Chapter

Physicochemical Properties of Sugarcane Industry Residues Aiming at Their Use in Energy Processes

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Abstract

According to the US Department of Agriculture, sugarcane global production for marketing year (MY) 2020/21 will forecast up 22 million tons in comparison with 2019/2020 MY, reaching 188 million tons (raw value), due to higher production in Brazil, India and Thailand. These countries alternate sugarcane uses for obtaining sugar, ethanol and other products, generating near to 152 million tons of residues. In a circular economy context, the reuse of the sugarcane industry by-products is desired. Nowadays, bagasse and, sometimes, straw are used for energy recovery through combustion, while filter cake and vinasse are commonly used for soil fertilization. However, while bagasse and straw present potential for energy recovery through the thermochemical route, vinasse and filter cake are better applied in anaerobic digestion processes to produce biogas and biofertilizer. These treatments, when correctly employed, can improve the performance of sugarcane industry by diversifying its energy sources and products. For this, the correct design of equipment and processes is essential, which requires the knowledge of physical and chemical properties of sugarcane industry's by-products. In this context, the chapter goal is to present an updated literature review for these properties, considering their use in energy recovery processes.

Keywords: waste-to-energy, agricultural wastes, physicochemical characterization, bagasse, sugarcane straw, vinasse, filter cake

1. Introduction

According to the United States Department of Agriculture, sugarcane global production for marketing year (MY) 2020/21 will forecast up 22 million tons in comparison with 2019/2020 MY, reaching 188 million tons (raw value), due to higher production in Brazil, India, and Thailand [1]. These countries alternate sugarcane uses for obtaining sugar, ethanol and other products, generating near to 152 million tons of residues.

It is estimated that only one-third of the energy potential of sugarcane is derived from its juice [2, 3], which has been efficiently used in the production of sugar and first-generation ethanol. The remainder of the energy potential is associated with the sugarcane bagasse and straw, which represent approximately two thirds of the crop energy potential [2–4].

In this context, Brazil is a world leader in renewable electricity generation and increased the focus on electricity generation from sugarcane biomass over the last few decades, driven especially by the increasing price of electricity sold to the grid, public–private initiatives and specific policies to encourage sales of surplus electricity [5].

Initially, electricity was generated only to meet the self-consumption supply of the sugarcane mills, but with a modernization of cogeneration systems and the growing use of bagasse and, in some cases, straw, many sugarcane mills have become net exporters of electricity [6]. In fact, cogeneration has become one of the most efficient technologies for the realistic use of primary fuel to produce electricity and heat [7]. Thus, since 2013, surplus electricity offered to the grid by the sugarcane sector has been greater than that used for self-consumption (i.e., in 2019, about 61% exported to the grid versus 39% for self-consumption; **Figure 1**).

However, although Brazilian mills already recover energy from bagasse trough cogeneration systems, there are other residues from sugar and ethanol production process that can also be valorized by recovering their energy: straw, vinasse, and filter cake. They can be used in energy conversion processes, such as the production of biofuels or in cogeneration processes, and also as a source of carbohydrates from other biomolecules of commercial interest, such as second generation ethanol, xylitol, enzymes, organic acids, proteins, and other bioproducts of industrial interest [8].

Nowadays, bagasse and, sometimes, straw are used for energy recovery through combustion, while filter cake and vinasse are commonly used for soil fertilization. The use of these residues as energy sources depends on their chemical and physical properties. In this context, this chapter has the main objective of presenting an updated literature review for these properties of the main sugar and alcohol industry's by-products, considering their use in energy recovery processes.

