g VS^{-1}	1033	18
Vinasse, swine manure	3% TS at a shorter technical digestion time, 53.9% higher productivity than vinasse-straw	pH 6.9–7.5; C/N:4.0; T = 37°C	676.7 L biogas/kg *VS*	676.7	14
Coffee pulp (CP) and cattle manure (CM)	4:1, 2:1, 4:3 (CP:CM)	Batch digester; mesophilic conditions	BMP 230.37–238.80 mL/g *VS* added	418.8–434.2	19
Filter cake (FC) sugarcane straw (SS)	70% SS/30% FC	4:1 inoculum/substrate semi-continuous CSTR; OLR 2.0 gVS/L.d	262.9 mL CH_4/g *VS*	478	16
Filter cake (FC) sugarcane bagasse (SB)	70% FC; 30% SB	Semi-continuous CSTR; OLR 1.0–3.0 gVS/L.d	0.99–1.45 m^3 biogas m^3/day	320	20
Filter cake (FC) 1G vinasse (V); Deacetylation liquor (DL)	70% V: 20% FC: 10%: DL of *VS*	Semi- feed - continuous CSTR; OLR 4.16 gVS/L.d	230 NmL CH_4/gVS	418.2	8
Corn stover (CS) chicken manure (CM) with biochar	2%:1% of *VS*	Semi-continuous CSTR; OLR 4.2 gVS/L.d	1.26–2.16 L CH_4/L/day	935	21
Corns stalks (CS), dairy manure (DM)	50:50 m/m	OLR: 3.2 gVS/L.d	19 L biogas	5937	22
Citrus pulp, olive pomace, cattle manure, poultry litter, whey, and corn silage	42%: 17%: 4%: 8%: 18%	Semi-continuous batch 750 mL bottles (reactor)	239 mL CH_4/g *VS*	434.5	23
Corn Stover, dairy manure, tomato residue	33%: 54%; with 13% of TS	Batch 1 L	415.4 L CH_4/kg *vs* feed	755.3	24
Coffee-pulp (CP) and cow-dung (CD)	40 wt% coffee-pulp, 40 wt% cow-dung and 20 wt% water	Batch digester, mesophilic conditions (35–45°C)	52.48 vol. % CH_4 (monodigestion CP: 22 vol. %) (monodigestion CD: 11 vol. %)	1261	25
Dairy manure, corn stover	DM:CS at the mixture ratio of 80:20 and 60:40	Continuous stirred-tank reactor (CSTR); 0,75 L	99; 83 ± 4 CH_4 production (mL/TS loading) respectively	151–180 L/kg TS	26
Coffee processing wastewater – CPW and waste activated sludge (WAS)	97.2 wt% CPW – 2.8 wt% WAS	Anaerobic membrane bioreactor (AnMBR), thermophilic conditions (55°C), OLRs 0.87–9.16 gCOD/L/d	CH_4 yield of 0.28 L CH_4/g COD removed	5090 L/kg COD	27
Orange peel waste, citrus wastewater (monodigestion)	19% TS; 97% *VS* of TS	OLR 0.51 kg COD/m^3 day	0.116 m^3 CH_4/kg waste; 2.1 m^3 CH_4/m^3 wastewater	211; 3818 L/kg	28

Table 1. (Continued)

Substrates	Feeding features	Operational parameters	Biogas/CH_4 productivity	Comparative productivity* (L biogas. Kg VS^{-1})	Reference
Wastewater sludge(S), food waste (F), swine manure (SM), fat and oil (FO)	-	-	8.7; 13; 8.6; 26 MJ/kg waste	1320.5 L/kg waste	29

*55% methane content in biogas; calorific potential (CH_4) of 35.8 MJ/Nm^3. Units converted into volume of biogas/kg volatile solids; except for those indicated due lack of volatile solids values.

- Adoption of economic concepts to assess value variations and acquisition and opportunity costs of co-products used in the agricultural market in Brazil.

No other study has been devoted to the analysis of technical and valuation parameters of typical co-substrates. Our ultimate objective is to offer an auxiliary guide for biochemicals and agroindustry managers of the different substrate combinations for the effective performance of biodigesters.

Technical and valuation parameters of co-substrates

Compilation of co-substrates composition

There is a lack of publications gathering data on the biochemical composition of Brazilian agricultural and livestock waste. Table 2 shows that these characteristics are influenced by regional practices, soil geomorphology, climate, fertilizer use, and, in the case of animal waste, by the nutritional impact of animal feed.

In general, the pH values refer to the liquid phases under natural conditions. The chemical oxygen demand (COD) is an indirect measure of the organic matter content and it complements the analysis of the total solid (TS) and total volatile solid (TVS) content present in the materials. Due to features of the physicochemical analysis, COD is typically employed for liquid substrates.[51]

The production of biogas through co-AD is directly related to the concentration of TVS or biodegradable organic compounds. The dry matter content (total solids, TS) and volatile organic compounds (VOCs) in raw materials are important parameters to be balanced before bioreactor feeding. Total volatile solids (TVS) are an equivalent of organic matter content in most circumstances. In addition to *VS*, sufficient retention time must be provided for microorganisms to convert into biogas. As a result, the organic load rate (OLR), an operational parameter, must be determined precisely.[3]

In practical terms, the correct adjustment of OLR configures the best combination between two co-substrates. For example, vinasse (a liquid co-substrate) and filter cake (a predominantly solid waste) respectively contain 20–30 g/L TVS and 60–70% TS, which enables the feed rate to be adjusted during co-digestion. Wastewater from orange and coffee processing, thin stillage from corn ethanol, and animal manure have low solid content, which could be combined with substrates with higher solid content, namely orange fibers, bagasse, coffee husk, pulp, and soybean hulls.

Straw, leaves, and bagasse are examples of lignocellulosic materials that require pretreatment before anaerobic process. Pretreatment improves the biodegradability of lignocellulosic substances, increasing carbohydrate content availability, and, consequently, boosts biogas production.[3] Physical-mechanical (crushing, sieving, compression, drying, evaporation, heat), chemical (alkaline), and biological processing (enzymatic or pre-digestion) are the known pretreatments. The characteristics of the different co-substrates affect the selection of pretreatment technology.[4]

Different pH values are required for the microorganisms' development during the decomposition stages. The optimal pH is 5.2 to 6.3 for both hydrolytic and acidogenic bacteria. However, these bacteria are not strictly limited to this range and are able to convert substrates in slightly increased pH values, with a partial reduction in activity.[52] After the hydrolysis stage, the pH drops significantly due to the accumulation of volatile fatty acids (VFAs). The pH of the digester needs to be maintained at 6.8–7.2 to ensure an effective transformation of VFAs into CH_4 and CO_2, although CO_2 is continuously produced during the anerobic process. The CO_2 that is generated also influences the pH of the digestate.[3] Regarding this parameter, orange waste and coffee effluent, in particular, have a strongly acidic pH. Depending on the proportion of co-substrates in the digester feed, the addition of animal manure and filter cake, which have naturally neutral or slightly alkaline pH, is recommended.

The automatic control of pH has been employed in co-AD operations through, for example, supervisory systems. However, where there is only occasional imbalance in the biological process caused by inhibitors, contamination, or excessive organic load, the requirement for continuous pH control can make the system economically unfeasible.

Table 2. Composition of co-substrates from the main Brazilian sources.

		pH	COD (g/L)	Ca (g/kg)	Mg (g/kg)	N (g/kg)	C (g/kg)	S (SO4) (g/L, %)	P (g/kg)	K (g/kg)	TS (g/L)	TVS (g/L)	Cell	Hemi	Lignin	Other
													(%m/m, dry basis)			
Sugarcane	Vinasse 1G	4–5	28.3–31.7	0.83–1.71	0.50	0.57–1.60		0.2–3.5	0.51–5.51	3.93–5.85	26.00	18.40	-	-	-	-
	Vinasse 2G	4.0–4.9	48.67	0.08	0.04	0.20–0.46		nd	2.70	3.02	33.20	26.30	-	-	-	-
	Filter cake (% TS)	7.7	22.3% (dry-basis)	16.58	2.68	1.72–1.93%	40.8%	0.16%	0.38–0.6%	1.28	21.9–30.3%	62.3–75.5%	17.17	15.31	14.14	13.59 (protein)
	Straw (% TS)	-	-	3.3–13.1	1.1–6.0	4.4–12.3		0.09%	0.8–1.3	3.1–17.2	92.5%	70.4%	39.8	28.6	22.5	-
Orange	Peel waste (dry basis)	3.42–3.92	370.0–1085.0	-	-	1.38–12.24	41.6%	nd	1.18	-	4.31–19.2%	95.7%	9.21	10.5–15.0	1.33–7.52	42.5 (pectin)
	Vinasse (yellow water)	4.1	107.0	2.27	0.177	0.65		432.1	2.24	2.68	19%	18.4%	-	-	-	-
Corn	Corn Stover	-	-	1.8–2.2	1.4–1.8	5.9–6.5		0.4–0.7	0.–0.7	7.9–12.8	93	97	40.8	34	22	-
	Thin stillage (untreated)	4.6	85.04	0.027	0.58	-		0.52	1.50	2.38	7.21%	6.27%	-	-	-	-
Soy	Hull	-	-	-	-	-		nd	-	-	-	87.2%	28.6–35.8	20.0–23.1	9.1–13.1	15.4 (protein)
	Straw	-	-	-	-	-		nd	-	-	-	86.85%	42.3	16.7	21.6	-
Coffee	Husk + pulp (solid)	4.0–7.0	9.80	0.638%	0.193%	2.5%	45.2%		1.6%		94.8%	84.2–90%	43±8.0	7±3.0	9 ±1.6	-
	Mucilage	4.3	-	0.337	0.081	47.1%		-	0.115	0.116	94.38%	85.1%	-	-	-	-
	Wastewater	3.87–5.5	2.08; 9.27–52.0	0.144	0.072	0.187 - 25			0.063	1.80	6.64–20.17	6.10–15.04	-	-	-	-
Waste	Chicken manure (% TS)	7.91	26.0%	-	2.13%	3.38%–5.0%	35–38%	<0.1%	1.27–5.72%	2.46–5.4%	25%–40%	69.8%–75%	-	-	-	-
	Swine (slurry% TS)	7.4	20.6–35.0	-	1.68%	2.30%	26.6%	nd	0.68%	1.06%	55	35	-	-	21.0	20.0 (protein)
	Bovine (slurry% TS)	7.3	17.4%	-	1.48%	1.24%	17.4%	nd	0.65%	1.21%	25%	76%	-	-	-	-

Abbreviation: -, Not determined or not applicable; TS, total solids; TVS, total volatile solids.
Note: Corn wastes can also be stem, straw, bark, and corn cob. Vinasse from juice, molasses or mix of both. Arabica coffee is the most predominant specie in Brazilian territory. Mucilage requires pretreatment before co-digestion. Orange peel composition before pretreatment. After pretreatment there is no significant difference, see Martin *et al*. (2010). Sugarcane:[6,16,20,30-32] Orange:[28,30,33-36.] Corn:[6,32,37-39.] Soybean:[40-43.] Coffee:[44-46.] Animal manure:[47-50.]

Strict operational monitoring of the reactor is therefore very necessary to avoid possible process imbalances. The pH adjustment can be made with the addition of KOH, but NaOH solution is most commonly recommended due to economic advantages. In practice, the pH of the reactor is set to a specific value after a certain period, for example every 24 h, to achieve an optimized operation.[3,4]

Micronutrients and macronutrients must also be added to supply the needs of microorganism. The concentration and availability of nutrients influence growth and biological activity. Although the correct range of restrictions for each species is not completely understood, the diversity of cultures is capable of exceptional adaptability.[52] Magnesium (Mg), iron (Fe), and manganese (Mn) are essential micronutrients for electron transport and enzyme function. The amount of CH_4 to be produced is determined by the protein content, fatty acids, and carbohydrates found in the composition. After carbon, nitrogen is the most important nutrient necessary for enzymes acting on the metabolism of bacteria.[51] Microbial activity would be significantly inhibited if there are insufficient quantities of these elements, so periodic supplementation is required. Several reports also indicated that the supplementation containing trace elements could effectively reduce the accumulation of VFAs. Trace metals, such as iron (Fe), cobalt (Co), copper (Cu), molybdenum (Mo), selenium (Se), manganese (Mn), Zinc (Zn), and nickel (Ni) are frequently used to promote the performance of anaerobic digestion. The order of the bioavailability of trace metals is: Se > Mn > Zn > Ni > Mo > Cu > Co > Fe.[3]

The nutrients in Table 2 are the main compounds cited in the literature for co-AD for agricultural and livestock substrates. The most frequently mentioned nutrients are Ca, Mg, N, P, and K. Filter cake, animal manure, and straw from corn and sugarcane contain significant levels of Mg. Other major elements found in the biofertilizer, a by-product of the biodigestion process, are Ca, N, P, and K. In addition to poultry manure, filter cake, corn, and sugarcane straw have high levels of Ca and Mg, as well as N, P, and K.

The thin stillage, a corn ethanol co-product, does not require pre-treatment and can be digested together with other agricultural substrates. Its composition presents a high concentration of minerals such as Zn (97.9 mg/kg), Mn (33.7 mg/kg), Fe (31.9 mg/kg), S (10.2 mg/kg), and K (32.2 mg/kg).[53] The co-AD is recommended as supplement to other substrates that are deficient in these micronutrients, especially solid wastes such as orange peel and filter cake. The sulfur (S) content expressed as SO_4 in Table 2 defines the eventual need for and level of the desulfurization unit, and consequently the investment level required for the purification system. Further information concerning micronutrients in sugarcane substrates for AD processes can be found in Janke *et al.*[20]

The C/N ratio also plays a crucial role in biogas production. The C/N ratio represents the relative amount of carbon over nitrogen present in a substrate and plays an important role in a variety of biological treatments. The co-AD process, with multiple types of feedstock, could overcome process instability due to an inappropriate C/N ratio for mono-digestion. Feedstocks with a lower C/N can be blended with those that have higher C/N to create suitable conditions for microbial growth.[3,4] It has been suggested that a C/N ratio between 20 and 35 is optimal for co-AD of agricultural and livestock wastes.[54] Eventually, with a surplus of N, ammonia inhibits the bioprocess.

Finally, the high concentration of lactic acid in sugarcane vinasse can have inhibitory effects on the formation of CH_4. Thus, the bioreaction is benefited by balancing the volatile composition of the fatty acid, adding a second solid substrate.[8] On the other hand, distilled dry corn grains (DDGS) have nutritional benefits for animals. Due to the crude protein concentration of 25% of the total dry mass, it is the most commonly employed alternative for this component in practice.[55]

The way in which the reuse of co-products should be carried out in the agroindustry will depend on the availability and composition of these substrates. As reuse alternatives become better known, these co-products acquire added value. The costs are discussed in the next section.

The substrates costs approach

There is an important distinction between the terms 'co-product' and 'by-product'. A clear definition is important in the agro-industrial sector, especially if considering applications for energy purposes. Co-products are outputs formed in the production chain and have a positive economic worth. A co-product used in a next stage of the process can be called raw material – because it is an input used for other purposes. Consequently, those that do not have immediate use and induce to a negative impact are called 'by-products'. However, some authors may use the terms 'co-product' and 'by-product' interchangeably.[56] The analogous term for 'co-product' used in agro-industrial management is a 'value-added substance', among other valuable materials, generated during a production process. Then, a by-product is also created, and this material should have a negative value in the supply-chain list.[57]

For a long time, there has been controversy concerning the inclusion of co-products in life cycle analysis. The lack of disclosure and price fluctuations are the two biggest challenges in determining their economic value. Additionally, commodity prices are another factor that must be considered, such as the inclusion of agricultural derivatives used for

Table 3. Valuation of liquid and solid co-products from agro-industrial and livestock wastes.

		*US$/ton (solid) or US$/m^3 (liquid)	US$/ton TVS	Opportunity cost (non-energy application)	Notes and references
Sugarcane	Vinasse 1G	0.53–0.85	3.75	Liquid fertilizer/fertirrigation	[a]
	Vinasse 2G	-	-	Liquid fertilizer	[a]
	Filter cake	-	-	Solid fertilizer	[a]
	Straw	12.26 - 37.0	17.41 - 52.0	Soil protection	782
Orange	Peel waste (dry basis)	250	261.23	Raw material of pectin	[b]
	Vinasse (yellow water)	-	-	Devalued	59
Corn	Corn stover	84.53–103.77	97.06	Animal feed/substrate for lactic acid	[c]
	Thin stillage	-	-	Devalued	[d]
	DDGS	159	1950.8	Animal feed	81
Soy	Hull	36.23	41.55	Livestock feed	[e]
	Straw	28.0	32.24	Soil protection	42
Coffee	Husk + pulp (solid)	-	-	Devalued	60
	Mucilage	-	-	Devalued	60
	Wastewater	-	-	Devalued	60
Waste	Poultry	37.74	52.42	Solid fertilizer	[f]
	Swine	0.46–1.42	2.68	Sporadic fertilizer	61,62
	Bovine	5–8	0.85	Sporadic fertilizer	59,63,64

*US$/R$5.30 on July 4, 2022. BCB - (Banco Central do Brasil): https://www.bcb.gov.br/estabilidadefinanceira/historicocotacoes.
Notes: a - As practiced in sugarcane industry (technical instruction from managers). b - estimated by specialists.[59] c- Price of corn silage, include corn stover. Available at: https://agro2business.com/marketplace/1402/silagem-de-milho. Maize silage. d- As practiced in flex and corn ethanol plants. e - Cereal residues: € 30/ton fresh, see table 8.2 in reference[52] f- Non official data: APAVI and MFRural.com.br - accessed in June 2021.

animal feed.[58] Some authors classify wastes or effluents as costless materials, which is not always appropriate.

From an economical perspective, we assumed materials with positive economic value (as co-product) and materials with negative economic value (as trash or by-products). In an agricultural scenario, the biochemical properties must be considered, as they often have value, especially if reuse as a substrate via anaerobic digestion technology is envisaged. In this way, the substrates selected for the co-AD process can be called co-products. They can eventually assume economic value and their cost as raw material must be incorporated into the biogas plants' assessments.

Table 3 shows the current costs (acquisition, opportunity cost, transportation cost) of the wastes studied.

The operational costs of a biogas plant also include the cost of raw materials – henceforth referred to as substrates. The co-AD process may become unfeasible depending on the opportunity cost. The concept of opportunity cost is fundamental because resources are scarce in relation to demands, thus using resources in a conventional way prevents other forms of application. Choices imply rejecting alternatives, so the opportunity cost considers the better condition whose the final product will represent more profitability, for instance, rejecting the other alternatives.[65]

Corroborating the information in Table 3, some agricultural wastes, such as sugarcane and corn straw, orange, and soybean residues, as well as poultry manure (chicken litter), will assume economic value because of their conventional applications.

Citrus residues have multiple reuses as long as annexed orange facilities are implemented . Large orange-juice manufacturers find it more profitable to invest in industrial units to produce essential oil, terpenes, pectins, and pellets. For example, pellets are highly profitable when commercialized in European countries as animal feed for US$200–300 per ton. However, due to competition with corn derivatives used for the same purpose, this commodity may face price variations on the international market.

