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A review of energy generation with biogas derived from sugarcane vinasse in Brazil

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Abstract. *Currently, world ethanol production each year is increasing, and Brazil is the second largest producer, after the USA. Due to high productivity, there is a large generation of residues, and some examples are sugarcane bagasse and vinasse. Vinasse is considered the big environmental passive in the sugar and alcohol industry because it contains a lot of organic matter, besides nitrogen, phosphorus, and sulfur. Nowadays, the main utilization of vinasse is fertirrigation. However, there is a potential for biogas production, because there is a higher chemical oxygen demand. The biogas production obtained from vinasse brings economic and environmental advantages as being a renewable energy source. For the purpose of contributing to the advancement of research and projects on the use of vinasse, this article presents a general review of the production and properties of vinasse and biogas in the Brazilian scenario.*

Keywords: *Vinasse, biogas, energy generation, biofuels*

1. INTRODUCTION

The economic, technical, and environmental viabilization for the use of biofuels for partial or total replacement of fossil fuels has stimulated many projects and much research. Thus, renewable sources and biofuels are increasingly on the rise as substitutes for fossil fuels. One for decreasing costs is to use biofuels as an energy source, rather than treating them as waste (Kolesárová *et al.*, 2011), (Veroneze *et al.*, 2019).

The other discussion is the use of land for generating biofuels instead of food. This causes a dilemma due to the risk of diverting agricultural land or crops to the production of liquid biofuels, which is detrimental to food supply on a global scale. There is disagreement about how significant this is and what is causing it; what the impact is and what should or should not be done about it, and this is currently causing enormous discussion (Demirbas, 2011).

To overcome these challenges, there is the generation of energy from conventional renewable sources and also the use of waste to generate biofuels. There is a great need to make good use of waste materials and use renewable energy sources more and more. Biomass is the primary source of energy resources in the world that can replace fossil fuels (Parsae *et al.*, 2019).

The market implementation of biofuels depends mainly on making them more competitive. One option is to decrease the costs of biofuels as an energy source, rather than treating them as waste (Kolesárová *et al.*, 2011), (Veroneze *et al.*, 2019).

The cost of raw material is an essential factor in the viability of biofuel production. Renewable alcohols are at present more expensive than synthesis of ethanol from ethylene and of methanol from natural gas. Producing biomethanol (from sugarcane juice) with ethanol together may be more economically viable (Demirbas, 2011). The cost of bioethanol in a dry mill plant currently totals US\$ 1.65 / gallon. The size of the plant can decrease the operational costs by 15-20%, (Demirbas, 2011).

Bioethanol can be used directly in cars designed to run on pure ethanol or blended with gasoline to make “gasohol”. Anhydrous ethanol is required for blending with gas, and engines do not need modification when using this blend. Ethanol can be used as an octane-boosting additive in gasoline, and helps to avoid knock (Demirbas, 2011). In Brazil, up to 27% anhydrous ethanol blended in gasoline is permitted.

In Brazil in 2002, the Incentive Program for Alternative Sources of Electricity (PROINFA), had as its primary objectives the diversification of the energy matrix, increasing the security of the electricity supply and also the reduction of greenhouse gas emissions; also to improve the importance of the utilization of organic waste as an energy source (Salomon and Lora, 2009). The supply of energy in Brazil has been changing over the years; the energy obtained from sugarcane products and hydro-electric energy are examples of sources that grow over the years (EPE and de Minas e Energia, 2018).

Some residues in the sugarcane industry are utilized, such as bagasse is being used as fuel in boilers, for vapor generation and cogeneration. Each ton of sugarcane produces about 320 kg of bagasse, where 90% of the challenges is

the disposal of vinasse, the main residue of the sugar and alcohol industry, and also an environmental liability.

The production of energy from the use of a by-product of the process is the most relevant economic factor to add value to what is considered waste, whose final destination would be disposal in the environment (CENBIO, 2001).

Energy aspects are very relevant for the viability of agroindustrial activity (Andrade *et al.*, 2002). Other important issues are new technologies developed for this sector and that the process is for sustainable development (Veroneze *et al.*, 2019).

According to Szymanski *et al.* (2010), the advantages of electric power generation from biogas are strategic: decentralized generation near the point of loading, and economical use of fuel available locally and low cost (process residue).

The review of the literature shows the properties of vinasse and biogas from vinasse. This work also demonstrates energy generation of biogas and its advantages in the Brazilian context.

2. ETHANOL AND VINASSE

Sugarcane is one more essential commodity in the world (FAO, 2012) and is generally processed to produce sugar and/or ethanol. Sugarcane is cultivated in more than 100 countries around the world (Evans *et al.*, 2010), and production in 2018 was 1533.83 ton/m^3 , of which Brazil was responsible for about 48% of this production.