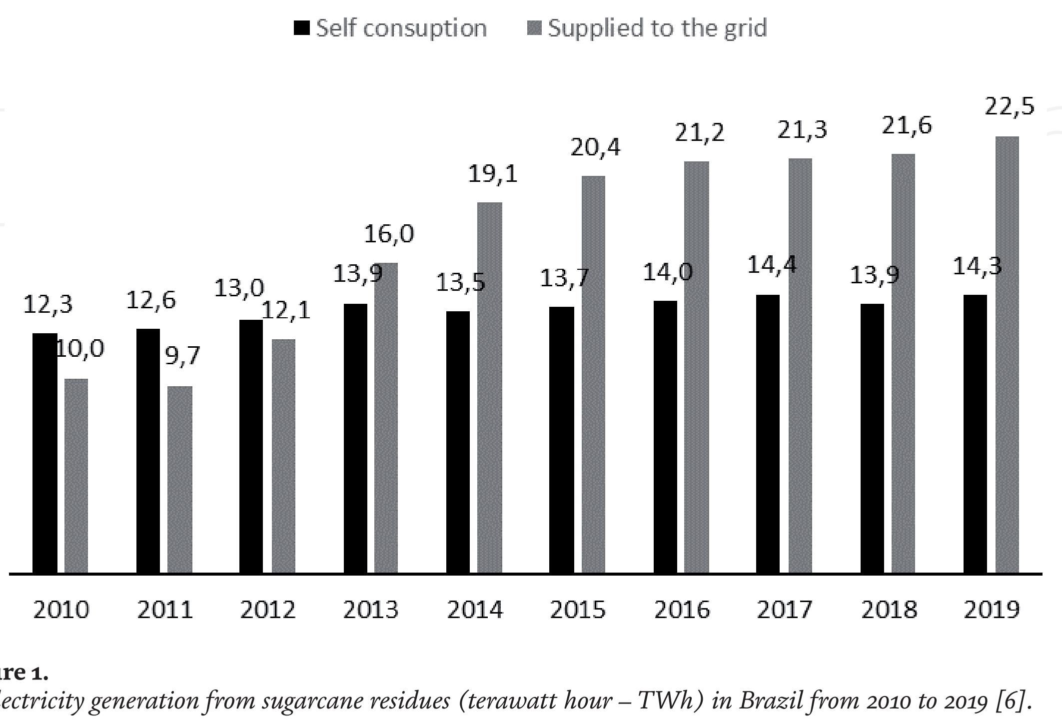

Figure 1.
Bioelectricity generation from sugarcane residues (terawatt hour – TWh) in Brazil from 2010 to 2019 [6].

2. Sugar and alcohol production process and its by-products

The main residues from sugar and alcohol production are straw, bagasse, vinasse and filter cake. A simplified scheme of sugar and ethanol production from sugarcane is shown in **Figure 2**, where the generation of each residue can be seen.

The straw, also called trash, is an agricultural waste composed by tops and leaves of the sugarcane. Sugarcane straw comes from its mechanized harvest, as shown in **Figure 2**, and its production (on a mass basis) depends on some factors such as the harvesting system, the height of the tips, the sugarcane variety, the age of the crop (cutting stage) besides soil and climate conditions, among others [9]. Some authors reported that straw production varies between 10 and 18 ton/ha (dry basis) and the ratio straw (dry basis)/stalk (wet basis) between 11 and 17% [4].

The straw used to be burned during the manual harvest, but, since the 2010/2011 harvest, the mechanization started to be disseminated. In this process, the green and dry leaves and the tips of the sugarcane are cut and mixed in the extractor. With this, part of the straw is left at the field, for soil protection, and part of it is carried to the mills, together with the sugarcane with levels of impurity that vary according to the harvesting system used [10].

Several studies indicate that sugarcane fields contain an average of 8–30 ton·ha^{-1} dry mass of straw and its production varies according to crop variety, vegetative stage, edaphoclimatic conditions and management practices [5]. Straw has similar properties