The SPS, the most Brazilian orange producer, farmers are located nearby sugarcane-plantations, resulting in competition by areas in the border regions between green belts. Frozen concentrated orange juice (FCOJ) is generally a major product, being exported globally for US$ 1.9/kg.[66] Recently, producers and marketing associations discontinued historical quotation data for citrus components in their websites. The fact illustrates one of the challenges in establishing official market for agricultural co-products. Unti now, the costs for reusable co-products have not been openly discussed among orange organizations.

Besides external factors, such as foreign exchange, soy agribusinesses maintain continuous commercialization of co-products. During the pandemic, however, the average price of grains in SPS increased from R$80 to R$100 per 60 kg.[67] The supply of soybean meal is also influenced by international demand for animal protein, particularly because Brazil is a major producer especially of beef, followed by chicken and pork. Due to exchange rate variations, the prices of grains and derivatives vary sharply, affecting supply and, consequently, the use of soybean waste for renewable energy purposes.

Some publications[28,68] have been exploring the impact of sharing bioenergy by co-AD from different agro-industrial wastes in an integrated process, particularly in the sugarcane industry. This debate is crucial to enable material exchange, especially in SPS, where the citrus and sugarcane belts are adjacent. The sugarcane bagasse, now so-called a co-product, has its opportunity cost as a source to produce bioelectricity and its value reaches US$ 10–15 a ton.[69]

However, while this study was carried out, no reasonable value for vinasse, the most recommended co-product for AD, could be identified in the scientific literature. The distilleries still regard it as an effluent (a by-product), simply focusing on its chemical properties for soil nutrition, particularly potassium replacement. In sugarcane cultivation, traditional application as a liquid fertilizer includes the transportation and fertigation costs, deducting the gains by reducing mineral fertilizer purchasing. Part of the expenses - fuel, tank trucks, pipes, container boxes, and motor pumps - has high relevance in the operation. Vinasse fertigation would become unfeasible for the farm managers at R$ 4.5/m^3, requiring other strategies. For example, at a sugarcane facility in SPS, the cost of shipping vinasse by tank trucks and installing the sprinkler's quick coupling was R$2.8 m^{-3}. The use of vinasse as a substrate in co-AD drops the fertigated volume, minimizing logistical costs.[70,71]

The Council of Sugarcane, Sugar, and Ethanol Producers of Sao Paulo (CONSECANA) is a significant organization for the sugarcane businesses, which, among other responsibilities, manages raw materials valuation to meet the expectations of farmers and sugarcane mill stakeholders, and communicates the input and output prices.

The payment for sugarcane suppliers is a mechanism based on the revenue per ton of processed cane generated by the industry that produces goods (energy, ethanol, and sugar), as well as the sucrose content of the raw material, known as total recoverable sugar (TRA). CONSECANA argues that fiber has a negative impact on sugarcane quality and, as a result, is deducted from the final cost of the raw material destined to sugar and ethanol productions. The author also recommended the adoption of total recoverable biomass (TRB) as a form of payment to the sugarcane supplier. The amount payable to exploit biomass for power generation would be R$56.2 per ton of TRB (US$10.6 ton^{-1}), equivalent to R$3.1 per ton of cane, or 5% of the conventional value.[72]

In practice, certain cogeneration plants are charged for using the fiber content of the raw material, and part of this revenue can be paid to the producer, although this procedure has not been formalized in CONSECANA. On the other hand, for the corn and soybean sectors, there is a lack of official costs and prices for agricultural co-products, notably straw. Some authors[73] frequently claim the cost of diesel used in storage and transportation.

Biomass is employed by European farmers to generate heat and energy, frequently under long-term contracts to guarantee better prices. For instance, straw delivered directly at €60–80 per ton in Northern Europe would be a reasonable average, but €30–40 per ton in Southern and Eastern Europe would be more realistic. Collection and transportation might cost up to €30 per ton. Taking these factors into account, the farmer's net profit margin is modest, projected at around €30–40 per commercialized ton of straw.[73] Eventually, feed-in tariffs, premium tariffs, and tax incentives are applied by European governments to stimulate the development of biogas businesses. Feed-in tariffs are the minimum prices guaranteed by governments for each kWh generated, whether injected into the grid or used directly, for a specified period. Italy, Austria, France, and the United Kingdom are currently eligible for this incentive. Premium tariffs are set a higher price than the cost of electricity generated. Producers receive profits from the energy sales on the open market from premium tariffs. It has been shown that biomethane destined for transportation is compensated with a certificate value of €375, as it proceeded through compression, liquefaction, and distribution stages provided by concessionaires.[74] In Egypt, farmers are rewarded for field preparation, cultivation, and transport of cereal straw at US$ 100 per ton. However, this value refers to small-scale commercialization.[75]

In Brazil, the sugarcane straw seems to be competitive in comparison with international prices. According to a recent study, the operational cost of collecting and baling system was estimated around US$12.3 - 37.0 ton^{-1}, limiting the material's potential for reuse. However, recent studies have pointed out that its feasibility is strongly linked to the industrial scale as well as the electricity price.[82]

Several challenges remain regarding the conversion and utilization of biomass in order to clarify its feasibility for the production of bioenergy.[76] Technical barriers hinder production on a larger scale. These difficulties are related to the physicochemical characteristics of biomass such as low energy density, low volumetric density, high moisture content, and hydrophilicity.[77] Moreover, raw biomass usually contains more than carbon and hydrogen, which makes it less energy efficient. All of the properties of biomass mentioned above can lead to low energy conversion as well as cost inefficiencies related to its handling, transport, and storage. To improve raw biomass energy and volumetric densities, some studies recommend pre-processing before using it as an energy source. Energy densification of biomass is usually done by pelletizing the solid raw biomasses, which is performed at high temperatures (~300°C).[78] However, this additional stage of the process would drive up the investment and would only be suitable for solid co-substrates, especially straw and filter cake.

Various options can be considered for dealing with the available biomass.[5] The focus of this study was to highlight the importance of the valuation of co-substrates, with the aim of contributing to the debate on bioenergy competitiveness in an innovative supply chain, as well as the opportunity to discuss different non-energy uses. Further economic analysis will be required to compare the outcomes with other energy sources and market conditions.

Finally, it is essential to assess the sustainable potential for bioenergy generation in rural areas. This potential relates to the environmental role of waste, such as mitigating the erosive impact of rain and wind, protecting the soil against excessive solar radiation and evaporation, and possible contributions to nutrient recycling, organic matter fixation, and biological activity.[79] Farmers are particularly aware of this benefit, even though it cannot be assessed economically yet.

Conclusion

The design of an industrial co-AD plant for biogas production requires an accurate discussion of the characteristics of raw materials used as co-substrates. An adequate combination of biochemicals in the co-substrates will optimize biogas production and solve environmental issues, including final disposal.

The choice for substrates with high organic matter content combined with low cost of acquisition seems to be the best option. As discussed, liquid substrates such as vinasse 1G and 2G, thin stillage, coffee, and orange effluents, as well as animal manure, are the most profitable for a co-AD pathway. Among the solids, soy straw, coffee pulp, mucilage, and filter cake are particularly recommended. However, additional co-AD experiments combining the co-substrates, beyond the results cited, are needed in order to evaluate the theoretical CH_4 potential, and to overcome technical issues.

The geographical proximity between the co-substrate generators is important because the logistical expenses become costly, especially because of diesel price fluctuations. Proper storage must be considered, with substrates preferably ensiled for a long period of continuous biodigester operation. In this case, seasonality and the availability are parameters to be taken into account when considering appropriate combinations.

The technical and valuation parameters reported here will assist in the expansion of the agricultural and livestock sectors, supporting an innovative and diversified production chain as well as the generation of new income for the producers. The economic feasibility of future biogas projects using co-AD technique is therefore intimately connected with the evaluation of substrate parameters. In the near future, it is reasonable to believe that co-products such as vinasse and filter cake will be valued as they are expected to benefit entrepreneurs. Finally, the following aspects are highlighted:

- Agricultural and livestock wastes are economically valuable co-products.
- Acquisition costs for co-substrates in biogas production range from US$12-300/ton or m^3.
- Solid wastes from agroindustry have higher opportunity cost than liquid wastes.
- Composition and energy density are relevant for combining substrates to co-digestion.
- Brazilian agroindustry is a pioneer in valuating agricultural and livestock co-products.

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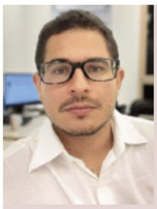

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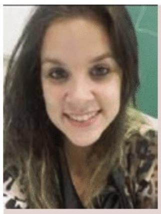

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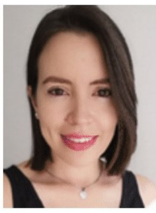

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CHAPTER 3

Pioneering case study of biogas hub integrating agricultural, and livestock wastes within the Brazilian São Paulo State: techno-economic assessment

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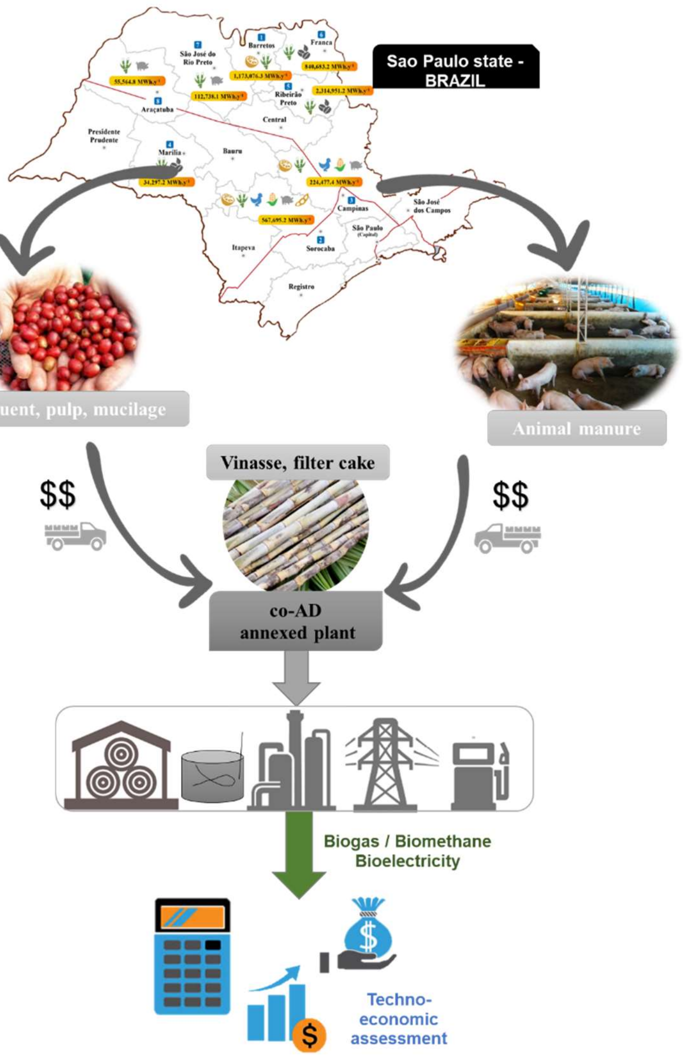
Abstract

Biogas is considered a decentralized and versatile energy solution, especially in agricultural regions, where a large amount of biomass is generated annually. São Paulo state (SPS) is the largest producer of sugarcane in the world and has the greatest potential for maximizing biogas/biomethane production through integration with other energy crops. This study assessed the techno-economic feasibility of bioenergy production (biogas, biomethane, and bioelectricity) via co-digestion (co-AD) of both agricultural and livestock residues (i.e., vinasse, filter cake, coffee residues, and swine manure) in a centralized sugarcane facility. The pioneering case study is in the Northeastern region of SPS, and it uses real data based on co-substrate availability, logistic costs, total capital investment, and detailed operational costs. The methodology describes a new integration strategy, incorporating geographical information from the Bioenergy Atlas of SPS and the acquisition cost of substrates. The results revealed the feasibility of biomethane production instead of bioelectricity, with an internal rate of return (IRR) of 15%, and 11 years of discounted payback, among other estimated indicators. In addition, revenues from decarbonization credits (CBIOS), supported by the Brazilian Biofuel Program (Renovabio), doubly favor biomethane as a biofuel alternative (IRR 37%; 4 years). The scenario of bioelectricity production is profitable for high electrical prices >25% of the current value, although the energetic demand for biogas is crucial. Additionally, the product costs were innovatively estimated in this work. The pioneering conception of hubs integrating rural regions promotes a new business model in the Brazilian agroindustry.

Keywords: feasibility, co-digestion, agroindustry, integration, biomethane, bioelectricity.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Biomass is a geographically widespread energy resource. Whether in solid or liquid form, biomass is generated in large quantities in agricultural and livestock activities. The large-scale generation of biomass warrants studies into sustainable strategies its efficient reuse, especially within the context of bioenergy generation [2]. Biogas, formed naturally by biogenic matter under anaerobic conditions, also confer economic and ecological advantages in the local agroindustry promoting sustainability [3]. The bioenergy produced from agriculture and livestock residues has proven significant environmental benefits across various Brazilian municipalities. Its traceability has received attention from researchers and government to boost new projects in rural areas [4]. However, a significant amount of residues remains unused among them 56% have energetic potential [4,5]. Typical residues generated from corn, soybean, coffee, and oranges crops, as well as livestock, have been considered for reuse in integrated biorefineries to produce a range of bio-based products [6,7]. There is limited research delving into biogas productivity and its associated economic indicators. Table 1 shows the recent economic assessment of pilot-scale and commercial biogas plants using co-digested residues published in the last five years.

In addition, recent SPS biogas plants have been limiting co-AD with vinasse and filter cake as co-substrates [8]. Within the Brazilian context, the SPS agroindustry has a wide array of crops, including sugarcane, oranges, maize, coffee, soybean, bovine, swine, and poultry cattle.

The hubs can be considered a way of integrating energy crops as an effective alternative to reusing co-products with energy density [9]. Within this context, sugarcane plantations usually provide positive impact of producing bioenergy through vinasse and filter cake. Opportunities associated in large-scale include investments in biomethane as a power source whether biofuel or bioelectricity for sugarcane mills and surrounding areas. The capillarity of natural gas (NG) across the state is one advantages of an integrated business model [10]. Thus, a biogas plant annexed to a sugarcane facility processing different residues has not yet been detailed in scientific studies [11] even more detailed techno-economic assessment of a hypothetical case study integrating sugarcane residues, coffee crop and, animal manure.

Table 1: Recent techno-economic assessments of bioenergy production through co-AD from agricultural and livestock residues

Co-substrates	Capacity	Productivity	Economic indicators	Reference
Conventional process: mono-digestion (vinasse)	4.0 MT sugarcane; 10K – 16K m^3 vinasse/day	8.35-12.97 kWh per tonne of sugarcane	CAPEX: US$ 24-26 million[1]	[12]
Filter cake and vinasse	5.0 MT sugarcane 11.2K m^3 vinasse/day. 2x8,000 m^3 UASB	Biogas: 11,500 Nm^3/d 138,000 MWh/year	CAPEX: R$ 200M OPEX: R$ 3M/y IRR: 15% Payback: 7-8 years	*Interview with Brazilian specialist in 2020*
Filter cake, bagasse, and cattle manure	24,000 m^3 bioreactor; 27,606 tonne VS/y	1,008 m^3 biogas/h (²)	Not evaluated Biomethane price: 1.34€ kWh	[58]
Cattle manure, maize silage, and grass silage	A mixture of 40% maize/grass and 60% cattle manure	Biogas is converted into bioelectricity. Power plants 100 - 1,000 kWe	CAPEX: US$ 588K for power plants 100kWe, US$2.4 million for power plants 1000kWe. IRR: 2.2%-18% Payback 11-25 years	[13]
Sweet potato and dairy cattle manure	20 units of semicontinuous digesters. Full-scale digester of 5.5 m^3 processing 30 kg manure/day from 200 confined lactating cows	Bioelectricity 2376.44 kWh/d ; Biofertilizer: 26 tN/year; 20 tP/year and 23 t K/year	>600,000 NPV IRR: 46.8%- 57%. Payback: 2-3 years.	[14]
Maize silage, pig slurry, olive pomace	2x2,000 m^3 (1st stage); 1x5,000 m^3 (2nd stage)	1,995,791 Nm^3 CH_4/year or 0.287 Nm^3 CH_4/kg VS	CAPEX 600 €/MW el 45,000 € y/person Energy cost: 113-120 €/MWh	[15]
Livestock manure and cheese whey	Reactor of 1,174 m^3 to process annually 15,250 m^3 of raw manure + 30% cheese whey	530 to 622 NLbiogas / Kg COD or 0.178 m^3/Kg COD)	312,901€ NPV IRR: 12.05% Payback: 9 years ROI< 10%. Indicated capital cost and operational expenses	[16]
Cattle manure, and wheat straw	Reactors (100, 200, 400, and 1,052 m^3) with best OLR of 2 kg VS/m^3.day	0.300-0.345 m^3 biogas/kg VS added)	CAPEX 500K€-600K€ NPV>150,000 IRR >9% ROI in 11 years	[17]

Food waste and cow dung	5 m^3 and 8 m^3 for replacing LGP in a household	4.21 L/day biogas from 90% VS and 43% VS respectively	US$176-352 NPV; IRR: 8-18% Payback: 5.5-9.9 years	[18]

[1] corresponding to CE-2 or investment in two-phase AD with biogas-H_2 purification for sale
[2] See section topic 3.4: Preliminary assessment for large-scale process design

The first and second assessments are references for mono-digested hypothetical simulation in on an industrial scale, and existing biogas plants operating in SPS, respectively. It is also noted that selected co-substrates were typically mixed with solid and liquid wastes in proportions of 30-70% and 40-60%. Many projects have included animal manure mixed with solid agricultural waste. For example, [14] focused on biodigester revenue, while [13,17] looked into the acquisition costs of substrates. However, little has been conducted on co-AD on an industrial scale.

Henceforth, the case study under evaluation stands as the sole instance that offers a comprehensive techno-economic assessment of bioenergy production through the implementation of a business model reliant on the integration of three large-scale agricultural waste units, with the objective of producing biomethane and bioelectricity. While the potential of this approach has been acknowledged by previous research, such as the aforementioned [1], a thorough evaluation of the current case study had not been undertaken in that way so far.