The USA will continue to be the most prominent producer of ethanol with 45%, followed by Brazil with 31%, then the EU with 8%, China, India, and Thailand; the total global production will be 158 billion liters. Considering that each liter of ethanol generates about 9-14 liters of vinasse, foresee the 6 trillion liters of residue that will need to be managed in 2023 (Carrilho *et al.*, 2016).

The National Ethanol Program (Proálcool) was created in Brazil to decrease the import of petroleum during the 1972 crisis, which increased Brazil's energy security and positioned it as the largest ethanol producer for decades (Goldemberg *et al.*, 2008). According to the National Energy Plan (PEN 2030), the vehicle fleet powered by ethanol surpassed 75% in 1986 (Pazuch *et al.*, 2017).

Brazil has over 300 active sugarcane biorefineries (Reis *et al.*, 2017). There are three types of sugarcane processing plants: plants that produce only sugar, plants with annexed distilleries to produce ethanol and sugar, and autonomous plants that produce only ethanol. 68% are annexed distilleries, and the autonomous represent 28% of total sugar cane processing in Brazil (Bernal *et al.*, 2017). The production of vinasse in 2023 in the USA is predicted to be 711 billion liters, and that of vinasse in Brazil is predicted to be 490 billion liters Carrilho *et al.* (2016).

Figure 1 presents the flow of the ethanol production chain. According to CETESB (1985), vinasse is the liquid derived from the distillation, which is the result of the fermentation of the juice of the sugarcane or molasses.

According to Navarro *et al.* (2000), if one distillery with a daily production of 100,000 liters of ethanol consumed $1,128.6 \cdot 10^6$ kJ/day (11,286 kcal/l anhydrous ethanol) for distillation and produced as waste approximately 1300 ton/day vinasse with a solids content of about 9% d.m, for each gallon of ethanol produced, up to 13 gallons of vinasse would be generated (Nitayavardhana and Khanal, 2010). Brazilian sugarcane mills, for each liter of ethanol, approximately 10-15 L of vinasse are produced (Bernal *et al.*, 2017),(Moraes *et al.*, 2015) (Cavalett *et al.*, 2012), leaving the distillation column at a temperature of 85-90 °C (Wilkie *et al.*, 2000).

Essential characteristics of sugarcane vinasse include low pH, high levels of BOD, COD, potassium, sulfate, and color Wilkie *et al.* (2000). Even though some difference in its composition, vinasse is mainly formed of 93% water and 7% solids. 75% of these solids correspond to organic matter.

Some properties, such as COD and pH, depend on the type of raw material and other factors, such as temperature. Sugarcane vinasse has a higher chemical oxygen demand (COD) compared with vinasse obtained from different materials such as sugar beet, sweet sorghum, grape, and agave (Parsae *et al.*, 2019).

Vinasse is produced in many countries as a byproduct of ethanol from different raw materials: sugarcane in South America (Hannon and Trenkle, 1990), beet, wine and fruit in Europe, and corn and tequila in North America (Gamboa *et al.*, 2012), (Christofoletti *et al.*, 2013). Gamboa *et al.* (2012), reviewed the different vinasse compositions and treatments available. According to these authors, the characteristics of vinasse depend on the raw material (biomass) used for the production of ethanol. Table 1 shows these properties. In Brazil, vinasse is obtained from cane molasses and sugarcane principally.

COD values vary significantly for these same raw materials presented in the work of Wilkie *et al.* (2000) work: fresh beet and molasses with 38 or 65 g/l, cane melon with 45-113 g/l and cane juice with 12-25 g/l and corn with 37 - 56 g/l. From this raw materials, cane melasse generates $50 \cdot 10^6$ l/year of ethanol, followed by cane juice at $24 \cdot 10^6$ per annum, corn at $7-70 \cdot 10^6$ per annum, and beet at $18.8 \cdot 10^6$ per annum. Cane molasses is the raw material that has the best COD/liter ethanol yield.

In sugarcane vinasse, there is a higher content of sulfate, potassium and iron than other sources of vinasse (Gamboa *et al.*, 2012). Cane molasses stillage exhibits the highest levels of biochemical oxygen demand (BOD), COD, COD/BOD ratio, potassium, phosphorous and sulfate, while cane juice stillage exhibits the lowest levels of COD and BOD (Wilkie *et al.*, 2000). The use of $150m^3/ha$ vinasse as fertilizer in fields is equal to 61 kg/ha of nitrogen, 40 kg/ha of phosphorus, 343 kg/ha of potassium, 108 kg/ha of calcium, and 80 kg/ha of sulfur (Salomon and Lora, 2009).