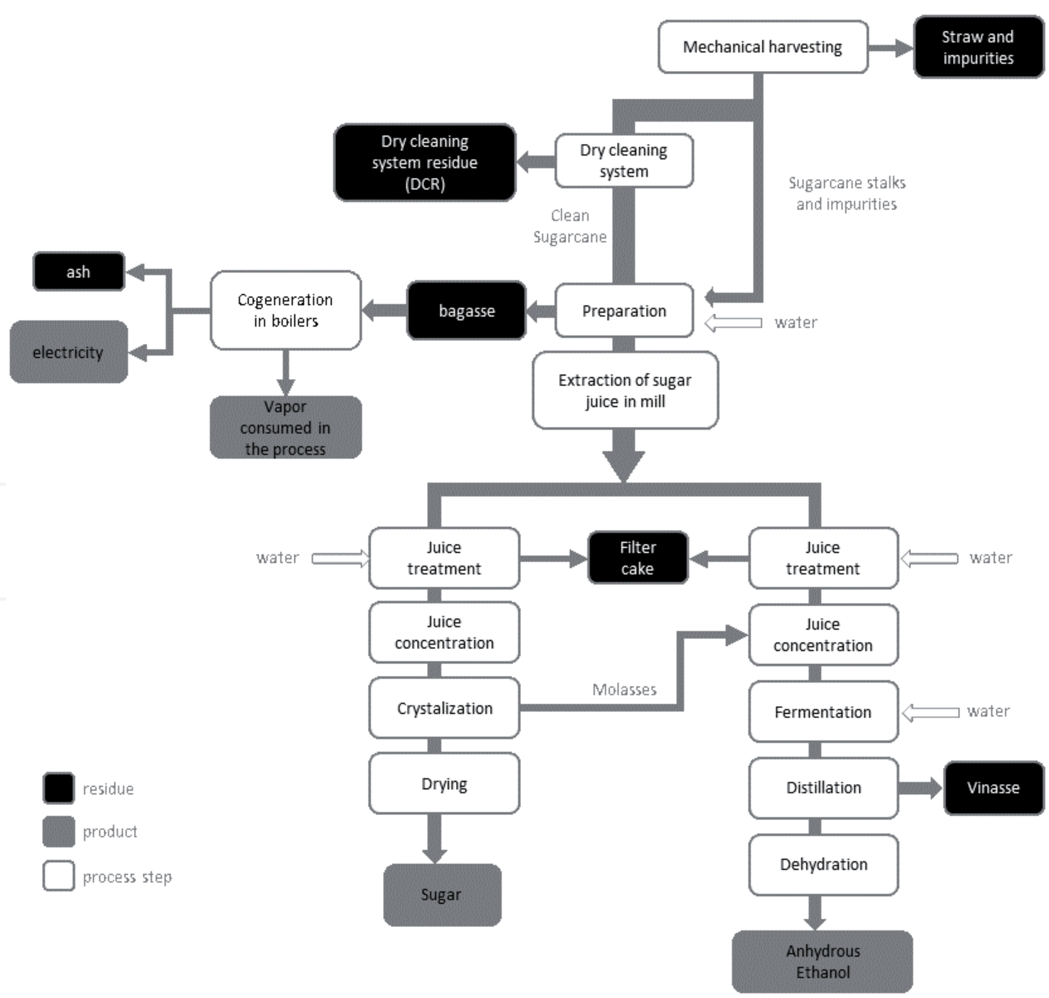

Figure 2.
Simplified scheme of sugar and ethanol production from sugarcane.

to bagasse, which makes it a good fuel to supplement bagasse for surplus power generation at mill through the burn system. However, considering that straw is also necessary in field for soil protection, it is only partially available for energy recovery. The amount of straw left in the field in relation to the total production of sugarcane taken to the mill can vary from 10 to 60% in Colombia and from 20 to 35% in South Africa [9].

According to [11], an average of 140 kg of straw is generated for each ton of harvested cane (dry basis). This represents nearly the same amount of bagasse available at the end of the juice extraction process. Some authors estimated the total electricity surplus when 40–50% of the straw available in the field is used as additional fuel to bagasse and showed results between 130 and 185 kWh per ton of cane [12, 13].

In the work of [9], it was estimated that the amount of straw left in the field per sugarcane hectare is 10 tons/ha in India. In other hand, the same author presents that 39 tons of straw/sugarcane ha are left on the soil and its productivity is of 81.49 t/ha in the region of the Rio Grande Valley, Texas in the United States. The authors report some benefits of keeping sugarcane residue in the field, such as:

- Protection of the wind surface of the soil against erosion caused by rain and hair;
- Reduction of variations in soil temperature, as the soil is protected from the direct action of solar radiation;
- Increased biological activity in the soil;
- More water available, due to reduced water evaporation from the soil surface;
- Weed control.

After the harvesting, the sugarcane cleaning is required, which can be carried by dry system or by cane washing. The dry-cleaning system residue, or simply DCR, is produced from the dry cleaning of the sugarcane right after its mechanized harvest in the field, as shown in **Figure 2**. That is, the sugarcane goes through a cleaning process without the use of water (sugarcane washing) to remove soil and impurities (leaves and straw).

The cleaning system has the advantage of reducing water consumption by plants, however, as its use is not yet very diffused, the cleaning residue properties are still unknown and, in most cases, it ends up being discarded.

As it can be seen in **Figure 2**, after sugarcane cleaning, the next step is to extract the juice through mills or diffusers, from which the bagasse, another by-product of the process, comes from.

The bagasse is the fiber that results from juice extraction process in the mills. It is estimated that 135 kg of bagasse are generated for each ton of clean cane [11]. According to [10, 14], one ton of harvested sugar cane (wet basis) originates about 250–270 kg of bagasse containing 50% moisture, 48% fibers and 2% soluble solids. Bagasse properties can vary according to the process for juice extraction [15].

Sugar and alcohol plants use the bagasse resulting from the ethanol production process in cogeneration systems, converting their chemical energy into thermal and electrical energy for their own plant. Sugarcane facilities currently use a cogeneration system based on the Rankine cycle, in which sugarcane bagasse is burnt in a boiler, producing steam that is expanded in turbines coupled with electric generators; turbines exhaust steam is used as thermal energy source for the various unit operations of the sugar and ethanol production process. Most facilities use only back-pressure steam turbines, which limit the amount of fuel that can be burnt to supply the steam demand of the process [16].

After sugarcane juice extraction, the next steps are to filtrate and to treat it, from which filter cake, or press mud, comes out as residue (**Figure 2**). It is a compound from the clarification and filtration of the juice extracted from the mills in the rotating filters, consisting in a solid fibrous residue that represents about 3–4% (w/w) of the crushed sugar cane [17].