2. METHODS FOR THE CASE STUDY ASSESSMENT

Capital Expenditure (CAPEX)

CAPEX is a fixed investment necessary to acquire all equipment including tanks, bioreactors, accessories, and other expenses such as assembly, interconnections, automation, engineering, and eventually, acquisition of additional land. A power plant of 500 kWel demands a referential area of 4,000 m^{2}and agricultural waste requires an additional storage capacity of 5400 m^2 (EPP *et al.*, 2008). Moreover, agricultural and livestock residues are usually transported using heavy vehicles, which require convenient roads. The chosen industrial site was well selected to avoid conflict with neighboring areas. The CAPEX also includes conditioning, transportation, processing, silage use, hydropumps, hammermills, and digesters. Two-phase bioreactors are recommended to improve biogas production; furthermore, the Continuous Stirred Tank Reactor (CSTR) is more suitable for co-AD processes [15]. Tanks, gas storage, electric generators, and biomethane facilities such as gas removal units, flares, and compression systems also need to be planned in the budget. The indirect costs (i.e., assembly and interconnections) were estimated to be between 5-15% of total equipment cost. These values are typically implemented in most engineering projects [19]. The emissions, noise, and risk of explosion must also be controlled by anti-hazard systems. Co-substrate reception is designed to receive trucks of different sizes: the solid feedstock must be conditioned in the silage, for previous preparation for feeding digesters. The feedstock may be decontaminated using hydro-pulpers, separating hammermills, and filter presses. The biodigesters are designed in series to supply the plant's capacity for ensuring its operation for 20 years. Other complementary accessories include pipes, flow meters, and condensate traps. The working capital (WC) for an industrial plant consists of the total capital necessary for raw materials, suppliers, finished and semi-finished products in stock, accounts receivable, and cash kept on hand for the monthly payment of operational expenses (salaries, wages, raw-material purchases, accounts, and taxes). The WC / CAPEX ratio varies with different companies, but most chemical plants use an initial WC of 10-20% [19].

The biogas upgrading must remove impurities such as carbon dioxide, hydrogen, ammonia, hydrogen sulfide, and oxygen that are present in the raw gas to comply with Brazilian Resolution n.8/2015 that establishes quality standards for biomethane [20]. In general, the main components to be removed from this industrial stage are carbon dioxide and hydrogen sulfide, the latter causing corrosion and increasing maintenance costs. Among several technologies for carbon dioxide removal, pressure water scrubbing, organic-physical scrubbing, amine scrubbing, and membranes are the most recommended. For hydrogen sulfide removal, average concentrations between 50kS/day and 50tonS/day biological systems are recommended as they require affordable investments and lower operating costs. For concentrations above 50tonS/day the use of solid/liquid media regenerators would be the best option, however, the operating cost becomes higher [21]. Thus, the biogas cleaning and upgrading should meet the requirements for utilization whether biomethane as fuel or injected into NG grid and not only the investment would be the criterion for selecting the technology [22,23].

Operational expenditure (OPEX)

OPEX normally consists of salaries, debt service charges, raw material acquisition, disposal charges (i.e., contaminants and digestate), electricity, maintenance, consumables, and taxes. The energy consumption associated with heating equipment is obtained from the bioenergy produced in the biogas plant annexed. In this plant, employees are assigned to the reception, storage, and biodigester operations. Qualified personnel are required to different functions similar to those practiced in small and medium plants. Maintenance cost is particularly a novelty in integrated biogas units remaining not well known by managers. Its annual cost corresponds to 8% of the total cost of equipment [19]. Electricity will be required during the off-season thus a biogas process must operate the whole year with occasional downtime for maintenance [3]. For example, bioenergy yield increases by up to 25% if the plant is well operated, moreover, this operation will achieve higher efficiency [24]. The geographic proximity between biomass supply and biogas plant is an aspect of the integrative business model, as it would ensure operational stability, thereby increasing profits. Finally, substrate costs are included in the OPEX. In this case study, we prioritize the economic aspect linked to the supply chain, the opportunity cost in eventual non-energy uses, as well as the logistical cost. All these factors are discussed in the following methodology section.

2.1 Co-substrates costs

Animal manure is an important carbon source in co-AD blending. Liquid manure is a useful substrate with low dry matter content which facilitates transport and storage; additionally, it also balances the VS content. Swine manure can be combined with solid co-substrates [6], however, in some cases, it requires pre-processing and operational planning before feeding digesters. Due to its high nitrogen content, swine manure inhibits the conversion of CH_4 during biodigestion [25]. The storage and transportation cost is US$0.46-1.42 per tonne [26] or US$2.68/tonne TVS [7]. Coffee production occurs in small municipalities in SPS, planted in the West of Ribeirão Preto, Franca, and

Campinas mesoregions. Coffee residues include mucilage, pulp, husks, and wastewater, which are generated during grain washing [27]. Coffee residues are usually not economically valuable to be traded; being reused as soil nutrients in local farms. The sugarcane industry generates the most important waste to be used for bioenergy purposes. Recent studies have proven the environmental and economic advantages of sugarcane biorefineries using vinasse, filter cake, and straw [5,28–30]. But straw brings a hindrance since it requires cleaning before biodigestion, therefore, in the case study we considered vinasse and filter cake as co-substrates from sugarcane. Most consultants in the agroindustry indicate that the transportation and storage of vinasse cost approximately US$ 0.53-0.85 per m^3. More detailed substrate acquisition costs see in [7].

2.2 Logistics

Logistic expenses related to feedstock and digestate are one of the factors that encumbrance a biogas plant. Investors must consider seasonality, availability, density, and state of aggregation, which will define the type of trucks, the volume of diesel required for round trips, and the capacity of the storage tanks. [5] adopted a distance ratio of 50 km from the waste collection for Brazilian biogas power plants. Long distances and high costs negatively impact the economic feasibility of integrated biogas plants. European models suggest that the energy content per volume transported is a necessary parameter to be considered in economic assessments. For example, with regards to animal manure, 5 km is feasible, while for waste crops, distances above 15 km are not feasible in European conditions (EPP et al., 2008). In many cases, pipelines that run directly from livestock sheds to biogas facilities are recommended for sugarcane mills close to animal farms. When large amounts of agro-industrial waste are available at a specific location, biodigesters are set up inside the agroindustry, eliminating expenses associated with piping systems (WELLINGER; MURPHY; BAXTER, 2013). In this case study, we address a scenario in which a biogas plant is installed inside a sugarcane mill. Road access is under good conditions and distance data are obtained from Google Maps. The swine manure is transported by tank trucks from the Cristais Paulista municipality to the "A" mill and coffee residues are transported using the same trucks. [13] detailed the logistic cost for a 25t-twin truck to be approximately 0.25 US$/km for a round trip.

2.3 Boundary conditions

Figure 1 shows the geographic location of the first integrated Brazilian co-AD case study. The hypothetical biogas facility is in Franca, a municipality in the Northeast of SPS. Coffee plantations are less prevalent and influenced by the state's proximity to Minas Gerais, the largest Brazilian coffee producer. Factors related to availability, the solid-liquid wastes combination, and the distance from sugarcane mills and farms were also analyzed.

Figure 1: SPS location for the case study

This region has the third highest potential bioelectricity from waste among eight previously analyzed regions [31]. The case study considered coffee husk and wastewater, filter cake, vinasse, swine manure, and slaughtering. The scope of the techno-economic process is shown in the flowchart in Figure 2.

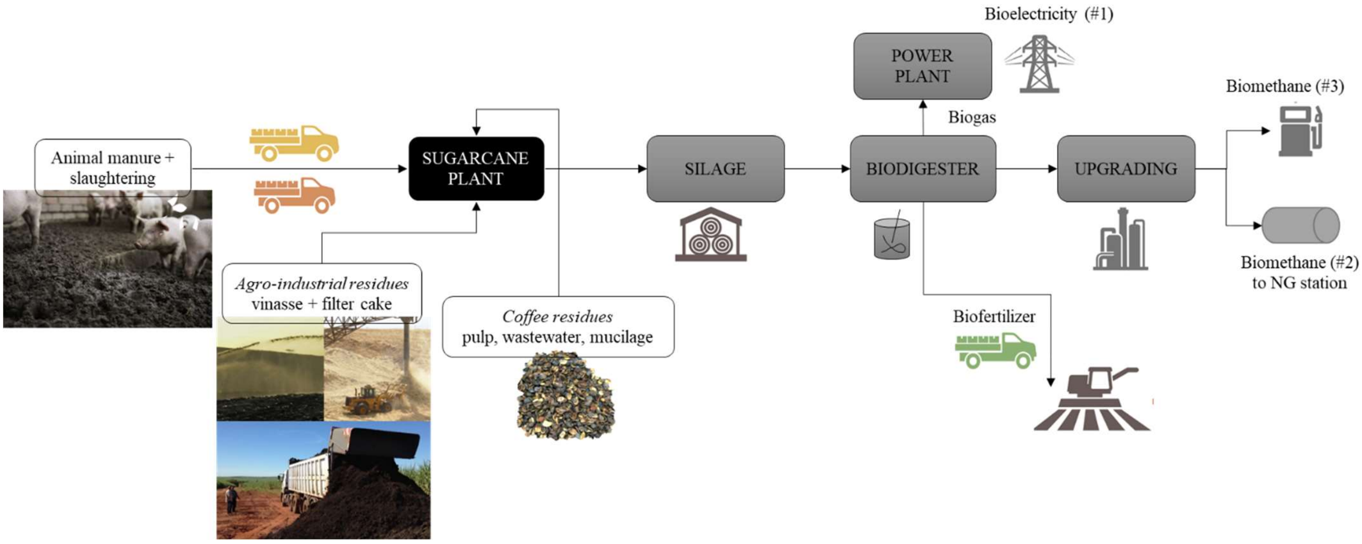


Figure 2: Boundaries for the techno-economic assessment

Considering the scarcity of information on official disclosures, interviews with entrepreneurs were conducted as part of field research. Typically, the average capacity of sugarcane mills in the region is 2.0-4.0 M tons of cane annually. This is the typical configuration used in biorefinery simulations in literature [12]. Solid and liquid residues are stored in appropriate tanks before the industrial biodigestion stage. Among the agroindustry analyzed, seasons coincide with the same period when high amounts of waste are generated, then, bioreactor operation is planned to achieve the best performance during the whole year. There are three alternative outputs for the final product. The biogas obtained can be converted into bioelectricity (alternative #1); by selling the surplus in bioenergy auctions or reforming it into biomethane (alternative #2), which can be injected into an NG distribution pipeline, particularly GasBrasiliano, which is 204 km from the natural gas station in the Ibitinga municipality. Biomethane can also be used as a biofuel (alternative #3) to supply vehicle fleets in cultivation activities. Alternative #1 requires an electric center interconnected to a turbo generator, as well as distribution lines. Alternative #2 requires permission to inject the volume of biomethane by prior contracts. Finally, alternative #3 requires tanks, a compression system, and sprinkler devices. In the sensitivity analysis, all these options are presented with their respective advantages and limitations. For an economic assessment, the revenues obtained from biomethane, or bioelectricity sales must be competitive with the NG prices and with electric auctions, respectively. Table 2 shows the average price charged by the three concessionaires operating in the SPS with NG.

Table 2: Average prices of NG from concessionaires operating in SPS (the year 2020)

Usage	Tariffs (R$.m^{-3})[1]		
	NATURGY	GASBRASILIANO	COMGAS
Residences	2.85	4.14	4.95
Commercial	2.84	3.94	3.59
Industry	2.33	2.61	1.88
Automotive			
Gas station	1.52	1.94	1.69
Public transport	1.45	1.86	1.58
Fleet	1.45	1.86	1.58

Source: Adapted from ARSESP – Regulation Agency for Paulista Public Services (ARSESP SÃO PAULO 2017). Available at [32]

[1] ICMS not included.

Customers pay tariffs for using the distribution system (TUSD). The prices vary depending on the segment and consumption range of the user. According to a recent study conducted by Energy Research Office (EPE), the average distribution margin accounts for 17% of the final price of natural gas, while 46% is for the molecule, 13% is from transportation, and 24% of taxes [33].

2.4 Techno-economic assessment model

The equipment costs were based on *Cost Estimator Website Tool* [34] and compared to the recent literature indicated in sections 2.1 and 2.2. The indirect costs (assembly, automation, and civil work) consist [34] of rubrics from the total investment cost. The OPEX was complemented by information obtained from interviews with experts and managers, especially regarding input costs, utilities, labor, and maintenance costs. The raw material costs were previously discussed. For further information see [7]. The techno-economic analysis was conducted over a timeline of 20 years. The annual cash flow contains the revenue from biomethane/bioelectricity sales. The product cost of the final products, a novelty of this study, is also estimated using cash flow. The values were compared with the market prices and for electricity reported as per the current auctions. The economic indicators assessed were net present value (NPV), internal rate of return (IRR), return on investment (ROI), and discounted payback (DPB).

3. RESULTS AND DISCUSSION

The results are presented in three sections:4.1- Key assumptions 4.2- Investment and operational costs; 4.3 - Sensitivity analysis.

3.1 Key assumptions

The real data of the case study is shown in Table 3:

Table 3: The analyzed case study in SPS

Municipalities	Agroindustry	Substrates (Estimated amount)
Buritizal Pedregulho Pedregulho Cristais Paulista (Franca)	• “A” Sugarcane Mill: 3.1 MTC • “B” Coffee farm: 2,400 kg/ha • “C” Swine farm: 1,120 matrices + 3,300 slaughter/month	Vinasse: 1,040,000 $m^3.season^{-1}$ Filter cake: 97,600 $tonnes.season^{-1}$ Coffee pulp: 214 $tonnes.season^{-1}$ Mucilage: 194 $m^3.season^{-1}$ Coffee effluent: 14,500 $m^3.season^{-1}$ Swine manure: 889 $m^3.year^{-1}$ Effluent slaughter: 15,493 $m^3.year^{-1}$

Grinding capacity data, coffee planting area, and pig farming information were obtained from the official databases of IBGE and the association of sugarcane producers – CTC (Centro de Tecnologia Canavieira). Some older values were validated through interviews, telephone contacts, and consultations with employees of the involved agro-industry. Residues were calculated based on estimates of waste generation cited in the literature, referenced in Table 4.

The map shows the geographical distribution and distance between farms and the biogas facility installed at the sugarcane mill “A”.

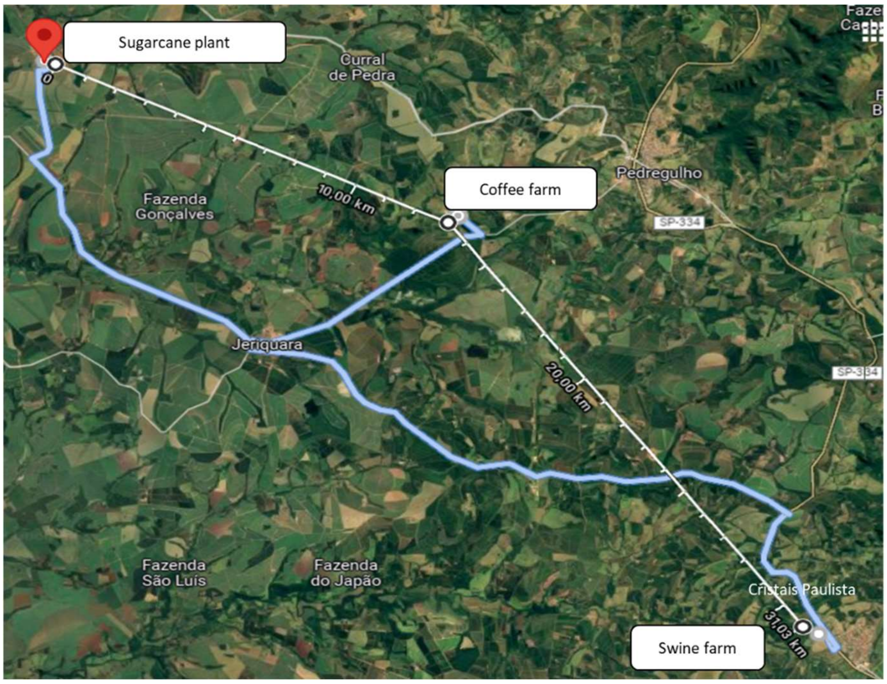


Figure 3: Franca region and distances between agro-industrial units

Most coffee farmers adopt bean dry extraction instead of the wet method because generates significantly fewer residues and wastewater. The chosen “B” farm had an estimated plantation area of 150 ha, corresponding to a medium farm, which is atypical in the SPS. The “C” swine farm currently has 1,120 active sows and slaughters 3,300 animals per month. The mill “A” produces sugar and ethanol with an annual hydrous ethanol production of 97,000 m^3. A 97 Mton filter cake is annually generated from sugarcane juice treatment and 1 Mm^3 of vinasse is generated in the distillery. From swine slaughter, water is used for washing and rinsing the carcass (which requires potable water, with low residual chlorine), and for cleaning equipment, floors, walls, and countertops, as well as for separation of blood, grease, and solid particles. From the total volume of water used in the slaughterhouse, 80% to 95% is considered wastewater with a high organic content comprising fat, nitrogen, phosphorus, and salt, with pH and temperature fluctuations [35,36]. Table 4 shows the key assumptions to perform the economic assessment of the biogas facility annexed to the sugarcane mill in the Franca region.

Table 4: Key assumptions for the integrated biogas facility

Description	Assumptions
Period of biogas production (days)	328 d
Effectiveness (Eff_{ind})	90%
Efficiency motor (Eff_{eng})	40%
Hours of operation	7,128 h
Energetic demand for biogas plant operation	18-20% of total MWh generated. Adapted from [11] and specialist consultants

"BNDES Finem" (Investments in production, storage, and food processing for human and animal use. Conventional or 1G biofuels also included)	Financial cost: TLP[1] (long-term rate) BNDES spreads (remuneration): 1.3% per year. Financeable amount up to 100% Deadline up to 20 years
Logistical parameters	Variable: max. 60 km (for sugarcane mills) Roundtrip: 120 km for coffee residues and swine manure
Co-AD mixing	Average 40%-60% solid/liquid mix
Efficiency of biogas productivity by co-AD (Eff_{COD})	85% (or 15% loss)
Vinasse proportion Filter cake (FC) generation Swine manure Effluent swine slaughter Green coffee production Proportion cherry/green grain coffees Pulp cherry coffee Mucilage generation in cherry grain Coffee Effluent	12 l/l ethanol (this study) 35 FC/ton sugarcane [37] 367.6 kg/(year.head) [1] 115 water gal / slaughtered [35] 2,400 kg/ha [38] 6:1 (kg/kg) [39] 9,9% [39] 90 mL/kg cherry coffee [40] 6,7 L/kg cherry coffee [41]

[1] the final interest rate of the contracts will consist of TLP, added to BNDES's accredited financial agent's spreads (in the case of indirect operations) and the credit risk rate BNDES (2020)

The monthly methane produced can be estimated as follows:

$$V_{CH4}(m^3) = Eff_{COD}.Waste(ton).PBMT\left(\frac{mL\ CH_4}{gVS}\right).g\ VS\left(\frac{g}{m^3}\right)$$

where waste corresponds to the quantity collected and recovered with 90% effectiveness. The PBMT is the biological potential of methane to be produced; and "VS" is the average concentration of volatile solids in wastes. The volume in terms of biogas is obtained by dividing by 55% CH_4. Technical literature for commercial plants reported CH_4 losses of 1–2%, and agro-industrial availability is typically 95–96% [43]. Therefore, considering the co-AD approach and the unknown limitations of the biological process involving the combination of co-substrates, biogas productivity is assumed with an inefficacy of 15%. Accurate productivity through co-AD for the selected co-substrates would require pilot-scale experimental tests.