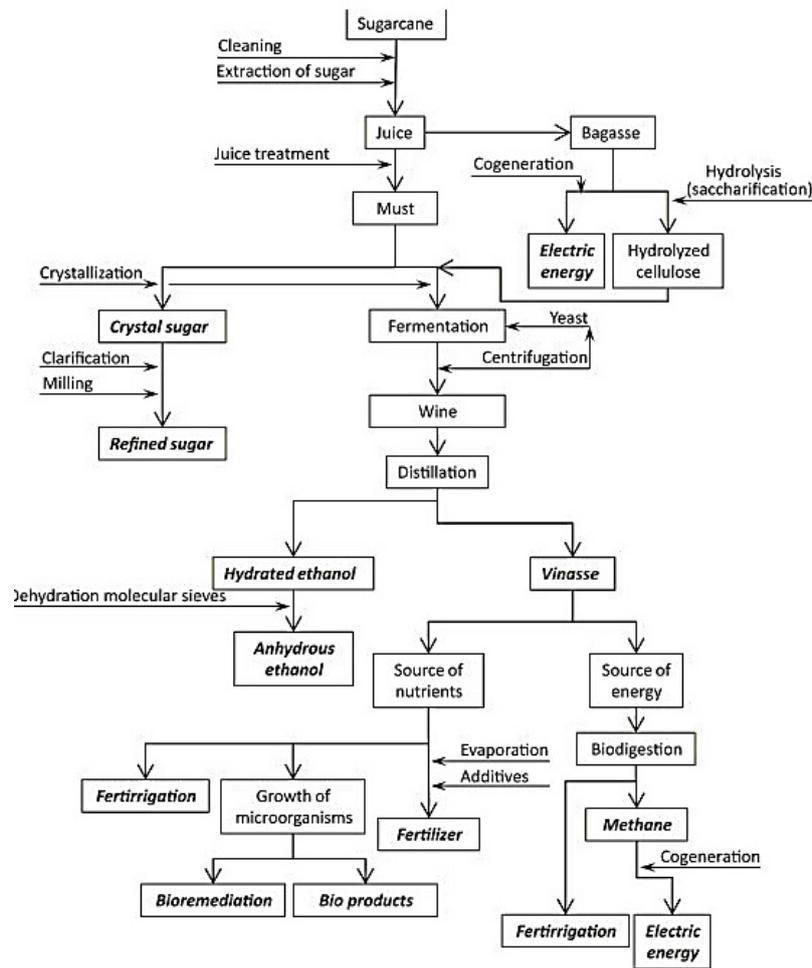


Figure 1. Flowchart of the main alternatives for the use/discharge of sugar cane vinasse (Carrilho *et al.*, 2016)

COD is an essential property because it is directly related to the generation of biogas, and the amount of methane that this biogas contains. From 1 gCOD at standard conditions (0 °C and 1 atm), 0.35L of methane gas can be produced; therefore, 1 gCOD can produce 0.395L of methane gas at 35°C and 1 atm (Syaichurrozi, 2016).

Many studies and projects utilize the main values for the properties of sugar cane vinasse as: pH 4, COD 14833 mg/l, BOD 23801 mg/l, potassium 2.2 kg/m³, organic load 285 gDQO/L ethanol, total solid 3.2%, temperature (without heat recuperation) (Fiesp *et al.*, 2009). Carrilho *et al.* (2016) shows that the COD coming from molasses is 65000 mg/l, the juice varies between 1500-3300 mg/l and mixed molasses and juice 45000 mgO₂/L.

The pH value during anaerobic biodigestion (AD) depends on the production of Fatty Acid Methyl Esters (FAME) and the degradation of the raw material to form methane. The bacteria that produce methane grow better in the range pH between 6.6 and 7.4. For biodigestion with one phase the pH (effluent) is 8.5, and for two phases (pathogenesis) the value is 5.1, and for two phases, methanogenesis the pH is 8.1 (Fuess and Zaiat, 2018). Wilkie *et al.* (2000) utilized the pH 6.6. The vinasse studied by Souza *et al.* (1992), was collected in the São Martinho plant in Brazil, presented the pH=3.9 and the COD 31.5 g/l, e SO₄ 0.42g/l.

The COD varies 20.000 a 35.000 mg/L, while your pH stands between 3.7 and 5 Szymanski *et al.* (2010). In the work of the Mariano *et al.* (2009), they utilized the value OD 32000 mg/l, and pH 3.85, the concentration of the organic matter 3.96%, and this vinasse was from a plant in Araras-SP, Brazil.