The generated bioenergy (AEE) is calculated as follows:

$$AEE\left(\frac{MWh}{month}\right) = \left. Eff_{ind}\,.Eff_{eng}\,.\dot{v}_{CH}\ \left(\frac{m^3}{month}\right).HHV\left(\frac{MJ}{Nm^3}\right) \middle/ 96{,}400 \right.$$

Where the High Heating Value, HHV, of methane corresponds to 35.8 MJ/Nm³, assuming a 90% runtime of the Otto Cycle engine, and a 40% efficiency at converting biomass to bioelectricity [11]. At 18% of the energy demand to operate the biogas plant, the net electricity (NE) will be,

$$NE\left(\frac{MWh}{period}\right) = (1 - 0.18)\,.\,AEE\,\frac{MWh}{period}$$

The electricity produced from biomass was quoted at R$877,321/MW per year or R$123/MWh according to the recent ANEEL's 1st Capacity Reserve Auction, on December 2021 [44]. The auction aimed to hire electrical power and energy from new or current businesses. The authors essentially considered the Brazilian economic scenario, with financial conditions supported by BNDES Renovabio, a modality recently launched by the Bank (BNDES–BRAZILIAN DEVELOPMENT BANK, 2021).

3.2 Investment and operational costs

The CAPEX and OPEX spreadsheets were prepared in Excel Office 365, as well as the cash flow.

3.2.1 CAPEX

The Process Flow Diagram – PFD in Figure 4 shows the Process Equipment and the Process Streams for the integrated biogas plant project.

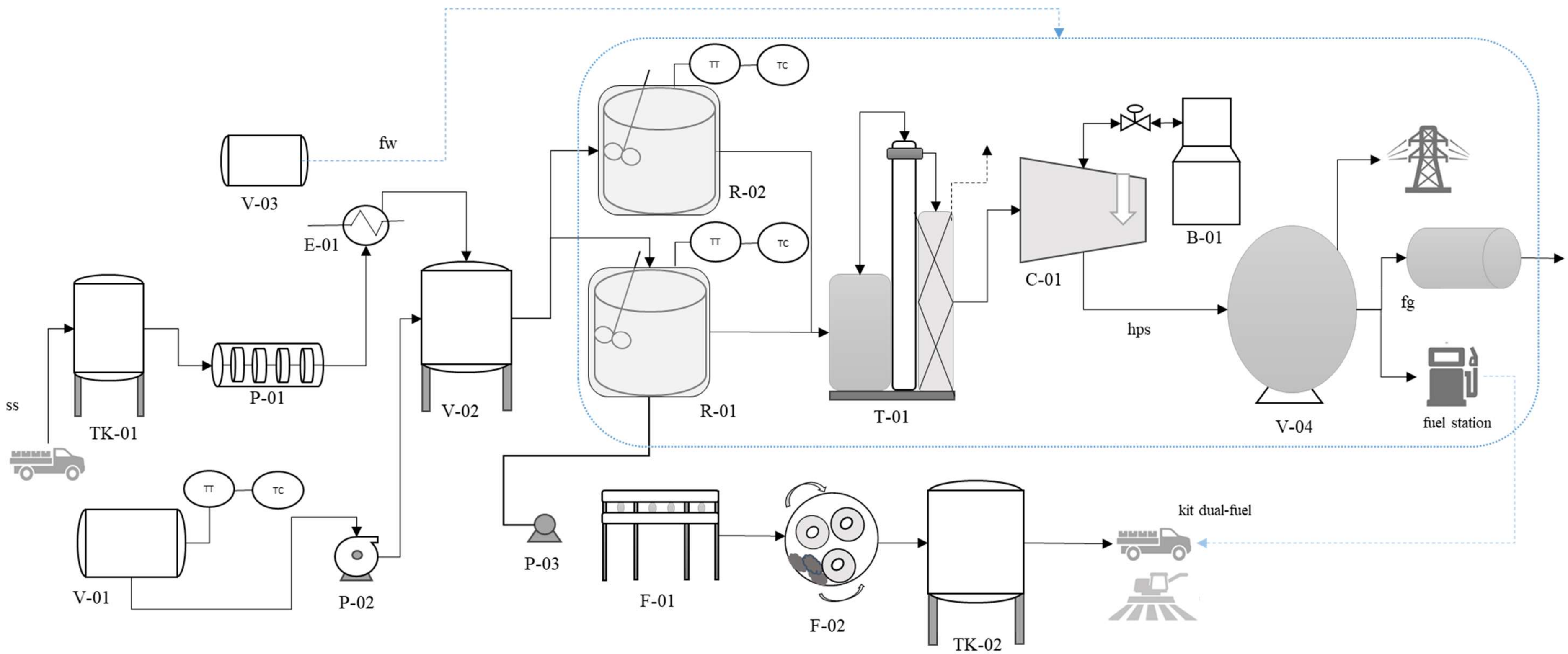


Figure 4: PFD of the integrated biogas plant

PROCESS EQUIPMENT AND PROCESS STREAM

TK- 01	Silage tank	R-01	Bioreactor (biodigester)	V-03	Water vessel (Anti-Fire)
P-01	Rotary pump	R-02	Bioreactor (biodigester)	V-04	Gas storage
P-02	Centrifugal pump	C-01	Gas Compressor	B-01	Flare (Burner)
P-03	Centrifugal pump	T-01	Scrubber + Gas removal Towers	*hps*	*high pressure stream*
E-01	Pre-heater	F-01	Filter Press	*fg*	*fuel gas*
V-01	Inoculum vessel	F-02	Filter + Stabilizer	*fw*	*Anti-fire water safety*
V-02	Pre-digester	TK-02	Digestate storage	*ss*	*Substrate stream*

The detailed equipment costs are listed in Table 5. The dimensions were calculated according to the amount to be processed, considering the gradual expansion of production over 20 years.

Table 5: Summarized Capital Expenditure for the Franca case study

	× **1000 US$**	**Reference**
BIOPROCESS FACILITY	**4,530**	
Silage tank, digester, filter press, inoculum tank, pipelines.		[17][34]
ELECTRIC CENTRAL	**14.600**	
CHP for 20MWe	10,085	[13,46]
Connection to the electric grid	4,473	[13]
BIOMETHANE FACILITY	**10,145**	
H_2S removal (air injection + scrubber)	7,770	[13,46]
CO_2 removal	0.276	[46]
Flare system	0.956	[13]
Compression system	0.165	[12]
Pipeline dispatch into the NG gate	0.397	[47]
Kit dual-fuel diesel biomethane for trucks	0.439	[48]

The filter cake is stabilized to be reused in the sugarcane off-season, as previously clarified. After dewatering using a typical filter press, the solid fraction can be stabilized by drying and heating. Specifically, thermal drying frequently increases the total solid content to 98%. This study considered additional equipment destinated to digestate pelletization, as reported in [49,50]. The digestate is partially pre-treated by removing water to replace urea as a biofertilizer. According to the average composition cited by [7], the available nitrogen makes up the updated price of R$19.61/kg in terms of urea [11], where the savings of fossil fertilizer was US$536,395/year.

Some equipment is made of stainless-steel type 304 L, e.g., tanks, reservoirs, and silage. Except for the gas storage and biodigester, which must be made of 316 L because of corrosive fluids and gases. The anti-fire project prevents accidents with anti-foam and anti-leak systems, hydrants, and monitoring cameras. Automation, sensors, assembly, interconnections, and engineering contracts are estimated to be approximately 2% of total equipment costs [19] or $8,151\times10^3$ US$. Once the biogas plant is installed in the sugarcane mill, the land cost can be suppressed. Biogas upgrading cost comprises technology to hydrogen sulfide and carbon dioxide removals. The house power is for bioelectricity conversion and grid injection was also reported in the budget.

Biomethane sold to the three NG companies whether used as a biofuel for trucks in the "A" sugarcane industry will demand fixed capital investment in infrastructure, such as compression systems, and private gas stations. In SPS, a 200-bar compression is required to exceed the pressure in NGV fuel tanks and approximately 200 km for pipelines connected to the next gate. WC ($4,444\times10^3$ US$) was included in the amount of CAPEX amortized in the first year.

3.2.2 OPEX

In general, continuous biogas plant operations are partially affected by the availability of co-substrates. This case study assisted a scenario in which year-round operations are maintained, with a scheduled shutdown. Figure 5 shows the monthly handling operations in the season.

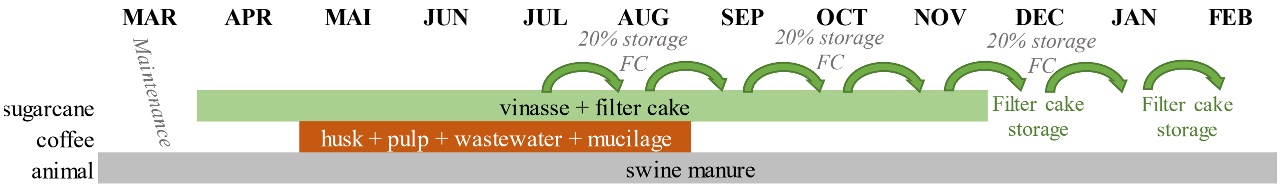


Figure 5: Seasonality, storage, and distribution of co-substrates in the integrated process. "FC" is filter cake

Production spikes occur most frequently when raising animals, and the swine slaughter is not well defined, although waste is produced year-round for confined animals [1]. Therefore, only swine manure was considered in January, February, and December. In this case study, partial filter cake would be stored under these circumstances during the off-season. Despite the natural contamination by fungi, the filter cake is biostabilized for better preservation in medium-term use. In addition, a high VS content in swine manure would promote a balanced mixture in the co-AD process during this period. Vinasse is stored in open tanks near ethanol distilleries, where its organic content is quickly degraded. Medium-term storage was assumed to be a conventional dedicated structure. The volume of vinasse available in mid-November (the end of sugarcane season) would allow the biodigestion for a few weeks until mid-December. The main issue, however, occurs during January, February, and March, before the beginning of sugarcane harvest. The coffee harvest period was shorter and coincided with the sugarcane harvest period. The available residues are easily co-processed together with the sugarcane wastes being necessary to balance the feeding mixture concerning the VS content. The volumetric load is not considered because the amount of coffee residue is much lower compared to the sugarcane substrates. However, the biomethane or bioelectricity applications must be evaluated due to the sugarcane off-season, where no energy demand for machines is required. For biomethane, it seems plausible to destinate a portion of the vehicle fleet used in agricultural operations; however, it would be a lower-use-intensity alternative. Moreover, hydroelectricity prices during the rainy season (i.e., December, January, and February) are competitive, which brings financial loss to the hypothetical hub idealized in this study.

Inputs, utilities, and labor are determined in Table 6. The data were accurate for the practices adopted in a conventional Brazilian sugarcane facility. Data also includes chemical additives such as those applied to alkalinization and biogas upgrading. Therefore, a large plant requires a 24-hour work team thus, the OPEX includes employees working on distillery units as well as on agricultural departments charged with raw material handling, maintenance (mechanical and hydraulic), bioreactor operation, digestate operation, upgrading unit, and for biological and chemical analysis. A manager would respond to all demands, ensuring the smooth operation of the plant.

Table 6: Summarized Operational Expenditure for the Franca case study

	Description	**× 10³ US$.y⁻¹**	**Reference**
INPUTS		**119.9**	
Vinasse, filter cake, swine manure, effluent slaughter*, coffee pulp*, mucilage*, and coffee wastewater*	0.53-0.85 US$/Kg or m³		This study
Alkalinization (NaOH 50.4%) 89-113mg	1.51 NaOH/L vinasse		Adapted from [12]
UTILITIES AND MAINTENANCE		**7,319.0**	
Electric consumption (US$/MWh)**	18% of the energy produced	2,689	Adapted from [11]
Transport - coffee residues***	Annual RT 533 km	15.9	This study
Transport - swine wastes***	Annual RT 1.602 km	48.0	This study
Fixed cost for biomass transportation	US$ 3,947/month	39.5	[13]
Biogas Upgrading operations	0.026 EUR/Nm³ biogas	1,976	[12]
Biomethane delivery	64.5 EUR/h	80.3	[48]
Maintenance	10%year of CAPEX	2,372	[19]
EMPLOYEES		**101. 9**	
Raw material handling, maintenance, and plant operation	13		This study

RT – annual round trip
**Market value, opportunity cost, or logistical expenses.*
***Biomass electricity auction (price nº 11/2021): 503.88 R$/MWh updated value with IPCA tax* [51]
****0.25 US$/km, twin truck -capacity 25ton*

The taxes, financing expenditures under BNDES Renovabio modality (1.23%.y^{-1}) [45], insurance, R&D, ESG (1%CAPEX), and charges regarding labor benefits (53.8%) [52] add up monthly the cash flow. The biodigester operates continuously, with a CSTR modeled for a mesophilic system with a range of 35-40ºC. The organic load rate (OLR) is 3.0 kg/m³. d, hydraulic retention 20-35 days, pH 6,8-8,0 with semi continuous feed [11]. The corresponding CAPEX and OPEX profiles are indicated in Figure 6:

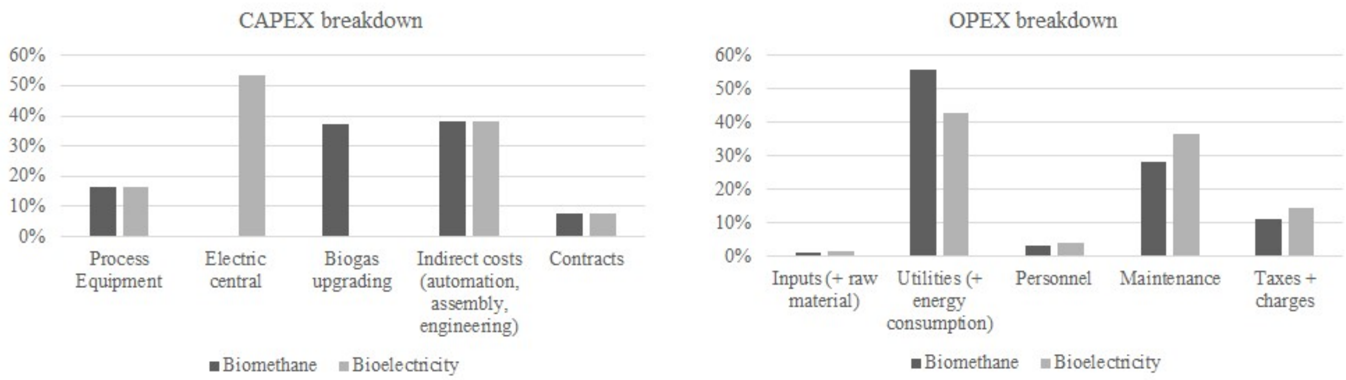


Figure 6: Breakdown of CAPEX and OPEX

The equipment cost is almost 20% of the total fixed investment, while the electrical center burdens alternative #1. Raw materials and other inputs represent together less than 5% of OPEX in both alternatives: biomethane and bioelectricity. However, maintenance and energy consumption together represent an important portion of the operational cost. Labor cost and related charges reach about 15% of operational expenses.

3.2.3 Economic Indicators for the three alternatives

Cash flow scenarios considered revenues from biomethane (included CBIOS), and bioelectricity with different CAPEX due to a new CHP or the existing one annexed to the sugarcane mill. In addition, it accounted for the monetary benefit of using digestate as a source of nutrients for soil applications. Table 7 shows the main economic indicators for the three alternatives.

Table 7: Economic breakdown for the pioneering integrated co-AD biogas plant in SPS

Economic parameters	**Biomethane (#2, #3)**	**Biomethane + CBIOS (#2, #3)**	**Bioelectricity (#1)**	**Bioelectricity with previous Electric central installed**
Production ($\times 10^3$ $m^3.y^{-1}$; $MWh.y^{-1}$)	44,812	44,812	149,298	149,298
CAPEX ($\times 10^6$ US$)	32	32	36	22
OPEX ($\times 10^6$ US$)	8.7	8.7	6.6	6.6
Product cost* (US$/$Nm^3$; US$/MWh)	0.19	0.19	51.5	51.5
Sales price (US$/$Nm^3$; US$/MWh)	1.63	1.63	95.07	95.07
NPV (US$ MM)	2.6	21.4	4.9	8.6
IRR (%)	14.7	36.9	16.7	25.6
DPB (year)	11	4	9	6
ROI (%)	8.3	67.0	13.6	40.0
Financial conditions	BNDES Renovabio	BNDES Renovabio	BNDES Fundo Clima	BNDES Fundo Clima

**Excluded state and federal taxes as ICMS – Tax on the circulation of goods and provision of services; PIS – Contribution to social integration program; and COFINS – Contribution to social security.*

The alternatives #2 and #3 are eligible especially due to decarbonization credits (CBIOS). In addition, the sugarcane mill "A," first negotiated CBIOS from ethanol by R$90.17/ton CO_2 equivalent and the current quotation traded by B3, the Brazilian Stock

Exchange is R$ 114.25/ton CO_2 eq [53]. Energy-Environmental Efficiency Score (NEEA) is 61.8 gCO_2eq/MJ, factor is 750 liters/CBiO, and Carbon Intensity (IC) is 25.6 gCO_2eq/MJ. The mill already receives carbon credits from bioethanol produced from a conventional process [54]. According to the RenovaCalc tool, the IC was 4.92 gCO_2eq/MJ and NEEA was 81.78 with an emission reduction of 94.3% [55]. As shown in Table 9, biomethane becomes more attractive with the CBIOS revenues supported by the Renovabio program, whereas, without CBIOS, the economic indicators are supportive to recommend the alternatives.

Biomethane and NG have usually similar chemical composition with few exceptions, which is an important measurement criterion. Local gas distribution companies (LDC)require fewer CBIOS to reach their target. Instead of buying CBIOS from another source, LDC can minimize its objectives by injecting biomethane into the gas grid. On the other hand, CBIOS need to be confirmed by commercialized biomethane, which is still limited in Brazil compared to bioethanol and biodiesel. Standardized criteria for awarding credits for the gas mix, such as industrial use (one of NG´s main consumers), would be more willing to participate in LDCs. Producers must have sales guarantees for LDCs in market expansion. Bus and truck fleets have been growing at a rate of 3.5% and 1.3% per year, and the Federal government expects to advance toward a less carbon-intensive public transportation system, with renewable sources accounting for nearly 30% of transport energy usage, although almost 100% of them derived from biofuels [56].

In 2019, the value of auctions for biomass electricity reached R$180-188/MWh [57]. Bioelectricity from agricultural biomass was estimated to be 110-134 Euros/MWh by other authors [15,58]. The current price quoted in the last biomass auction is currently included with the IPCA – Consumer Price Index into the cashflow (~503 R$/MWh), which was 29% during the period of 2018-2022 [59]. Therefore, NPV > 0 for alternative #1, represents an economic feasibility. The few differences between the two financial conditions were related to the tax (1.26%) when looked at through a 20-year timeline. Additionally, there were also differences in the specific depreciation times for the electrical equipment.

The estimated product cost was an additional outcome of the financial analysis. In the case study, the cost of producing biomethane was calculated to be US$0.19/$Nm^3$, whereas the cost of generating bioelectricity was US$51.5 per MWh. These values exclude state and federal taxes, respectively, ICMS (17%), the PIS (0.65%), as well as the COFINS[3] (3%). Product costs determine the market value of the final product originally produced from this methodology. The FOB value (Free on Board), that is, the volume delivered and injected directly into the distribution network, must be competitive compared to NG. Despite the limited data, rural producers must decide whether to rent land for agribusiness or, eventually, become raw material suppliers. The investigation of economic analysis faces conflicts of interest. Moreover, technological evolution and scientific advances have unveiled profitable alternatives for the implementation of new investments in reusing agricultural and livestock residues together. The

[3] ICMS is a Brazilian tax on the circulation of goods, interstate, and intercity transportation; PIS and COFINS are federal social contributions levied on gross revenue.

next section clarifies the economic parameters established and their interaction with the feasibility.

Another new option for revenue is the renewable energy certificate market, GAS-REC[4] and I-REC, which ensures that every megawatt-hour generated comes from a renewable energy source. The certificate costs BRL 1.80/each (~BRL 0.30/MWh discounted) and guarantees the tracking of energy generated and distributed in plants across the country. Global companies with operations in Brazil can acquire and fulfill the commitments signed at Conference of Parties - COP26 for methane reduction. According to the amount of bioelectricity generated in the case study, the annual revenue obtained with I-REC certificates would be BRL 223,947 or US$ 42,254/year.

3.3 Sensitivity analysis

Primarily, according to the classes of investment cost estimates by Turton [5]et al. (2011), the detailing of the case study indicates Class 2 (with precision from 30% to 70% of the definitive estimate, due to includes list and sizing of the main equipment). For the achieving the Class 1 value (most detailed estimate, -4% to 6% accuracy) would be:

Current CAPEX of the Integrated Biogas Plant (alternatives #1 and #2): 32-36 $\times 10^6$ US$

Minor expected value: **32.6 – 36.0** ($\times 10^6$ US$)

Major expected value: **29.9 – 40.1** ($\times 10^6$ US$)

The expected accuracy range reaches from 1 to 3, which represents an estimate for the bidding proposal for a final greenfield investment. The CAPEX range calculated above coincides with the following sensitivity analysis of CAPEX variations applied in the next subsections.

3.3.1 Biomethane Alternatives (#2, #3)

The sensibility analysis entails delving into the impacts of the profitability, considering the alternatives between biomethane for supply vehicles, and bioelectricity sold in energy auctions. As addressed in the OPEX, both options compensate for diesel demand in transportation according to their revenues obtained in this study. Variations in CAPEX-OPEX were analyzed with +/-20% as shown in Figures 7 and 8.

[4] See more in: www.institutototum.com.br/index.php/servicos/273-i-rec
[5] Turton, R., Baile, R. C., Whiting, W. B., Shaeiwitz, J.A. Analysis, Synthesis, and Design of Chemical Processes. 3rd ed., 2011. Prentice Hall, in chapter 7.

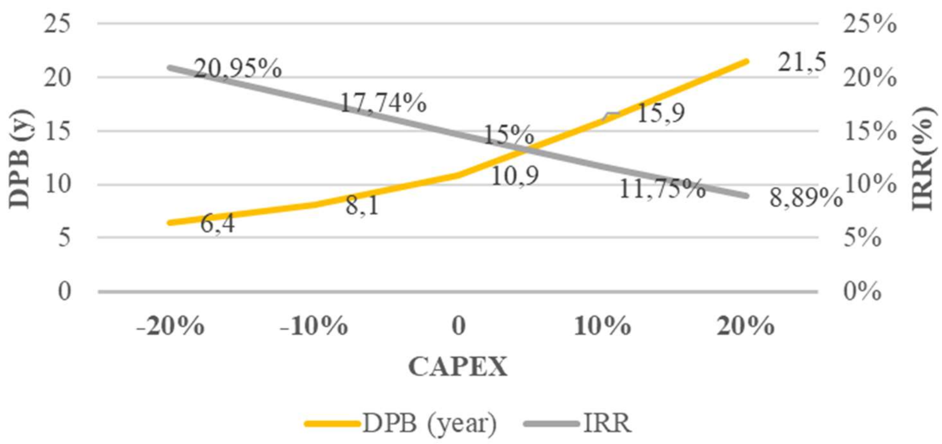


Figure 7: DPB and IRR% with CAPEX variation +/-20% for standard biomethane

10% higher fixed investment makes biomethane unfeasible without CBIOS, as the DPB reaches over 10 years, and the IRR approaches the lower permissible limit (10%) in agro-industrial projects. On the other hand, in Figure 7 CBIOS revenues prove that feasibility is confirmed regardless of any CAPEX variations.

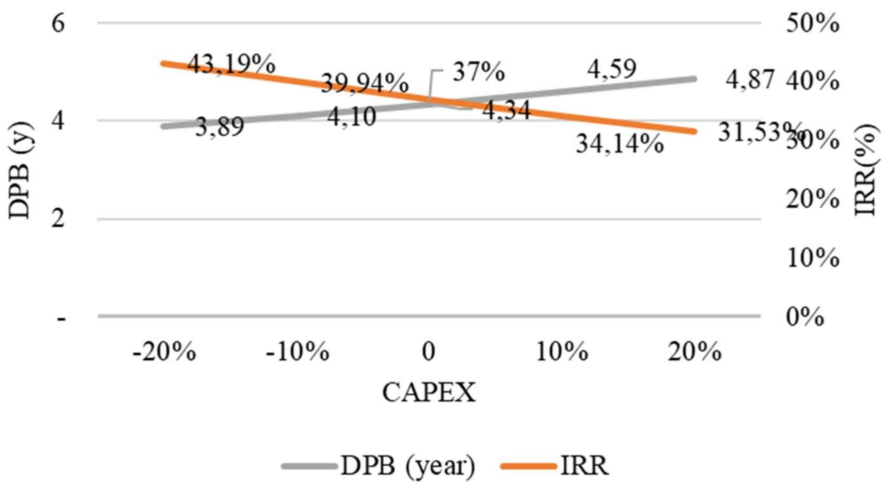


Figure 8: DPB and IRR% with CAPEX variation with CBIOS revenues

The indicators would show that the project was not recommended if CAPEX increased to amounts greater than 50% of the estimated value. It may be argued that this hypothetical scenario would be rather unusual when considering the accuracy of the details that constitute the total fixed investment, nevertheless. Figure 9 below shows the +/-60% CBIOS price variation.

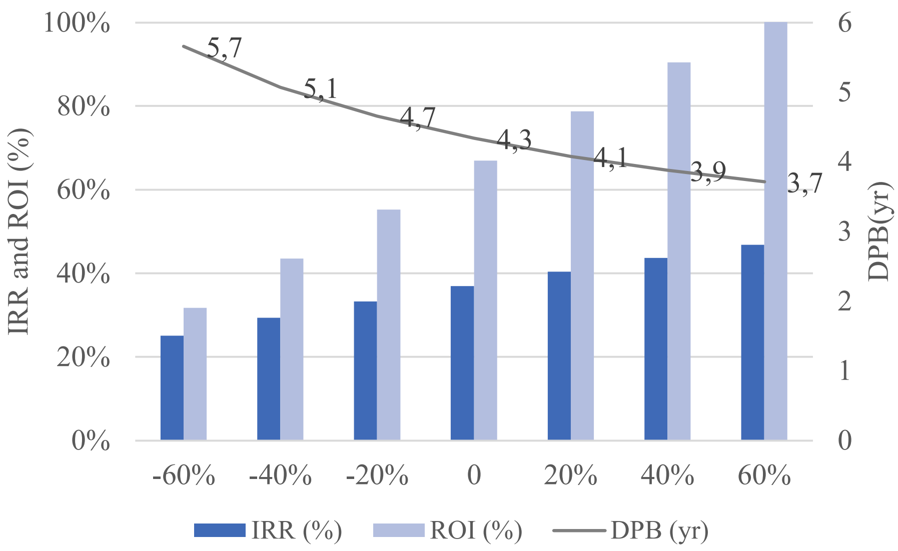


Figure 9: CBIOs variation price and its influence on performance indicators

Renovabio and CBIOS revenues are essential for the successful performance of the integrated business model.

3.3.2 Bioelectricity alternative (#1)

DUTENKEFER *et al.* (2018) showed that, for most price scenarios, bioelectricity is not economically feasible. Furthermore, the insertion of biogas into the portfolio yields a gain in the overall efficiency of sugarcane mills. The attractive bioelectricity price would be >240 R$/MWh to reach an NPV>0 for a positive revenue.

Although the low cost of MWh from biomass auctions makes the project economically infeasible, the (CAPEX) × electric production ratio (1,644 US$/KWh) meets with the referential parameter of the Brazilian biogas plant. The reference value for the Guariba plant of the Raízen group was US$1,800/KWh. For new biogas plants, the reference value indicated by European projects was US$ 3,500/KWh according to experts, which would be infeasible in Brazilian conditions. In the best alternative, the price variation strongly influences the economic parameters, as shown in Figure 10.

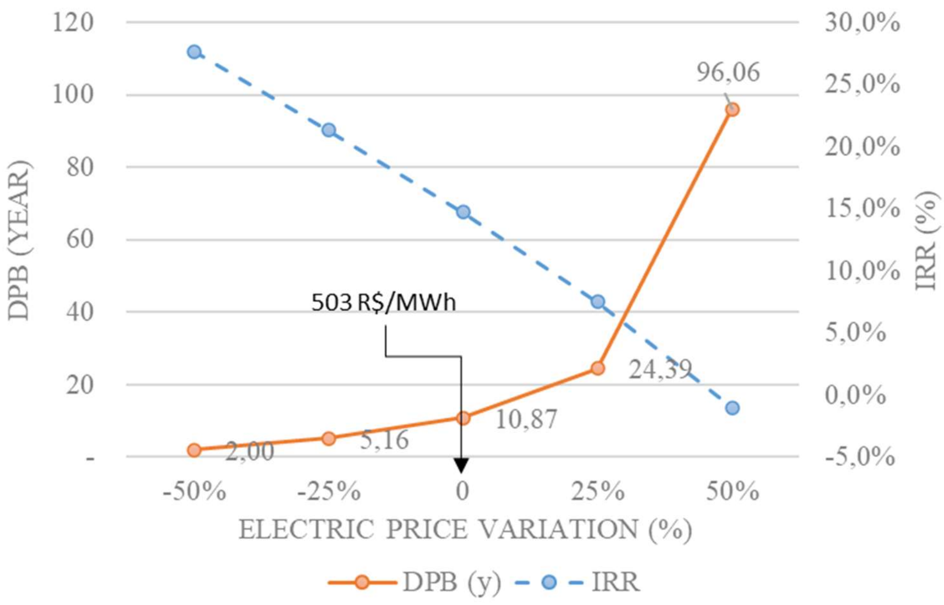


Figure 10: Electric price variation under the biomethane feasibility

The adoption of a maximum 50% variation in the price of electricity is reasonable, as can be seen in the last 5-year-historical data [61]. Recent economic assessments, whether in Brazil or in Europe, evidenced the significant impact of the electricity cost for projects that reuse biomass for energy purposes [2,16,21]. In addition, it seems that electric demand for upgrading facilities is crucial to validate investments in bioelectricity as a product. Therefore, the generator and upgrading system must be well-designed to achieve the best performance in terms of energy consumption. A 25% reduction in the electric tariff drops the DPB by almost one year. An increase of 25% in the price makes the biomethane project infeasible (high DPB and ROI < 10%).

3.3.3 Logistic influence

The logistic costs for transported co-substrates (swine manure and coffee residues) seem to be irrelevant in the case study. Figure 11 shows the economic indicators for biomethane alternative as best option.

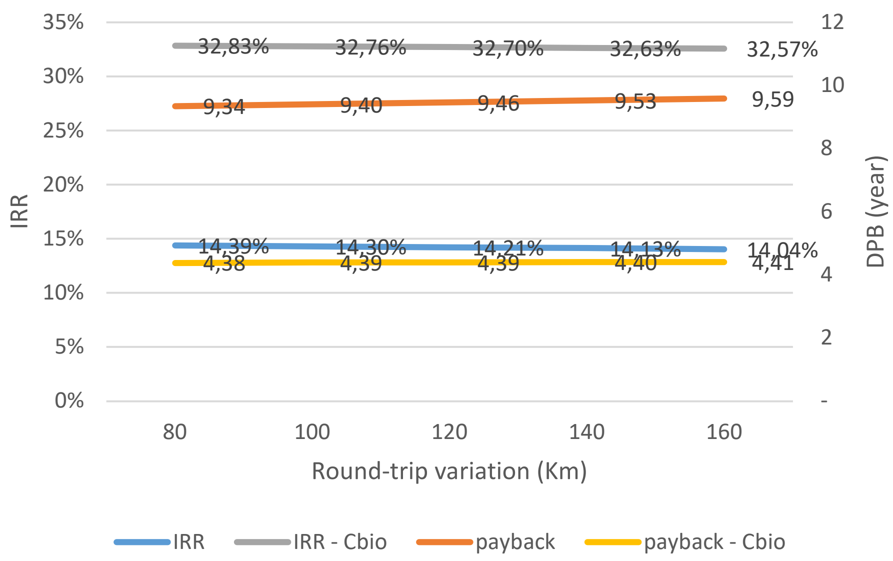


Figure 11: Influence of roundtrip in alternatives #2 and #3

The performance of economic decision indicators regarding the logistic factor was less important. One of the likely reasons is since the transportation cost is relatively lower than the total operational cost, the revenue obtained outweighs the influence of the transportation cost relative to fossil fuel. As previously highlighted, the acquisition cost of raw materials was also small compared to the annual diesel demand. Contrary to that demonstrated by [16], the system was highly sensitive to changes in cost in the case of using straw in co-digestion, possibly because it referred to a small project with low capacity. [13] was a rare study that considered the cost of substrates, on an industrial scale. However, perhaps justified by the high substrates cost of maize and elephant grass silage, the acquisition cost proved to influence the final feasibility of the project. In any case, the logistical cost, as a practical recommendation, could meet the criteria for transporting sugarcane, whose collection radius is around 30km.

3.3.4 co-AD efficiency (Eff_{COD})

As discussed, the blend of several co-substrates proposed in this study has not been experimentally tested in the laboratory, therefore, the potential of methane in this co-AD conversion is unknown. An Eff_{COD} of 85% was adopted in the simulation (Table 4), but what would be the effect if the efficiency reached a value lower than this parameter? Figure 12 shows the sensitivity of the main economic indicators.

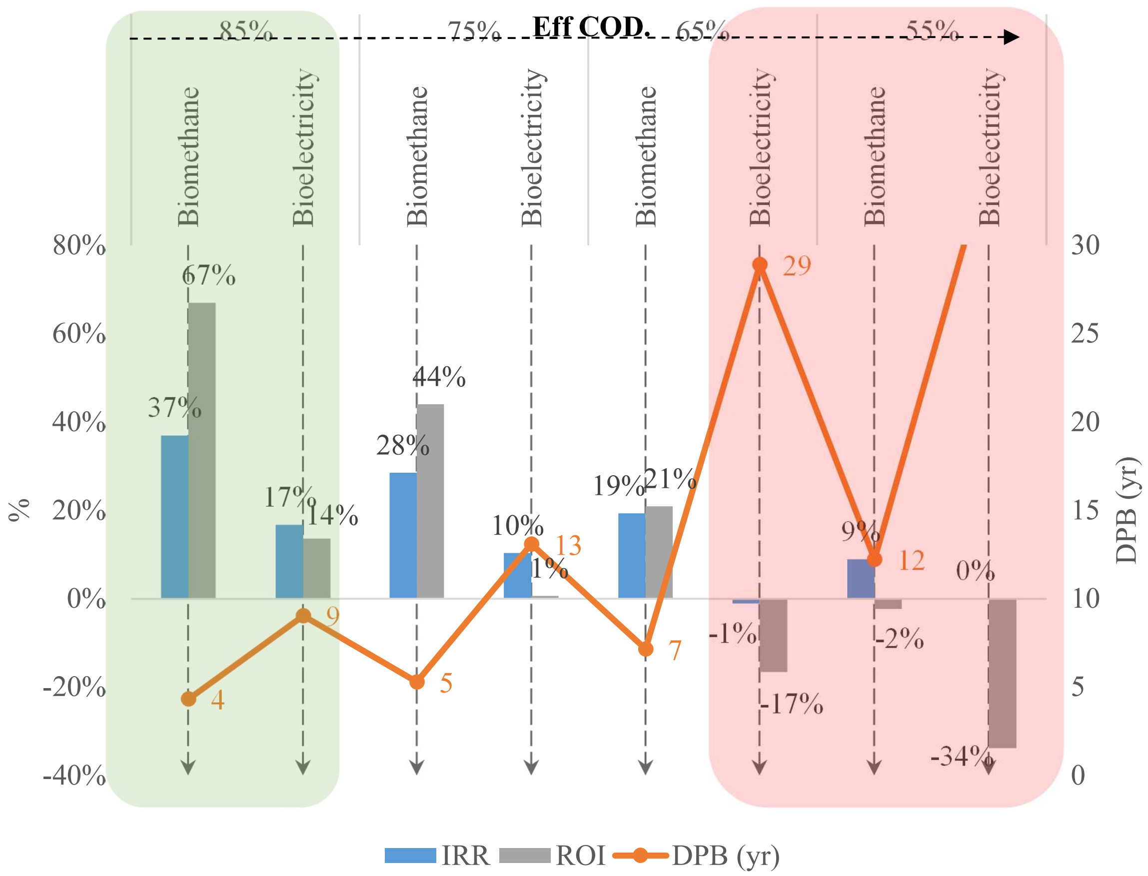


Figure 12: Economic indicators influenced by the theoretical co-AD efficiency of several co-substrates

The green area corresponds to the previous results found in this case study. The area in red corresponds to project losses, that is, at the Eff_{COD} threshold of 65% the project becomes economically unfeasible. However, it is expected that, with the adequate combination of co-substrates based on their biochemical composition and nutrients as well as the good operation of the biogas plant, this efficiency will reach higher yields.

4. CONCLUSION

Through the case study, we identify the most realistic conditions to economically assess an integrated biogas project gathering agro-industry and livestock residues. Co-substrates from coffee crops and animal creation have a minor influence on the feasibility, mainly because the amount of sugarcane waste is proportionally more relevant. The influence of the energetic density for transported co-substrates seems to be relevant as a parameter to achieve profitability in integrated processes. The main aspects highlighted follow.

- The electric price variation is crucial for the biomethane or bioelectricity feasibility.

- CBIOS revenues are essential for investments to produce biomethane whether as fuel or as an NG alternative.
- Integrated operations would be influenced by distances over 100 km.
- A legal framework to support biomethane as a fuel and CBIOS revenues are both necessary to achieve the project feasibility.