According to Moraes *et al.* (2014), and CETESB (1985), for example, the COD of organic matter content can vary between 10 and 65 g/L. There is data that COD depends on the type of plant; in an annexed distillery; the value is 30.9 g/l, and in an autonomous distillery it is 21 g/l (Fuess and Zaiat, 2018).

The wastewater of ethanol distillation (vinasse or stillage) is produced and discharged without treatment directly into surface water (rivers, streams or lakes) or in some cases is used for crop irrigation. Vinasse has an acid pH (3–4) and a high content of organic matter (35,000–50,000 mgO₂/L as BOD or 100,000– 150,000 mg O₂/L as COD), which is usually toxic and recalcitrant; consequently, this effluent can produce severe environmental impacts such as: anoxia, eutrophication, and death of aquatic life (Cruz-Salomón *et al.*, 2017).

Vinasse is a suitable residue for energy extraction because it has a high COD value (Gamboa *et al.*, 2012). In this

context, anaerobic biodigestion (AD) of vinasse comes as an alternative treatment for this byproduct, and the economic consequences of this use: the production of methane and its exploitation as a source of thermal and / or electric energy

At the same time, vinasse can pollute soil and groundwater if disposed of in the environment because of its high organic demand of 100-130 g/liter of carbon (COD) (Goldemberg *et al.*, 2008). The content of dissolved organic matter in vinasse is high, varying from 10,973 to 14,801 mg/L of dissolved organic carbon (Christofoletti *et al.*, 2013), (Carrilho *et al.*, 2016). This high organic content may cause problems in groundwater through an increase in nutrient supply (Gamboa *et al.*, 2012).

Table 1. Properties the vinasse the different raw material (Christofoletti *et al.*, 2013).

Parameters	Vinasse			
	Sugar Cane	Grape	Beet	Sweet Sorghum
pH	3.9	2.9	5.1	4.5
BOD	5046	18900	78300	46
COD	13380	n/D	n/D	n/D
Potassium	2056	118–800	10.000 a 10.030	n/D
Sodium	50.2	n/D	3.79	n/D
Sulfate	710	120	0.62	n/D
Calcium	719	n/D	0.71	n/D
Magnesium	237	n/D	1.23	n/D
Total Phosphorus	190	83	91	1990
Hardness	2493	n/D	n/D	n/D
As	n/D	n/D	n/D	n/D
Ba	0.41	n/D	n/D	n/D
Cd	n/D	0.05–0.08	<1	n/D
Cr	0.04	n/D	n/D	n/D
Cu	0.35	0.2–3,26	2.1-5	37
Hg	0.0019	n/D	n/D	n/D
Mo	0.008	n/D	n/D	n/D
Ni	0.03	n/D	n/D	n/D
Pb	n/D	0,55–1,34	<5*	n/D
Se	n/D	n/D	n/D	n/D
Zn	1.66	n/D	n/D	n/D

Another problem is that transport is complicated through pumps and tubes, it being preferable to transport vinasse by way of open channels. The challenge to this practice is the emissions that are associated with these channels; these emissions can reach 455 gCO_2eq/L (Bernal *et al.*, 2017). In general, scientific study in this area can be very controversial. In the study of Moraes *et al.* (2014), the methane emissions of the soil were not observed after the discarding of the vinasse in the area of sugarcane cultivation, during 15 days of the observation. However, most CH_4 emissions occurred in the open distribution channels. In this case, the environmental impact would be more damaging because the global warming potential of nitrogen monoxide (N_2O) is 296 times higher than that of carbon dioxide (CO_2) (Moraes *et al.*, 2014).

The Table 2 show the advantages and disadvantages that each application the vinasse.

A medium-sized ethanol plant, producing 106 l ethanol / year generates stills with a pollution level equivalent to the sewage of a city with a population of 500,000 (Wilkie *et al.*, 2000). The polluting potential of vinasse gives a mean dose of 500 m^3 of alcohol/day, which is equivalent to the consumption of a city with 1,700,000 inhabitants (Fiesp *et al.*, 2009). Currently, sugar and ethanol plants do not have a varied mode of value-added processing of co-products, especially vinasse, which is a solution after recovery of ethanol (Nair and Taherzadeh, 2016).

Among the alternatives for the use of vinasse developed worldwide, fertirrigation is the most used, since it requires low initial investment (tubes, pumps, trucks and settling tanks), low maintenance costs, fast application, does not require sophisticated technologies and increases crop productivity (Camargo *et al.*, 2009). This practice has totally or partially replaced the use of chemical fertilizers, especially those containing phosphorus (Christofoletti *et al.*, 2013). Terrestrial application, known as fertirrigation (fertilization + irrigation), is the current disposal method in Brazil that is blamed for contamination of groundwater in several areas (Goldemberg *et al.*, 2008).