The Renovabio Program is influenced by externalities, such as adequate public policies to help eco-parks business model become a reality. These policies could include the integration of agro-industrial sectors here addressed, especially because the sugarcane sector is spread in the Brazilian agroindustry. Finally, this study revealed an important alternative to boost bioenergy production annexed to sugarcane mills anticipating environmental issues and improving the Brazilian energy matrix.

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SUPPLEMENTARY MATERIAL

Economic Indicators

$$NPV = \sum_{j=1}^{n} \frac{CF_j}{(1+i)^j}$$

Where CF is the fixed investment and “i” is the tax applied in the cash flow. If NPV > 0, then the alternative is economically viable. If NPV < 0, then the alternative is economically infeasible. If NPV = 0, it is neutral to invest in, but still viable. The NPV is a good measure of a project's profitability and can be used for alternative comparisons.

$$NPV = \sum_{j=1}^{n} \frac{CF_j}{(1+IRR)^j} = 0$$

The discount rate represents the tax that cancels the NPV. Therefore, in the case where NPV = 0, the discount rate “i” will be referred to as the IRR.

Payback is an indicator used to judge the relative attractiveness of investment options. In general, the longer the investment payback period, the less interesting it becomes to the entrepreneur.

$$\sum_{0}^{t} CF = CAPEX_0$$

In practice, paybacks up to 7 years are attractive.

The ROI is calculated by dividing the estimated yearly net income by the total invested capital and expressing the result as a percentage.

$$ROI\ (\%) = \frac{Net\ revenue}{CAPEX} x100$$

This is the percentage return on investment that investors can expect in the long term. For fluctuating rates, the acceptable ROI should be approximately 15%, and for fixed rates, approximately 30%. If investment involves a significant level of risk, these values may be greater. Sensitivity analyses were conducted to evaluate the influence of IRR, electricity fluctuation price, biomethane, and CAPEX-OPEX on the feasibility.

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DISCUSSIONS

Chapter 1 brought a current overview of the São Paulo state from the recently released Atlas of Bioenergy in 2020. The article revealed the theoretical potential of bioenergy distributed in the state´s main regions, with a regionalized view for co-substrate integration. Discussions regarding legal measures would facilitate the achievement of partnerships and boost a legal framework for Brazilian biogas/biomethane. The so-called *IntAgriCo* strategy (Agroindustry Co-digestion Integrated Process) is aligned with the national and international frameworks of sustainability. Although this study had geographical boundaries, it is known that similar bioenergy Atlas has been launched by other federative units, such as Minas Gerais, Espírito Santo, Rio Grande do Sul, and Alagoas (in additional references) [1]. One of the questions from reviewers regarded the restriction of scope, which focused on the main Brazilian agricultural regions, but even so, contributed to a comprehensive discussion at national and international levels. It is believed that the regional strategy can spread the discussion itself. Given the international importance to São Paulo´s economy, especially the sugarcane agroindustry, the article was published in an international journal. The initial idea consisted of submitting to a renowned Brazilian journal, therefore the discussion also reflects externalities for common crops worldwide. To meet the Ph.D. program guidelines, the manuscript was finally transcribed into the English language. In addition, process descriptions of waste generation in the agroindustry were academically innovative since some productive sectors are still restricted with little disclosure of information.

Next, **Chapter 2** assisted the acquisition costs of co-substrates which represents a necessary step to be discussed in biogas techno-economic assessments. The survey with the most recent articles internationally published found that none of the 17 articles cited in Table 1 included the co-product valuation. Of a total of 32 articles that discussed specifically the economic effects of agricultural and livestock residues in bioenergy, only 10 articles (or 31%) considered the acquisition cost of substrates in the OPEX. Operational costs would include acquiring raw materials, transportation, and opportunity costs. The two alternatives offer positive impacts such as pollution reduction of organic load from residue /effluent. Therefore, one of the best options may be to evaluate co-products by correlating volatile solids contents (TVS), as shown in Table 3, chapter 2. Thus, the techno-economic benefit was measured for energy purposes.

Beyond the sugarcane industry, minor impacts are also observed in other sectors. For example, citrus residues (part of the peel, albedo, and pits) have useful applications in animal nutrition, especially for ruminants, such as dairy cows. Economically, its residue seasonality attenuates the need for fodder, competing to increase livestock productivity in most of the rural regions in Brazil. The productive period of citrus pulp (June-February) covers the off-season of corn, which is the period of fodder scarcity. Thus, while corn prices reach the maximum value, and pastures have their demand increase, citrus pulp represents an important alternative supplementation for animal nutrition. However, orange residues have limitations such as low density, low protein content, large water content, and high cost of collection, transportation, and storage [62][63], in additional references. The drying stage requires additional investment which corresponds to the second energy consumption in medium plants, attracting greater interest from companies in developing markets for wet citrus animal food. This scenario mostly occurs in small citrus plants where concentrated orange juice is produced. The alternatives include extracting pectin, which requires new investment and generates a larger environmental impact; D-limonene, an essential oil employed in the pharmaceutical industry, yields the second-highest revenue and the lowest environmental impact (see additional references). Hence, if the orange industry provides enough D-limonene extraction, as well as small orange juice facilities without oil extraction and animal food production, both configurations will serve as a waste source *for an IntAgriCo* attached to sugarcane plants. As mentioned in Chapters 2 and 3, lower amounts of this inhibitor would not affect productivity via co-digestion. In addition, big citrus plants, such as Citrosuco, have no available residues, only wastewater. The general characteristics of effluent (for a medium-sized 120,000 box/day generating 110m^3/h effluent; COD 5,000-10,000mg/L, pH 5-6) was observed in a technical visit.

As for the public policies addressed in Chapter 1, waste management occurs sporadically, primarily because no specific state legislation was found with this purpose. According to Cetesb – the Environmental Agency of SPS, soil and water quality follow-ups took place at annual intervals between 2008, 2015, and 2021. In this period, respectively, only soil conditions regarding native and agricultural vegetation areas were evaluated, considering metals and organic substances; in regions across Piracicaba, Capivari, and Jundiaí river basins. The main crops studied were sugarcane, citrus, beans, pumpkin, strawberry, and eucalyptus. Finally, the groundwater quality of companies´ licensing was evaluated only in terms of effluent composition and the volume [64], in additional references. The control, treatment and destination aim to avoid negative impacts that are foreseen in the environmental licensing stage of an agro-industrial plant. Cetesb has been monitoring the quality of internal waters, soil, and municipal waste since 1974. Most of the land use in the Midwest and northeast of SPS represents the agricultural region, where rivers and reservoirs belonging to Water Resources Management (UGRHIs) are less monitored compared to other industrial regions of the state (South and metropolitan regions). The negative impacts on soil and water – water contamination by vinasse, air pollution with straw burning, and soil impoverishment by the excess of nutrients – are long-term monitored by the government. Since 2015, Cetesb's official website has not disclosed any results of monitoring soil and water analyses.

Chapter 3 provides a case study in the real conditions of *IntAgriCo* operation. In fact, biomethane production is economically feasible instead of bioelectricity, mainly due to the current cost of MWh. This scenario can change in the medium and long term if, for example, local demand for energy supply is needed. Another point to figure out is the possibility to reflect different profitability by using other crops. Potential regions can be revealed beyond those indicated in Table 12 of Chapter 1. Therefore, new public policies can also foster feasibility and strengthen regional agriculture. In the case study, swine and poultry manures are excellent options, mainly to ensure the supply of substrate in the sugarcane off-season. The current high cost of animal feed derived from corn, soybeans, and other citrus accelerated serious economic issues for producers. If the transfer of manure to the *IntAgriCo* plant located inside the sugarcane agroindustry were monetized, for example with the biomethane portion generated, this action would strengthen the cooperative modality. Regarding coffee producers, farms frequently obtain "Regenerative" certification, a term used to describe the process of reusing waste in their process. Moreover, many local farmers have small planting areas (lower than 100ha), which results in reduced waste generation destined for co-digestion. The coffee beans processing also reflects the amount generated of bark, straw, and mucilage, which are commonly incorporated into the soil. In addition, coffee wastewater should not be sprinkled because of its high potassium content, which would burn foliage and new fruits, thus being redistributed via channels in the soil. Coffee residues are also better managed on Brazilian farms compared to references cited from Colombia. According to Corro et al (2013), every 1 kg of cherry coffee generates 6.7 liters of wastewater. In Brazilian farms, the average reaches 3.2 liters/kg of cherry coffee. On the other hand, the inputs have high costs, especially in regions where the climate and soil quality are less favorable. Finally, some farms located near citrus juice plants acquire citrus crushed-balanced nutrients to incorporate into coffee cultivation.

Finally, although each co-substrate used in the case study has different proportions in terms of volume and concentration, Figure 1 provides an overview of the final blend of organic matter and macronutrient levels. The data presented are based on the biochemical composition outlined in Table 2 of Chapter 2, as well as the estimated quantities of co-substrates mentioned in Table 3 of Chapter 3.

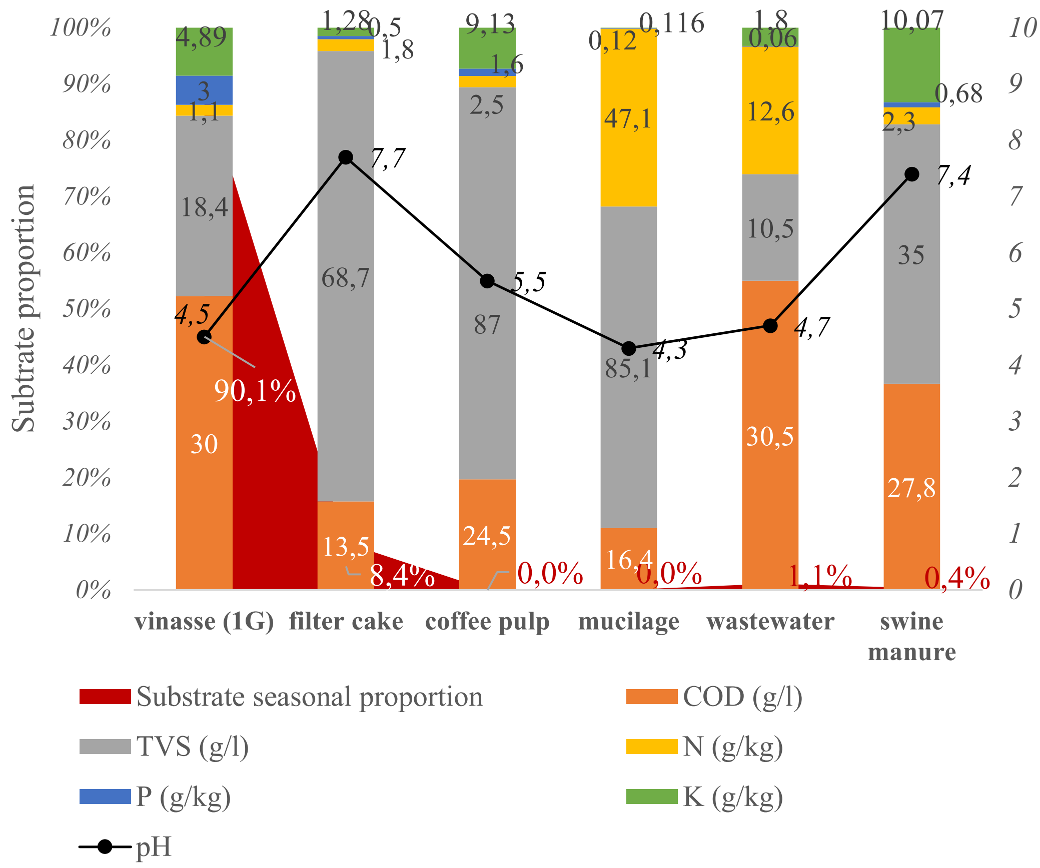


Figure 1: Proportional nutrient contribution for the co-substrates in the case study

The volume-weighted concentrations of co-substrates, namely vinasse, filter cake, coffee pulp, mucilage, wastewater, and swine manure (excluding the carcass), contain components such as COD, TVS, and macronutrients that are proportional to their respective volumes. In a multiple co-digestion process, it is important to consider the contribution of each substrate's composition, especially when the larger substrates (vinasse and filter cake) are added in amounts similar to those obtained from other agro-industrial sources. In this study, the volumes of vinasse and filter cake processed in co-AD are significantly higher (~98%) than the others, suggesting that the contribution of the smaller substrates is mainly attributed to their concentrations of macro-nutrients and micronutrients, as their organic matter content is considerably lower. This monthly analysis maintains the same configuration throughout the study.

CONCLUSION

Hence, I conclude that:

- Orange facilities with no-existing oil extraction and animal food steps will serve as a source of waste for an *IntAgriCo* attached to integrated sugarcane plants to bioenergy generation. Medium-sized citrus industries (< 100,000 boxes/day) would not offer enough residues as co-substrates.
- For coffee farms, whose residues and effluents are generated in low quantities compared to other crops, we consider little profitability for an *IntAgriCo* process, and may not recommend partnerships for co-digestion purposes.
- Referring to the case study, as an outcome, I concluded the coffee industry in SPS would not be feasible for co-AD, in addition, there is a clear producer's lack of interest.
- Soybean crops would have little contribution to *IntAgriCo*. Potential examples of gains from its reuse with another agroindustry were not evidenced in the study due to its unavailability.
- Bovine manure in confinement has great potential to be integrated because of its lower acquisition cost and availability, especially in Region 8 of SPS.
- Thin stillage promises to be the most promising corn residue. After the expansion of the corn frontier influenced by the neighboring state, Mato Grosso do Sul.

Certainly, there are numerous barriers, mainly economic, that still prevent the implementation of a large-scale bioenergy integration in agro-industry. Other economic assessments of regional case studies could minimize remaining doubts in the near future.

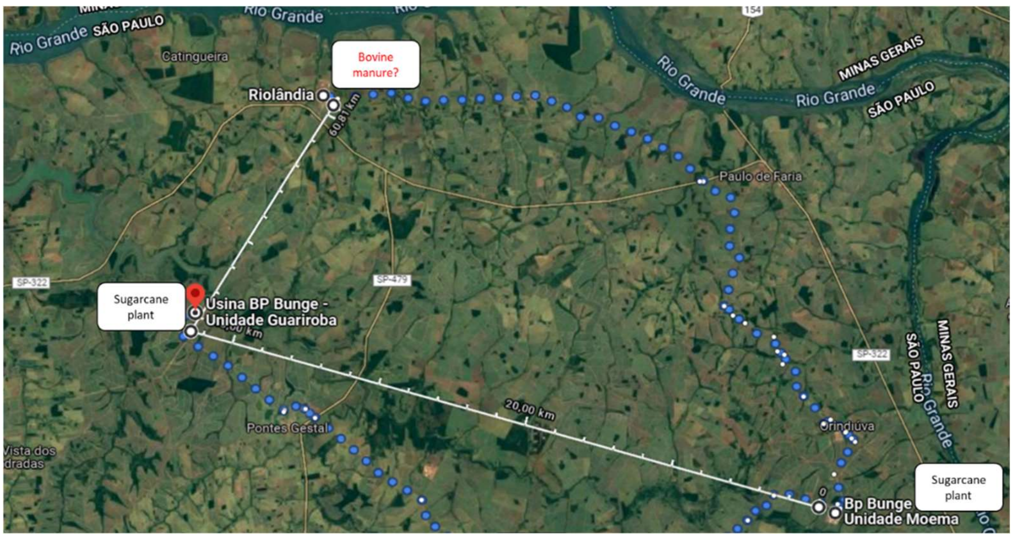
SUGGESTIONS FOR FUTURE WORKS

- Elaborate the LCA - Life cycle assessment of biomethane according to case #1 discussed in chapter 3 of the thesis, verifying the environmental impacts associated with emission and comparing it to the natural gas life cycle.
- Develop a study to evaluate social impacts related to case study #1 and show regional advantages and disadvantages regarding the job offer, improvement of education, and life quality.
- Perform case studies #2 and #3 as described in the table below. Case studies were selected during the evaluation of the scenarios. The table shows detailed data:

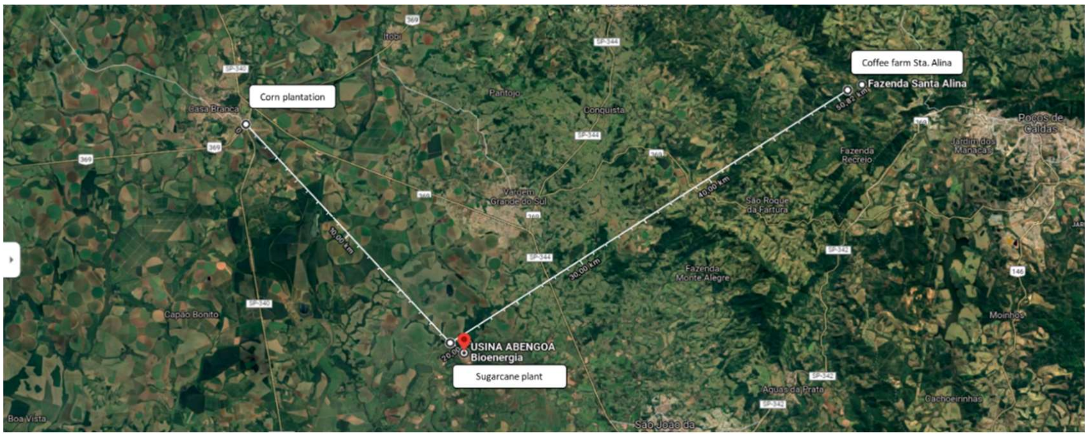
Table 1: Suggested case studies for future works

Case study	**Municipalities in SP**	**Agroindustry**	**Substrates (Available amount)**
2	Pontes Gestal Orindiúva Riolândia (Barretos)	- Guariroba mill: *1.4 MTC* - Moema mill: *3.8 MTC* - Bovine farm (owner Luiz Gonzaga)	Vinasse 1.43M m^3. season $^{-1}$; filter cake 163.8 Kt. season $^{-1}$ Cattle manure: 7,812 t. y^{-1}
3	São João da Boa Vista São Sebastião da Grama Casa Branca (Campinas)	- São João da Boa Vista Mill (ABENGOA): *2.6 MTC* - Fazenda Santa Alina - Krauss Citros	Vinasse 1.37M m^3. season $^{-1}$; filter cake 81.9 Kt. season $^{-1}$ Coffee pulp: 366 $ton.season^{-1}$ Mucilage 333 $m^3.season^{-1}$ Effluent 24,800 $m^3.season^{-1}$ Swine manure (1,120 matrices): 889 $t.y^{-1}$ Corn stover, thin stillage: $0m^3.y^{-1}$ (NA) Yellow water, orange bagasse: 4.1 $t.season^{-1}$

Geographical locations are respectively in the Region of Barretos; and in the Region of Campinas, as shown by the figures.



(a)



(b)

Figure 1: (a) Location for the case study #2; (b) Location for the case study #3.