In Brazil, specific legislation controls the application of sugarcane residues as fertilizer in agriculture, especially the relationship to soil contamination by metals (CETESB, 2015).

Table 2. Applications of vinasse: advantages and disadvantages (Christofoletti *et al.*, 2013)

Process/final use	Advantages	Disadvantages
Fertirrigation	Inexpensive	Expensive transportation
	Easy to be implemented	Unknown long-term effect
Animal Feed	Inexpensive Easy to be implemented	Little studied
Biodigestion/Biogas	Energy production	Expensive
	BOD reduction Effluent used as fertilizer	High technology
Combustion in Boilers	Complete disposal	Little studied
	Energy production Recovery of potassium in ashes	Small-scale tests
Protein production	Food	Expensive
	No residues	Little studied

2.1 BIOGAS

According to Bernal *et al.* (2017), the volume ratio of CH_4 present in the biogas varies from 50% to 75%; the remainder consists mainly of carbon dioxide (CO_2) and traces of other gases, such as hydrogen sulfide (H_2S) and water vapor (H_2O). The energy potential of biogas varies depending on the quantity of methane present, which determines its calorific value (Salomon and Lora, 2009). The LHV of the biogas is obtained according to the formulation of Okamura (2013), where it presents a constant as a function of the quantity of methane, $LHV_{bio} = 35.7134 * \%CH_4 [MJ/Nm^3]$. Segundo Parsaee *et al.* (2019) o LHV do methane is 55.5 MJ/kg.

The ethanol/biogas ratio ($1 m^3$ of ethanol = $185 m^3$ of biogas - 60% methane), the methane production potential can be estimated from the vinasse generated by the Brazilian production of ethanol from sugarcane (Salomon and Lora, 2007). In this context, vinasse comes up as the biomass with a potential for producing energy.

In the generation of biogas by means of vinasse, there are some factors that vary in the literature and influence the calculation of biogas generation, such as reactor yield (UASB), this being mesophilic or thermophilic, whether the ethanol plant is annexed or autonomous, because this interferes in COD and consequently the efficiency of biodigestion, and whether AD is in one phase or two phases.

Biomethane, which is purified biogas, is competing with natural gas from fossil fuel, i.e. petroleum, and it must contain at least 96.5% of methane, and at most 0.5% of oxygen, that the gases yield a maximum of 3% of CO_2 , $CO_2 + N_2 + O_2$ in the mixture and can reach a maximum of 3.5%, and the sulfur content should be, at most, $70 mg/m^3$ and H_2S $10 mg/m^3$. Currently, Itaipu generates biomethane from grass pruning and human waste, to be used in heavy vehicles.

Although the composition of vinasse is different because it has a content of AD, which produces biogas with a high sulfur content (Parsaee *et al.*, 2019), which causes corrosion damage to the burners due to the production of SO_2 . Removal of SO_x from biogas can be accomplished, among other technologies, through physical processes such as sulfur-specific membrane filters, or through biological processes (Barrera *et al.*, 2016). Using AD in sugar cane is characterized according to the number of phases, the temperature process, and the reactor project (Rajeshwari *et al.*, 2000).

The sulfur content of vinasse is between 4 to 10 times higher than the optimal concentration for the production of biogas (Rohstoffe, 2012). High sulfur makes the H_2S , that causes problems for the equipment and the formation of biogas because it inhibits the bioavailability of trace elements (Schmidt *et al.*, 2014). Therefore the removal of H_2S High sulfur makes the H_2S , that causes problems for the equipment and the formation of biogas because it inhibits the bioavailability of trace elements (Wilkie *et al.*, 2000).

Vinasse produces biogas rich in H_2S , and that are some techniques most used for its removal, as follows:

- By membranes (physical barrier): this has a generation efficiency of 90 to 96 % of methane at the end of the process. The disadvantage is that there is still a concentration of methane at a shallow temperature in the residues. The difficulty is the use of extra equipment and high energy consumption, and it generates biogas with 97% methane (Liu *et al.*, 2015);
- By membranes (physical barrier): this has a generation efficiency of 90 to 96 % of methane at the end of the process. The disadvantage is that there is still a concentration of methane at a shallow temperature in the residues. The difficulty is the use of extra equipment and high energy consumption, and it generates biogas with 97% methane (Khapre, 1989);

- Absorption purification, where purification occurs by pressure difference. The drawbacks are that the process is more expensive and requires pressure and temperature canisters and generates biogas with 97% methane (Hullu *et al.*, 2008);
- By biological purification. This process occurs by using plants that perform photosynthesis, the disadvantage of which is that there are few studies, and it generates biogas with 87 to 97% methane (Kao *et al.*, 2012).