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CHAPTER 1

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CHAPTER 2

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CHAPTER 3

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Appendix

Appendix 1: Detailed CAPEX and OPEX of the case study

Cotação	5,3	R$/US$	
	95%	US$/EUR	
		http://ww	

CAPEX				CASE #1		CASE #2		CASE #3	
Direct costs			*US$*	***31.951.035***		**-**		**-**	
LAND FOR BIOGAS PLANT				**US$**		**US$**		**US$**	
20,000 m²	*R$720/m²*			2.716.981		-		-	0,
									1
									2
BIOPROCESS FACILITY		**US$ (un)**	**Unit**	**Total (US$)**	**Unit**	**Total (US$)**	**Unit**	**Total (US$)**	
Silage tank (capacity of 90 t, 304L)		101.300	1	101.300		-		-	*Equipment Costs (McGrawHill)*
Drier (for stover and straw)			0	-		-		-	*Equipment Costs (McGrawHill)*
Crusher / grinder / cutter (for stover and straw) Cap.:3kg/s		22.972	0	-		-		-	*Equipment Costs (McGrawHill)*
Pumps (centrifugal) - SS motor included		15.658	2	31.316		-		-	*Equipment Costs (McGrawHill)*
Pumps (rotary) - carbon steel, 50 bar		32.040	2	64.080					*Equipment Costs (McGrawHill)*
Inoculum tank - field erected cap.2000m³		196.797	1	196.797		-		-	*Equipment Costs (McGrawHill)*
Pre-digester sCSTR - 1,000m³		367.682,60	1	367.683		-		-	*(eq. Imeni et al 2019)*
Digester sCSTR - 2,000 m³		670.408,60	2	1.340.817		-		-	*(eq. Imeni et al 2019)*
Filter presses for resulting mixture (0.5m²/TCH)		167.925	1	167.925		-		-	*This study*
Tank 1 Digestate 90m3 - 304L stainless steel		101.300	1	101.300		-		-	*Equipment Costs (McGrawHill)*
Gas storage - 316L stainless steel		492.530	1	492.530		-		-	*Equipment Costs (McGrawHill)*
Estabilization filter cake - dewatering, compression*		0,134	1	1.665.872					*Romero-Guiza (2015) and Alexander (2012)*
**250EUR/ton ; 10US$/764,5 L*				**4.529.619**					*0,238* US$/kg
									0,029 US$/kg
ELECTRIC CENTRAL									
CHP for 20MWe		10.085.956	1	10.085.956		-		-	*Velasquez Pina et al(2019); Budzianowski (2015)*
Connection to electrial grid		4.473.123	1	4.473.123		-		-	*Velasquez Pina et al (2019)*
				14.559.078		-		-	
BIOMETHANE FACILITY		**US$ (un)**	**Unit**	**Total (US$)**	**Unit**	**Total (US$)**	**Unit**	**Total (US$)**	
H2S removal (air injection + scrubber)		7.770.652,02	1	7.770.652		-		-	*Velasquez Pina et al(2019); Budzianowski (2015)*
CO2 removal		416.711,64	1	416.712		-		-	*Budzianowski (2015)*
Flare system		956.077,91	1	956.078					*Velasquez Pina et al(2019)*
Compression system		165.000,00	1	165.000					*Fuess et al (2018)*
Pipeline dispatch into the NG gate		397.880	1	397.880					*IRENA (2020)*
Kit dual-fuel biomethane for medium trucks		1,71		439.035					*Gustafsson and Svensoon (2021), pg.4*
				10.145.356		-		-	*1,8 EUR/km (driver, diesel, + related cost)*
Indirect costs			***US$***	***10.375.862***		**-**		**-**	
AUTOMATION									
Control, instrumentation, sensors		10% of equipments		**2.470.443**		-		-	*Peters and Timmerhaus (1991)*
ASSEMBLY AND INTERCONNECTIONS									
Interconections 316L SS, valves, outsourced labor		10% of equipments		**2.470.443**		-		-	*Peters and Timmerhaus (1991)*
Fire safety project ABNT		2% of equipments		**494.089**		-		-	*Peters and Timmerhaus (1991)*
CIVIL WORK									
Civil works		5% of equipments		**1.235.222**		-		-	*Peters and Timmerhaus (1991)*
ENGINEERING AND SUPERVISION									
Engineering and consultant		10% equipments		**3.705.665**		-		-	*Peters and Timmerhaus (1991)*
Contigency	*0,20*CF*	0,20	**US$**	8.465.379		-		-	*Peters and Timmerhaus (1991)*
Contracts	*0,05*CF*	*0,05*	**US$**	*2.116.345*		-		-	*Peters and Timmerhaus (1991)*
Working capital									*Peters and Timmerhaus (1991)*
(0,10*CF)		0,10	**US$**	**4.444.324**		-		-	

CAPEX (Direct + indirect costs)	US$	44.443.242		-		-	
			-20%		-10%	10%	20%
CAPEX - biomethane	**$**	**32.000.509**	$25.600.407	$	28.800.458	$35.200.560	$ 38.400.610
CAPEX - electricity	**$**	**36.414.230**	$29.131.384	$	32.772.807	$40.055.653	$ 43.697.076
CAPEX - electricity with a previous CHP installed as well connection to grid	$	**21.855.152**	$17.484.122	$	19.669.637	$24.040.668	$ 26.226.183

OPEX - annual

INPUTS	US$/Kg or m³ *	CASE #1 Total (US$)	
Vinasse	0.53-0.85	-	*Author*
Filter cake	-	-	*Author*
Corn stover*	0,1037	-	*Author*
Orange bagasse*	0,25	-	*Author*
Yellow vinasse*	-	-	*Author*
Bovine manure*	0,038	-	*Author*
Swine manure + effluent slaughter*	0,94	14.563	*Author*
Coffee pulp*	-	5.329	*Author*
Mucilage*	-	5.329	*Author*
Coffee effluent*	-	5.329	*Author*
Alkalinization (NaOH 50.4%) 89-113mg NaOH/L vinasse	1,51	89.342	*Fuess et al (2019)*
**Market value, opportunity cost or logistical expense*		**119.892,31**	***1,8%*** - -

UTILITIES	Factor	Total (US$)		
Electric energy consumption (US$/MWh)**	18%	2.689.401	*BERNS; SCHNICKE; BOMBONATTI;*	30,9%
Raw material transport - coffee residues		15.987		
Raw material transport - swine wastes		48.051	*Velasquez Pina el al(2019)*	
Fixed cost for biomass transportation	3947 US$/month	39.470	*Velasquez Pina el al(2019)*	
Waste treatment	US$ 2/m³.d			
Biogas Upgrading operations	0,026 EUR/Nm³ biogas	1.976.000	*Fuess et al (2019)*	22,7%
Loading and unloading biomethane (4h per delivery)	64.5 EUR/h	80.334	*Gustafsson and Svensoon (2021), pg.4*	
503,88 ** *VRE for biogas (MME n°65/2018): R$390/MWh*	*503,88 R$/MWh*	**4.849.242**	https://www.ccee.org.br/web/guest/dados-e-analise:	-
29,20%	*95,07 US$/MWh*			

EMPLOYEES	US$ (month)	n°	Total (US$)	
Raw material handling	472	2	943	*Expert consultation*
Maintenance (mecanic and hydraulic)	566	2	1.132	*Expert consultation*
Bioreactor operation	472	2	943	*Expert consultation*
Digestate operation	566	1	566	*Expert consultation*
Upgrading unit	755	2	1.509	*Expert consultation*
Quality control	755	2	1.509	*Expert consultation*
Biomethane supply and deliver	755	1	755	*Expert consultation*
Plant manager	1.887	1	1.887	*Expert consultation*
		13	**9.245**	**110.943** - -

MAINTENANCE	Fator /CF	TOTAL (US$)	
Maintenance and general instrumentation	10%	**2.470.443**	*Peters and Timmerhaus (1991)*

Taxes, CHARGES	Fator /CF	TOTAL (US$)	
Taxes (property)	2%	**494.089**	*Peters and Timmerhaus (1991)*
Financing (interest)	-	-	*Peters and Timmerhaus (1991)*
Insurance	1%	**247.044**	*Peters and Timmerhaus (1991)*
Rent	-	-	*Peters and Timmerhaus (1991)*
Depreciation	in cashflow		*Peters and Timmerhaus (1991)*
Research & Development	1%	**247.044**	*Peters and Timmerhaus (1991)*
Labor benefits *(monthly employees)*	53,80%	170.631	*Cavalcanti, L. (2020)*
		1.158.808	

Variable costs (except Taxes and charges)	**7.550.521**
MANUFACTURE COST (Variable + Taxes + charges)	***8.709.329***
MANUFACTURE COST (for electricity)	**6.635.971**

OPEX	
-20%	6.967.464
-10%	7.838.397
0	8.709.329
10%	9.580.262
20%	10.451.195

fazer +1 aba cashf fazer +1 aba cashflow

PRODUCTION COST

Unit cost	$	0,19	/m³	R$	1,03	/m³
	$	51,49	/MWh	R$	272,92	/MWh

P/ 20MW instalada

10.000	m³ vinhaça/d
400	t/d (FC)

12	EtOH x vinasse (Fuess 2017; Moraes 2(
90%	recovery all wastes
35	kg/TC Filter cake (Prado et al, 2013)
3,5	kg yellow water/box (40.8kg each)
10850	box /day
4	months orange harvest
367,6	kg swine manure/year/head
3300 1120	swine heads (matrices)
115	gallon water/swine head
2170	kg bovine manure /year/head
4000	beef cattle heads

2400	green coffee prod.(kg/ha)
6	kg cherry coffee/kg green coffee
150	Surface plantation (ha) in #1
257	Surface plantation (ha) in #3
9,90%	pulp (residue) under cherry coffee
90	mL mucilage/kg cherry coffee
6,7	Lts washing water/kg cherry coffee
90	days

Transportation(Velasquez Pina el al(2019)

Twin truck -**cap.25t**	0,25	US$/km
Round-trip (RT)	120	km
RT year swine manure	1.602	
RT season coffee resid	533	
Diesel	1,23	US$/L
	256.151	km

NaOH em solução 50,4%

Coalhopar(PR)-bombonas 60kg

8,00 R$/kg

Granel p/usina NaOH 50,4%

1,47 R$/kg

CASES	1	2	3	TS (%)
Milling cane (TCS)	3,10E+06	5,20E+06	2,60E+06	
vinasse (m³)	1.047.600	1.436.400	1.371.600	2,6
Filter cake (ton)	97.650	163.800	81.900	68,5
Coffee pulp (ton)	192	-	330	94,8
Mucilage (m³)	175		300	94,8
Effluent (coffee washing) (m³)	13.025		22.316	13,0
Processed orange in site (ton)	-	-	165.000	
Orange effluent (ton)	-	-	4.101	19,0
Bovine manure (ton)	-	7.812	-	25,0
Swine manure (ton)	4.529	-	-	7,0
Effluent from swine slaughter (m³)	15.493			
Corn stover, leafs and stalks (ton)	-	-	56581	
~~Corn cob (ton)~~			~~39897~~	
Proportion co-substrates (L/S) in feed	70-30%	60-40%	70-30%	

CASE #1

FUESS et al

Biogas upgrading (H2S removal)	0,026 EUR/Nm³ biogas

Tabela VII.7 – Valores de conversão energética para diferentes tipos de efluente.
Fonte: COELHO et al (2012).

Origem	kg biogás/kg dejeto	Concentração de metano (%)
Suíno	0,062	66
Bovino	0,037	60
Aves	0,055	60

Tabela VII.5 — Informações sobre a criação de gado de corte. *Fonte:* Thiago, 1996; IPEA, 2012[a].

Descrição	Unidade	Quantidade
Peso inicial [a]	kg	300
Peso final [a]	kg	450
Geração de dejetos/ kg de animal vivo[b]	kg/dia	0,058
Dias de confinamento [b]		100

Appendix 2: BIOMETHANE cash flow

(BNDES FUNDING)

		-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
R$/	CASHFLOW (US$)	year -2	year -1	year 0	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year
5,3	Biomethane (Nm³)	1,63	R$/m³			22.406.301	44.812.601	44.812.601	44.812.601	44.812.601	44.812.601	44.812.601	44.812.601	44.812.601	44.812.601	44.812.601	44.812.601	44.812.601	44.812.601	44.812.601	44.812.601	44.812.601	44.812.601	44.81
		0,31	US$/m³			1/2 produção	100%																	
	Land for biogas plant																							
	CAPEX			- 16.000.254	- 16.000.254																			
90,00%	Financing			14.400.229	14.400.229																			
	BRUT REVENUE					7.145.100	14.290.200	14.290.200	14.290.200	14.290.200	14.290.200	14.290.200	14.290.200	14.290.200	14.290.200	14.290.200	14.290.200	14.290.200	14.290.200	14.290.200	14.290.200	14.290.200	14.290.200	14.290
9,25%	DIRECT TAXES					- 660.922	- 1.321.843	- 1.321.843	- 1.321.843	- 1.321.843	- 1.321.843	- 1.321.843	- 1.321.843	- 1.321.843	- 1.321.843	- 1.321.843	- 1.321.843	- 1.321.843	- 1.321.843	- 1.321.843	- 1.321.843	- 1.321.843	- 1.321.843	- 1.32
US$/ano	COSTS				- 4.444.324	- 6.096.531	- 8.709.329	- 8.709.329	- 8.709.329	- 8.709.329	- 8.709.329	- 8.709.329	- 8.709.329	- 8.709.329	- 8.709.329	- 8.709.329	- 8.709.329	- 8.709.329	- 8.709.329	- 8.709.329	- 8.709.329	- 8.709.329	- 8.709.329	- 8.709
	EBITDA					387.648	4.259.027	4.259.027	4.259.027	4.259.027	4.259.027	4.259.027	4.259.027	4.259.027	4.259.027	4.259.027	4.259.027	4.259.027	4.259.027	4.259.027	4.259.027	4.259.027	4.259.027	4.259.
20,00%	DEPRECIATION					- 6.400.102	- 6.400.102	- 6.400.102	- 6.400.102	- 6.400.102														
(ver tabela abaixo)	DESPESAS FINANCEIRAS = *juros*					- 354.887	- 335.171	- 315.455	- 295.739	- 276.023	- 256.307	- 236.591	- 216.875	- 197.160	- 177.444	- 157.728	- 138.012	- 118.296						
	LAIR					- 6.367.341	- 2.476.246	-2.456.530	- 2.436.814	- 2.417.098	4.002.719	4.022.435	4.042.151	4.061.867	4.081.583	4.101.299	4.121.015	4.140.731	4.259.027	4.259.027	4.259.027	4.259.027	4.259.027	4.259.
34,00%	IR + CSSL					-	-	-	-	-	1.360.925	1.367.628	1.374.331	1.381.035	1.387.738	1.394.442	1.401.145	1.407.849	1.448.069	1.448.069	1.448.069	1.448.069	1.448.069	1.448
	NET REVENUE					- 6.367.341	- 2.476.246	- 2.456.530	- 2.436.814	- 2.417.098	2.641.795	2.654.807	2.667.820	2.680.832	2.693.845	2.706.858	2.719.870	2.732.883	2.810.958	2.810.958	2.810.958	2.810.958	2.810.958	2.810
	Depreciation					6.400.102	6.400.102	6.400.102	6.400.102	6.400.102	-	-	-	-	-	-	-	-	-	-	-	-	-	
	Financing amortization					1.600.025	1.600.025	1.600.025	1.600.025	1.600.025	1.600.025	1.600.025	1.600.025	1.600.025	1.600.025	1.600.025	1.600.025	1.600.025	1.600.025	1.600.025	1.600.025	1.600.025	1.600.025	
(Invest - FinancBND)	FCL ACIONISTA			- 1.600.025	-6.044.350	- 1.567.265	2.323.830	2.343.546	2.363.262	2.382.978	1.041.769	1.054.782	1.067.794	1.080.807	1.093.820	1.106.832	1.119.845	1.132.857	1.210.932	1.210.932	1.210.932	1.210.932	1.210.932	2.810.
	FCLA ACUMULADO			- 1.600.025	- 7.644.375	- 9.211.640	- 6.887.810	- 4.544.264	- 2.181.001	201.977	1.243.746	2.298.528	3.366.322	4.447.130	5.540.949	6.647.781	7.767.626	8.900.483	10.111.415	11.322.348	12.533.280	13.744.212	14.955.144	17.766
10%	FCLA DESCONTADO			- 1.600.025	- 5.494.863	- 1.295.260	1.745.928	1.600.674	1.467.400	1.345.129	534.592	492.064	452.849	416.698	383.377	352.671	324.379	298.317	289.888	263.534	239.577	217.797	197.997	41
	FCLA DESCONTADO ACUMUL.			- 1.600.025	- 7.094.889	- 8.390.149	- 6.644.221	- 5.043.547	- 3.576.148	- 2.231.019	- 1.696.426	- 1.204.363	- 751.513	- 334.816	48.562	401.232	725.611	1.023.928	1.313.816	1.577.350	1.816.926	2.034.723	2.232.720	2.650
114,25																								
R$/tCO2 eq	CBIOs REVENUES					-	2.770.485	2.770.485	2.770.485	2.770.485	2.770.485	2.770.485	2.770.485	2.770.485	2.770.485	2.770.485	2.770.485	2.770.485	2.770.485	2.770.485	2.770.485	2.770.485	2.770.485	2.770
	FCL acionista + Cbios revenue			- 1.600.025	- 6.044.350	- 1.567.265	5.094.315	5.114.031	5.133.747	5.153.463	3.812.254	3.825.267	3.838.279	3.851.292	3.864.304	3.877.317	3.890.329	3.903.342	3.981.417	3.981.417	3.981.417	3.981.417,2	3.981.417,2	5.581.4
10%	FCLA descontado c/Cbio			- 1.600.025	- 5.494.863	- 1.295.260	3.827.434	3.492.952	3.187.653	2.908.996	1.956.289	1.784.515	1.627.805	1.484.840	1.354.415	1.235.433	1.126.890	1.027.872	953.120	866.472	787.702	716.092,9	650.993,5	829.6
	FCLA descontado Acuml. (Cbio)			- 1.600.025	- 7.094.889	- 8.390.149	- 4.562.715	- 1.069.763	2.117.890	5.026.886	6.983.175	8.767.690	10.395.495	11.880.335	13.234.750	14.470.183	15.597.073	16.624.945	17.578.064	18.444.537	19.232.239	19.948.332	20.599.325	21.428
	Biofertilizer REVENUE (USD) - save inorganic acquisition					268.198	536.395	536.395	536.395	536.395	536.395	536.395	536.395	536.395	536.395	536.395	536.395	536.395	536.395	536.395	536.395	536.395	536.395	536

10%	NPV	*2.650.551*		NPV c/Cbio	*21.428.971*	
	IRR	*14,69%*		IRR c/Cbio	*36,94%*	
	payback descontado	10,87	YEAR	Payback c/Cbio	4,34	YEAR
	ROI	8,3%			67,0%	