The Figure 2 show the schematic of a biogas plant for generating electric energy.

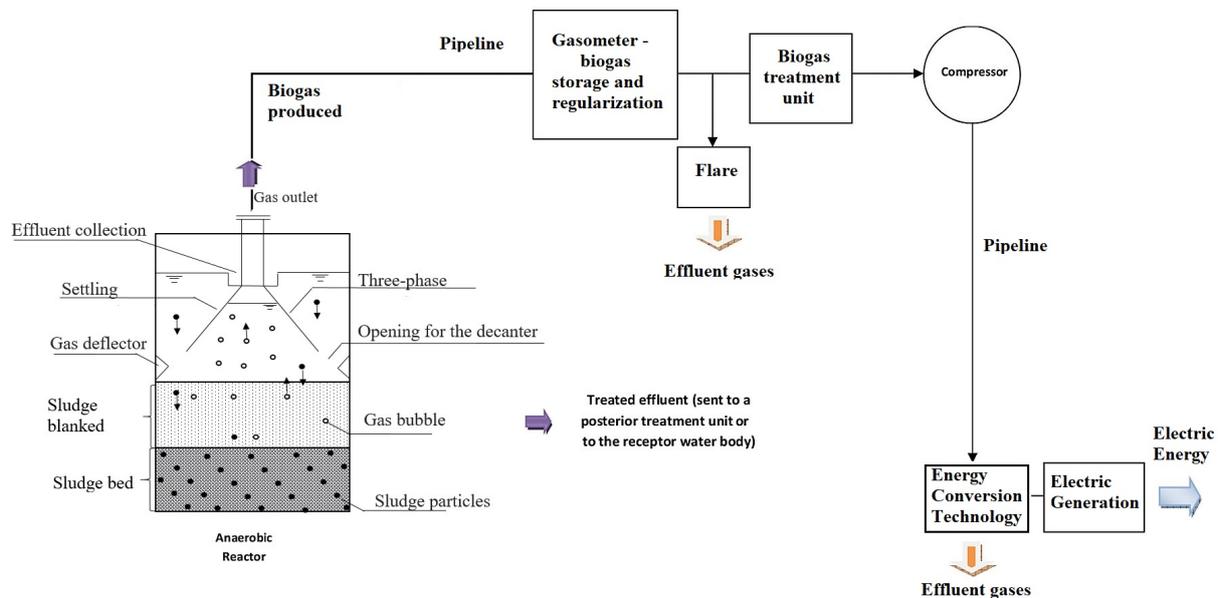


Figure 2. Schematic of a biogas electricity generation plant Modify (Bernal *et al.*, 2017) and Chernicaró (1997)

In the sugar-alcohol industry, the options for the use of biogas are as follows (Szymanski *et al.*, 2010): to burn, in its entirety, in the boiler for steam generation and cane grinding; use part of the biogas in substitution for the fuels used in the agroindustry during the harvest period (within the limits of the plant); use all the biogas to operate a gas turbine coupled to an electric generator.

An ethanol plant generally produces 85 liters of bioethanol per liter of sugarcane. The average production of vinasse is $12m^3/m^3$ of bioethanol and $14.23m^3$ of methane produced from the digestion of $1m^3$ of vinasse (Pazuch *et al.*, 2017). From 4000 tons of sugarcane, $500m^3$ of bioethanol, 720 tons of bagasse, and 4000 tons of vinasse are typically produced (Pazuch *et al.*, 2017), (Parsae *et al.*, 2019), (Meyer *et al.*, 2011). 1 gCOD of vinasse produces about 0.395l of methane ($35^{\circ}C$ and 1atm). In this way the generation of biogas for m^3 of wine is $10-26.4m^3$ with 60% CH_4 . $1 m^3$ of biogas is able to produce 1.5 to 10 kW of energy with motorcycle generator, ie a power of $6.5 kWh/m^3$ (Parsae *et al.*, 2019). The total energy in vinasse is about 18% of the energy produced by bioethanol produced in the plant Meyer *et al.* (2011).

Based on the Environmental Sanitation Technology Company CETESB (2006), Bernal *et al.* (2017), presented the basic components for the deployment of a biogas energy recovery plant. These components are: Burner: used for flue gas, which is not used for power generation; Gasometer: used for storage and gas flow regulation; the gasometer is important for the maintenance of power generation equipment. Compressor: used to collect gas and pump the gas through the pipe collection. Treatment Unit: used to remove impurities (H_2S , H_2O and siloxanes) and expand the methane content (CH_4) of biogas, increasing its calorific value and decreasing the risk of problems with the plant equipment. Internal Combustion Engine: transforms the chemical energy in the biogas into mechanical energy, working coupled to a generator. Pipeline: promotes biogas and transport in the system. Upflow Anaerobic Sludge Blanket Reactors (UASB) reactor: performs the anaerobic digestion of vinasse, generating methane gas.

The biodigestion can be realized in one tank is monophasic, where it occurs the hydrolyze and methanization together. Or two phases, where the hydrolyze and methanization happened and different tanks.

The biodigestion can be carried out in a monophasic tank, where the hydrolysis and methanization occur together; or in two phases, where the hydrolysis and methanization occur in different tanks.

Anaerobic biodigestion has received more attention only since the development of high-performance reactors, such as the UASB, which is the type most appropriate for vinasse. In this type of system, the sludge at the bottom of the reactor adsorbs most of the organic matter, while gas is produced in the reaction compartment as bubbles during the anaerobic process, and which is removed to a separate compartment (Christofolletti *et al.*, 2013). Biogas generation will be utilizing UASB, with the mesophilic temperature around 32 to $37^{\circ}C$ (Bernal *et al.*, 2017). According to Pazuch *et al.* (2017), the

anaerobic process is feasible under two different temperature ranges: mesophilic, between 10 and 42°C, and thermophilic, above 42°C. As stated by Souza *et al.* (1992), the UASB is more suitable for treating vinasse. This technology consists of a tank in which the effluent in natura is injected into the lower part, crossing an upwardly flowing sludge blanket consisting of granules of microorganisms (Bernal *et al.*, 2017).

The energy efficiency of the biogas produced from the vinasse in reciprocating combustion engines is 29%, while it is 32% in the gas turbines and micro turbines (Salomon *et al.*, 2011),(Parsaee *et al.*, 2019).

Another consideration is the technology utilized to convert the biogas into electric energy. There are variations was observed in the value of the engine efficiency, which significantly influences the energy generated by the biogas. In the work of Bernal *et al.* (2017) the amount used was 33% for a stationary engine, Parsaee *et al.* (2019), adopted 38% for a stationary engine, Szymanski *et al.* (2010) 35% for SI and Neto (2016) was 40% and did not measure engine type, this variation influence after in the prediction the electric energy generation.

The energy values produced from the vinasse biogas with a 25% efficiency (in the spark ignition engines, Brayton) are 22, 22, 31, and 34 kWh/t sugarcane for the condensing/extraction steam turbine, the biomass integrated gasification/gas turbine, the biochemical process (for example: acid hydrolysis, enzymatic hydrolysis, biodigestion), and the thermochemical process (for example: fast pyrolysis, gasification and gasification associated with a syngas conversion process, such as the Fischer-Tropsch (F-T) synthesis), respectively (Leal, 2007).

The production of biogas from the vinasse and the use of produced solids as fertilizers are evident in Brazil, and India (Meyer *et al.*, 2011). The vinasse has a significant potential for biogas production due to the higher organic content (Mota *et al.*, 2013), (Yono *et al.*, 2013), (Fuess and Zaiat, 2018). Biogas production from the vinasse is an economically viable process (Pazuch *et al.*, 2017), (Fernandes *et al.*, 2017), (Nogueira *et al.*, 2015).

The first production of biogas from bagasse was in the 80s (Prasad and Shih, 2016),(Fuess and Zaiat, 2018). Due to the lack of lignin, the production of biogas from the vinasse is more straightforward (Syaichurrozi, 2016) and faster than with other materials; for example bagasse (Janke *et al.*, 2016). The first industrial application in Brazil was in the 90s and consisted of an upward flowing anaerobic sludge manta reactor (UASB) at the São Martinho power plant with of 5,000 m³ (Souza *et al.*, 1992).The biogas generated from the UASB reactor was used in the drying process of the yeast.

The Table 3 show the equivalence of biogas with other fuels and the vehicle type.

Table 3. Data used for the calculation of vehicle fleet supplied with biogas according to vehicle type (Moraes *et al.*, 2014).

Fuel	Vehicle	Efficiency [km/L]	Average use [km/vehicle.d]
Diesel Oil	Light truck	7.6	50
	Medium truck	5.6	188
	Heavy-duty truck	3.2	362
	Double trailer truck	1.2	188
	Multi-trailer	1.1	212
Gasoline	Flex-fuel car	12	50
Ethanol	Flex-fuel car	8	50

According to Neto (2016) Brazil already has some ethanol plants with anaerobic biodigestion of vinasse, e.g at the São a Martinho plant, witch operated with a thermophilic UASB reactor since 1985. Two pilot units using biodigestion and vinasse concentration were installed at the São Francisco (BA) plants in 2008 and at the Santa Candida plant in 2010. The JB/CETREL plant uses a biodigester and a reactor, generating around 8870kW in 2012.