BNDES Renovabio

Amortization table

		SAC	1,23%	18,00 anos		
TJLP	4,50%	SDI	Juros	Amortização	Prestação	SDf
spread	1,5%	R$ 28.800.458				
Nominal	6,80%	R$ 28.800.458	R$ 354.887	R$ 1.600.025	R$ 1.954.913	R$ 27.200.432
Inflation	5,50%	R$ 27.200.432	R$ 335.171	R$ 1.600.025	R$ 1.935.197	R$ 25.600.407
Real cos	1,23%	R$ 25.600.407	R$ 315.455	R$ 1.600.025	R$ 1.915.481	R$ 24.000.381

Fonte de dados - BNDES

https://www.bndes.gov.br/wps/portal/site/home/financiamento/produto/bndes-credito-pequenas-empresas/!ut/p/z1/vVJNb6MwFPw1HB2bQBLYG4qisFuiNOq2Db5UxhhwBbZjm9D992uleummG_VSn-z3MW9mniGGR4gFOfOaWC4Fad07x8

Appendix 3: BIOELECTRICITY cash flow

(DING)											
	-2	-1	0	1	2	3	4	5	6	7	8
/ (US$)	year -2	year -1	year 0	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8
Bioelectricity (MWh)	503,88	R$/MWh			64.434	128.868	128.868	128.868	128.868	128.868	128.868
Land for biogas plant					1/2 produção	1					
CAPEX			- 18.207.115	- 18.207.115							
Financing			16.386.404	16.386.404							
BRUT REVENUE					6.394.056	12.788.111	12.788.111	12.788.111	12.788.111	12.788.111	12.788.111
DIRECT TAXES					- 591.450	- 1.182.900	- 1.182.900	- 1.182.900	- 1.182.900	- 1.182.900	- 1.182.900
COSTS				- 4.444.324	- 6.635.971	- 6.635.971	- 6.635.971	- 6.635.971	- 6.635.971	- 6.635.971	- 6.635.971
EBITDA					**- 833.366**	**4.969.239**	**4.969.239**	**4.969.239**	**4.969.239**	**4.969.239**	**4.969.239**
DEPRECIATION					- 3.641.423	- 3.641.423	- 3.641.423	- 3.641.423	- 3.641.423	- 3.641.423	- 3.641.423
DESPESAS FINANCEIRAS = *juros*					- 403.836	- 381.400	- 358.965	- 336.530	- 314.094	- 291.659	- 269.224
LAIR					**- 4.878.625**	**946.416**	**968.851**	**991.287**	**1.013.722**	**1.036.157**	**1.058.593**
IR + CSSL					-	321.781	329.409	337.037	344.665	352.293	359.921
NET REVENUE					- 4.878.625	624.635	639.442	654.249	669.056	683.864	698.671
Depreciation					3.641.423	3.641.423	3.641.423	3.641.423	3.641.423	3.641.423	3.641.423
Financing amortization					1.820.712	1.820.712	1.820.712	1.820.712	1.820.712	1.820.712	1.820.712
FCL ACIONISTA			**- 1.820.712**	**- 6.265.036**	**- 3.057.913**	**2.445.346**	**2.460.153**	**2.474.961**	**2.489.768**	**2.504.575**	**2.519.383**
FCLA ACUMULADO			- 1.820.712	- 8.085.747	- 11.143.660	- 8.698.314	- 6.238.161	- 3.763.200	- 1.273.432	1.231.143	3.750.526
FCLA DESCONTADO			- 1.820.712	- 5.695.487	- 2.527.201	1.837.225	1.680.318	1.536.756	1.405.409	1.285.243	1.175.311
FCLA DESCONTADO ACUMUL.			- 1.820.712	- 7.516.199	- 10.043.399	- 8.206.175	- 6.525.857	- 4.989.101	- 3.583.692	- 2.298.449	- 1.123.138
CBIOs REVENUES											
Biofertilizer REVENUE (USD) - save inorganic acquisition					268.198	536.395	536.395	536.395	536.395	536.395	536.395
NPV			$ 4.957.394								
IRR			16,75%								
payback			9,05	YEAR							
ROI			13,6%								

(DING)												
	9	10	11	12	13	14	15	16	17	18	19	20
/ (US$)	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year
Bioelectricity (MWh)	128.868	128.868	128.868	128.868	128.868	128.868	128.868	128.868	128.868	128.868	128.868	12
Land for biogas plant												
CAPEX												
Financing												
BRUT REVENUE	12.788.111	12.788.111	12.788.111	12.788.111	12.788.111	12.788.111	12.788.111	12.788.111	12.788.111	12.788.111	12.788.111	12.7
DIRECT TAXES	- 1.182.900	- 1.182.900	- 1.182.900	- 1.182.900	- 1.182.900	- 1.182.900	- 1.182.900	- 1.182.900	- 1.182.900	- 1.182.900	- 1.182.900	- 1.18
COSTS	- 6.635.971	- 6.635.971	- 6.635.971	- 6.635.971	- 6.635.971	- 6.635.971	- 6.635.971	- 6.635.971	- 6.635.971	- 6.635.971	- 6.635.971	- 6.63
EBITDA	**4.969.239**	**4.969.239**	**4.969.239**	**4.969.239**	**4.969.239**	**4.969.239**	**4.969.239**	**4.969.239**	**4.969.239**	**4.969.239**	**4.969.239**	**4.969**
DEPRECIATION	- 3.641.423	- 3.641.423	- 3.641.423									
DESPESAS FINANCEIRAS = *juros*	- 246.788	- 224.353	- 201.918	- 179.482	- 157.047	- 134.612						
LAIR	**1.081.028**	**1.103.463**	**1.125.898**	**4.789.757**	**4.812.192**	**4.834.627**	**4.969.239**	**4.969.239**	**4.969.239**	**4.969.239**	**4.969.239**	**4.969**
IR + CSSL	367.549	375.177	382.805	1.628.517	1.636.145	1.643.773	1.689.541	1.689.541	1.689.541	1.689.541	1.689.541	1.68
NET REVENUE	713.478	728.286	743.093	3.161.240	3.176.047	3.190.854	3.279.698	3.279.698	3.279.698	3.279.698	3.279.698	3.27
Depreciation	3.641.423	3.641.423	3.641.423	-	-	-	-	-	-	-	-	
Financing amortization	1.820.712	1.820.712	1.820.712	1.820.712	1.820.712	1.820.712	1.820.712	1.820.712	1.820.712	1.820.712	1.820.712	
FCL ACIONISTA	**2.534.190**	**2.548.997**	**2.563.805**	**1.340.528**	**1.355.335**	**1.370.143**	**1.458.986**	**1.458.986**	**1.458.986**	**1.458.986**	**1.458.986**	**3.279**
FCLA ACUMULADO	6.284.716	8.833.713	11.397.517	12.738.045	14.093.381	15.463.523	16.922.510	18.381.496	19.840.482	21.299.469	22.758.455	26.03
FCLA DESCONTADO	1.074.744	982.749	898.598	427.134	392.592	360.801	349.270	317.518	288.653	262.412	238.556	48
FCLA DESCONTADO ACUMUL.	- 48.394	934.354	1.832.952	2.260.086	2.652.678	3.013.480	3.362.749	3.680.267	3.968.920	4.231.331	4.469.887	4.95
CBIOs REVENUES												
Biofertilizer REVENUE (USD) - save inorganic acquisition	536.395	536.395	536.395	536.395	536.395	536.395	536.395	536.395	536.395	536.395	536.395	53

Author:
Variar este preço

https://www.bndes.gov.br/wps/portal/site/home/financiamento/produto/fundo-clima-energias-renovaveis/!ut/p/z1/vZLPk5owFMf_Ih44YqIJgr1RaqWKo65rIVx2QgiQjiRsiNj97xvoHnZ2tjq9NJck78e89_28Bwg4ASJpJ0pqhJL0bP8pmT75u0UUh3icLJLxBO4OwXa3D2K0iTA4DgHwLyeEgNzO_wEIIEyaxIQgzWTO2ychWyPMhQ0dOLBSNXdgISSVTNCaS6NaB56FrGjrNlq\

Appendix 4: Estimate of biomethane and bioelectricity productions

Milling cane (TCS)	3.100.000	12.917			931.200	
vinasse (m³)	1.047.600		116.400	m3/mês	3.880	m3/dia
Filter cake (ton)	97.650		10.850		362	ton/dia
Coffee pulp (ton)	192	*to be transported*				
Mucilage (m³)	175	*to be transported*				
Effluent (coffee washing) (m³)	13.025	*to be transported*			86.800	
Processed orange in site (ton)	-					
Orange effluent (ton)	-					
Bovine manure (ton)	-					
Swine manure (ton)	4.529	*to be transported*				
Swine slaughter (units/month)	3300	*to be transported*				
Slaughter effluent (m³)	15492,7	*to be transported*				
115,0	434,7	lts/animal abbated				
1 gallon	3,78	liters				

	Março	Abril	Maio	Junho	Julho	Agosto	Setembro	Outubro	Novembro	Dezembro	Janeiro	Fevereiro	Total Atualizado	
Dias de safra	-	30	31	30	31	31	30	31	30	25	30	28	**327,00**	dias totais
Cana-de-açúcar (mil ton)	-	292,50	395,25	432,43	437,10	437,10	418,50	404,55	282,57	0	0	0	3.100,00	
Torta de filtro ton (35 kg/TC) 100%		10.237,5	13.833,8	15.135,0	15.298,5	15.298,5	14.647,5	14.159,3	9.890,0				108.500,00	
Torta de filtro ton (35 kg/TC) 90% eff		9.213,8	12.450,4	13.621,5	13.768,7	13.768,7	13.182,8	12.743,3	8.901,0				97.650,00	
Distribuição torta de filtro p/co-DA (ton)	*Manutenção anual*	9.213,8	12.450,4	13.621,5	11.014,9	11.014,9	10.546,2	10.194,7	7.120,8	4.859,6	4.859,6	2753,73	97.650,00	
					20% storage	20% storage	20% storage	20% storage	20% storage					
					2.753,7	*2.753,7*	*2.636,6*	*2.548,7*	*1.780,2*	***SOMA***		*0,00*		
										12.472,9				

Densidades dos sólidos:		
filter cake (kg/m³)	Coffee pulp (kg/m³)	anure + effl. slaughter (kg/m³)
450	250	950

AMOUNT OF SUBSTRATES PER MONTH

	MAR	APR	MAI	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	conferir		
vinasse (m³)		133.029	133.029	133.029	133.029	133.029	133.029	133.029	58.200	58.200	0	0	1.047.600		
filter cake (ton)		9.214	12.450	13.622	11.015	11.015	10.546	10.195	7.121	4.860	4.860	2.754	97.650		*to be transported*
Coffee pulp (ton)		0	48	48	48	48	0	0	0	0	0	0	192	192	
Mucilage (m³)		0	44	44	44	44	0	0	0	0	0	0	175	175	
Effluent (coffee washing) (m³)		0	3.256	3.256	3.256	3.256	0	0	0	0	0	0	13.025	13.025	
Swine manure (ton)	377	377	377	377	377	377	377	377	377	377	377	377	4.529	4.529	
Swine slaughter effluent (m³)	1.291	1.291	1.291	1.291	1.291	1.291	1.291	1.291	1.291	1.291	1.291	1.291	15.493	15.493	
Volume wastes (m³/month)	1.756	155.260	165.945	168.547	162.755	162.755	158.221	157.440	75.780	70.755	12.555	7.876		33.413	ton/safra
Volume wastes (m³/day)	#DIV/0!	5.175	5.353	5.618	5.250	5.250	5.274	5.079	2.526	2.830	419	281			

ESTIMATION OF BIOMETHANE PRODUCTION COV ?

DQO (g/L)	SV (g/mL) ou g/g	ref	PBMT (mLCH4/gSV)	ref	PBMT (mLCH4/gSV) Com perda de 15%	
	0,0184	Volpi et al.	548	Volpi et al.	465,8	vinasse
	0,2021	Volpi et al.	900	Volpi et al.	765	filter cake
0,088	0,581	Minon Fuentes 2019	0,053012048	calculado	0,045060241	Coffee pulp
	0,91	Corro 2013	243	Chala et al	206,55	Coffee pulp
	0,8115	Chala et al	289,5	Chala et al	246,075	Mucilage
9,27	0,0061	sua ref	### ##############	calculado	452,10	Effluent (coffee washing)
20-35	0,035	Cuetos et al., 2011	320	Chala et al	272	Swine manure
4,4	0,1702	Bowser and Nelson (2021); Y	491	Yoon et al (2014)	417,35	blood
	0,2564	Yoon et al (2014)	511	Yoon et al (2014)	434,35	intestine residue
	0,2536	Yoon et al (2014)	361	Yoon et al (2014)	306,85	digestive tract content

85%	eff

Average SV (eff. Slaughter)	Average PBMT (effl. Slaughter)
0,227	328,26

METHANE (m³) FROM:

	MAR	APR	MAI	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB		
vinasse	-	1.140.151	1.140.151	1.140.151	1.140.151	1.140.151	1.140.151	1.140.151	498.816	498.816	-	-		
filter cake	-	3.165.568	4.277.575	4.679.939	3.784.396	3.784.396	3.623.358	3.502.579	2.446.493	1.669.602	1.669.602	946.099		
Coffee pulp	-	-	36.174	36.174	36.174	36.174	-	-	-	-	-	-		
Mucilage	-	-	8.734	8.734	8.734	8.734	-	-	-	-	-	-		
Effluent (coffee washing)	-	-	8.980	8.980	8.980	8.980	-	-	-	-	-	-		
Swine manure	3.782	3.782	3.782	3.782	3.782	3.782	3.782	3.782	3.782	3.782	3.782	3.782		
Swine slaughter effluent	101.146	101.146	101.146	101.146	101.146	101.146	101.146	101.146	101.146	101.146	101.146	101.146		
Volume CH4 (m³/month)	104.928	4.410.647	5.576.543	5.978.906	5.083.363	5.083.363	4.868.437	4.747.658	3.050.237	2.273.346	1.774.531	1.051.027	44.002.987	m³/safra metano
Volume CH4 (m³/day)	#DIV/0!	147.022	179.888	199.297	163.979	163.979	162.281	153.150	101.675	90.934	59.151	37.537	132.627	m³ médio/dia

BIOGAS PRODUCTION (55%CH4)	MAR	APR	MAI	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB		
month	190.778	8.019.358	10.139.168	10.870.738	9.242.479	9.242.479	8.851.703	8.632.106	5.545.886	4.133.357	3.226.419	1.910.958	79.814.652	m³ safra biogas
day	#DIV/0!	267.312	327.070	362.358	298.144	298.144	295.057	278.455	184.863	165.334	107.547	68.249		

BIOMETHANE PRODUCTION (m³)

2% loss CH4. Reduces volume due upgrading, from Munoz et al (2015)

96% CH4 content (90% mol according to RESOLUÇÃO ANP Nº 8, DE 30.1.2015)

	MAR	APR	MAI	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB		
month	107.114	4.502.535	5.692.721	6.103.467	5.189.267	5.189.267	4.969.862	4.846.568	3.113.784	2.320.708	1.811.500	1.072.924	44.812.601	m³ safra biomethane
day	#DIV/0!	150.085	183.636	203.449	167.396	167.396	165.662	156.341	103.793	92.828	60.383	38.319		

BIOELECTRICITY (MWh)

Poder calorífico do CH4 MJ/Nm³	*35,8*	
100 MJ	*0,027778*	*MWh*
Effectiveness time (%)	*90%*	
Combustion (machine)	*40%*	*BERNS; SCHNICKE; BOMBONATTI, 2015*
Conversão unidades	*86399,31*	*(MJ/d para MW)*

	MAR	APR	MAI	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB		
Bioelectricity (MJ/day)	#DIV/0!	5.263.372	6.440.007	7.134.828	5.870.465	5.870.465	5.809.668	5.482.779	3.639.950	3.255.432	2.117.606	1.343.813		
MW cap. instalada	#DIV/0!	60,9	74,5	82,6	67,9	67,9	67,2	63,5	42,1	37,7	24,5	15,6		
MW efetivo	#DIV/0!	24,4	29,8	33,0	27,2	27,2	26,9	25,4	16,9	15,1	9,8	6,2	22,0	capacidade instalada média
Bioelectricity (MWh/month)	#DIV/0!	15.790	19.964	21.405	18.199	18.199	17.429	16.997	10.920	8.139	6.353	3.763	157.156	MWh safra

47.147 MWh consumido para operação na saf

ELEGIBLE CBIOs FROM BIOMETHANE

https://observatoriodacana.com.br

https://www.gov.br/anp/pt-br/assuntos/renovabio/renovacalc

RenovaCalc v7 *Cotação Cbios b3* http://estatisticas.cetip.com.br/astec/series v05/paginas/lum web v05 series introducao.asp?str Modulo=Ativo&int Idioma=2&int Titulo=6&int NivelBD=2/

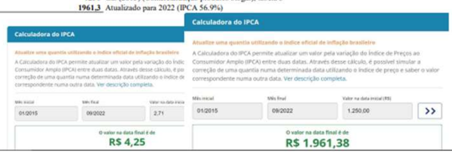
Data from sugarcane mill A (case study)		By RenovaCalc
NEEA (gCO2eq/MJ)	61,8	81,78
FACTOR CBIO	750	
IC (gCO2eq/MJ)	25,6	4,92

	MAR	APR	MAI	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB		
CBIOs amount (un)	0	12.913,16	16.326,58	17.504,59	14.882,69	14.882,69	14.253,44	13.899,83	8.930,25	6.655,73	5.195,34	3.077,12	128.521,40	CBIOs

Biofertilizer REVENUE

	N content (g/kg)	*N total (ton). Year⁻¹*		
vinasse (m³)	1,09	1.137		
filter cake (ton)	1,83	178		
Coffee pulp (ton)	0,03	0,0		
Mucilage (m³)	0,47	0,1		
Effluent (coffee washing) (m³)	12,59	164		
Swine manure (ton)	0,02	0,1		
TOTAL (ton N)		**1.479**		
TOTAL (ton N) x fator disponibilidade		**1.449**		
TOTAL USD . Y^{-1}		**1.162.331**	**$**	**536.395,17**
		COM N DISPONIVEL		COM UREIA

Premissas:		
Fator disponibilidade	98%	Giz (2015), tabela 8, seção 13.1 (Anteprojeto)
N inorg (R$/kg N disp)	2,71	Giz (2015) (Comercialização produtos biogas), tabela 3
N inorg (R$/kg N disp)	**4,25**	Atualizado para 2022 (IPCA 56.9%)
Ureia (R$/ton)	1250	Giz (2015) (Comercialização produtos biogas), tabela 3
Ureia (R$/ton)	**1961,3**	Atualizado para 2022 (IPCA 56.9%)



	P content (g/kg)	P total (ton). Year-1
vinasse (m³)	3	3.143
filter cake (ton)	0,45	44
Coffee pulp (ton)	1,6	0
Mucilage (m³)	0,115	0
Effluent (coffee washing) (m³)	0,063	1
Orange peel (ton)	1,18	

Annexes

Certifications and submissions proceeded

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FABRICIO MENDES

for serving as a reviewer for

WIREs Energy and Environment

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Thank you for reviewing 1 manuscript in 2022

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