The energy potential of Rio Grande do Sul in 2013 using residues from the sugar and alcohol industry was 167.87TWh; bagasse was responsible for 44% and straw for 49%, although the biogas production potential of vinasse was higher than that of straw and bagasse Neto (2016).

In São Paulo there are many plants that generate biomethane, small plants with up to 210⁶Nm³, medium-sized plants that produce from 2 to 610⁶Nm³ and a large plant where production is greater than 6 10⁶N m³. Ribeirão Preto is the city that generates the most with 13.9% of the state's generation.

The main obstacles to the use of biogas in Brazil are (Salomon and Lora, 2009), (Moraes *et al.*, 2015): high investment costs, insufficient funding and little research in the area of anaerobic digestion; lack of a national biogas program, specific financing and government incentives; the difficulties faced by small biogas plants in the sale of their carbon credits; lack of information and financing for farmers, the need to define biodigestion technology for each case separately; lack of specialized literature for the selection and evaluation of economic viability.

The advantages of biogas production from vinasse can be summarized as follows :

1. Contributing to the energy sector and reducing the disadvantages of fossil fuels, in which the toxic gases (mainly sulfur dioxide and nitrogen oxides) generated in burning biogas are less than 90% (Parsaee *et al.*, 2019);
2. Complete burning of biogas in boilers and producing the steam needed for the operation in the sugarcane industry

(7–9%). In this case, bagasse can be used for other purposes with higher values (Nogueira *et al.*, 2015), (Gamboa *et al.*, 2012), (Moraes *et al.*, 2014);

3. Possibility of using a third of the produced biogas as fuel in the agricultural industry after for removal processes of hydrogen sulfide and carbon dioxide gases (Nogueira *et al.*, 2015);
4. Using the total biogas produced and operating a gas turbine connected to a power generator can produce 2.5 times as much as the total electricity required for a plant or power distillery (Nogueira *et al.*, 2015), Moraes *et al.* (2014);
5. Application in all types of vehicles and urban buses (Moraes *et al.*, 2014);
6. Application in combined heat and power (CHP) systems Janke *et al.* (2016);
7. Application in distillation and vaporizing bioethanol Moraes *et al.* (2015);
8. Replacing diesel fuel in agricultural machinery and harvesters of sugarcane (Moraes *et al.*, 2014), thus reducing 40% of the required diesels (Reis *et al.*, 2017);
9. Providing energy needed for yeast drying (Reis *et al.*, 2017) ;
10. Using large-scale reactors in alcohol-producing factories can provide the electrical energy need of 130,000 people(Reis *et al.*, 2017) .

Studies show that the IRR per year when you have only one sugarcane mill at this rate is 11.9 % and the cost of anhydrous ethanol was 0.379US \$/l. For plants with electricity generation this rate increases to 12.2 % with the cost of ethanol being 0.365 US\$/l. If the plant sells the biomethane this rate rises to 12.6 and cost 0.341 (Moraes *et al.*, 2015).

In the study by Fuess and Zaiat (2018), there is an investment comparison that uses anaerobic digestion in one or two phases. In this study, it was verified that the two phases have a higher cost of investment and the costs of biogas generation are lower for even that of one phase.

In the study by Bernal *et al.* (2017) shows the comparison of the cost between autonomous and annexed plants. The autonomous plants present a cheaper initial investment which can be added to the same mass of ethanol, and NPV (10^6 USD) is higher. In addition, the autonomous plants produce more vinasse, from the same mass of sugar cane.

3. Conclusions

This bibliographic review focused on the production of sugarcane vinasse and consequently on the potential of biogas generation from this raw material and highlighted the most relevant properties of vinasse for the production of biogas and biomethane. As vinasse has a high COD, this property is one of the main advantages for the production of biogas. Currently, in Brazil, vinasse is used in fertirrigation, which is its most common use, but it results in several disadvantages. The best use of vinasse is in the generation of biogas for producing thermal or electrical energy in the plant and the excess electric energy can be sold. One of the obstacles to using this biogas is the H_2S present in vinasse, which compromises the quality of the biogas, but this review also presented measures for the removal of H_2S , which are viable for biogas to become a biofuel. Purified biogas (99% CH_4) can also replace natural gas. Nowadays, the best technology, from the economic point of view, is found in the literature for the conversion of biogas into electricity for internal combustion engines. In the economic studies carried out in the Brazilian context, the use of biogas in power generation plants proved to be economically advantageous, in addition to using a large environmental liability of the sugar and alcohol industry energetically.

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