Sugarcane filter cake is a semi-solid material composed of fiber, crude protein, sugar, wax, fat, and ash [18, 19]. It is a rich source of phosphorus and organic matter, with a moisture content, reasons why it has been used as a complete or partial substitute for mineral fertilizers in sugar cane or other crops cultivation. This using has been widespread in several countries, including Brazil, India, Australia, Cuba, Pakistan, Taiwan, South Africa, and Argentina [20].

Vinasse is produced from the distillation of wine during the hydrated ethanol production process. It is an aqueous effluent and a problem to the sector due to the large quantities produced and its potential effects as an environmental pollutant. It is largely composed of water, organic matter, and mineral elements. The environmental damage caused by discarding it into the soil or running waters was an incentive to studies aiming to find alternative, economic applications for this residue. Results from such studies indicate that, when properly applied, vinasse contributes to improvements in soil quality and agricultural productivity [20], while others, show that sue to vinasse and the filter-cake residues show considerable K and P concentrations, they are used as fertilizer [21–24].

According to [25], the vinasse generation is directly proportional to the alcohol production, obtaining between 11 and 15 liters of vinasse for each liters of ethanol [25, 26]. The study of [27, 28] state that, for autonomous distillery, approximately 910 liters of vinasse are obtained for each ton of processed sugarcane with 250 kg of bagasse and 30 kg of filter cake.

Among the residues from the alcohol production process, vinasse is considered to have the greatest polluting potential, since it has a solids content of around 7%, of which 75% is organic and biodegradable, in addition to having high COD (Chemical Oxygen Demand) and BOD (Biological Oxygen Demand) [29]. According to [30], the vinasse BOD and COD can varies, respectively, from 6,000 to 25,000 and 15,000 to 65,000 mgO_2/L, depending on whether it is derived directly from the juice or from the cane syrup. In addition, this residue has a corrosive character due to the fact that it is a buffered solution with a pH around 4.3 obtained at high temperature [29].

There are processes by which the polluting potential of vinasse and filter cake is minimized. Nowadays, both are directly applied as fertilizers, reducing the demand for irrigation and mining in the cultivation of sugarcane. However, according to [31], the anaerobic biodigestion process can be used in the treatment of these residue. This process has the advantage of treating the vinasse and the filter cake, keeping their fertilizing properties, while produces the biogas, composed of a mixture of methane gas (CH_4) and carbon dioxide (CO_2) in different proportions, depending on the substrate contained in wastewater. Biogas is an environmentally friendly alternative fuel that is, thus the liquid waste vinasse is utilized commercially [32].

3. Physicochemical characterization of sugarcane industry by-products and their use in energy processes (straw, bagasse, filter cake, vinasse)

3.1 Heating value

There are two variations for heating value. The higher heating value (HHV) which refers to the heat released during combustion per unit mass of the fuel, considering that the water formed in the combustion is in a liquid phase, in which the temperature of the gases and water produced is equal to the temperature of fuel before combustion. The lower heating value (LHV) is the heat released during combustion per unit mass of the fuel, considering that the water formed during combustion is in a gaseous phase, in which the temperature of the gases and water produced is the same as that of the fuel before combustion [33].

The HHV can be determined experimentally, using the methodology described in ASTM D2015–00 Standard test method for gross heating value of coal and coke by adiabatic bomb calorimeter by means of a calorimetric pump [34].

Normally, the heating value of solid fuels is determined in a calorimetric pump, that is, the higher heating value is calculated on a dry basis (zero moisture content), from which the lower heating value can be calculated, which is used, for example, in the design of boilers.

The study of [33] present an equation for calculating the lower heating value on a wet basis, from the higher heating value on a dry basis, both in $MJ{\cdot}kg^{-1}$, according to Eq. (1):

$$LHV = HHV \cdot \left(1 - \frac{H_2O}{100}\right) - 2.444 \cdot \frac{H_2O}{100} - 2.444 \cdot \frac{h}{100} \cdot 8.936 \cdot \left(1 - \frac{H_2O}{100}\right) \quad (1)$$

Where:
LHV = lower heating value on a wet basis ($MJ{\cdot}kg^{-1}$);
HHV = higher heating value on a dry basis ($MJ{\cdot}kg^{-1}$);
H_2O = moisture content of the fuel on a wet basis (% mass);
h = Hydrogen concentration on a dry basis (% mass).

The first term of the equation converts the HHV from dry to wet basis, the second term corresponds to the latent heat of water vaporization contained in the biomass (the latent heat of water vaporization at 25°C and constant pressure is 2.444 $MJ{\cdot}kg^{-1}$). Finally, the third term refers to the vaporization of the water produced when the hydrogen contained in the biomass is combusted.

The author in [33] also refer to other empirical equations for calculating higher heating value, as shown in Eq. (2), described by [35].

$$\begin{aligned} HHV = 0.3491 * X_C + 1.1783 * X_H + 0.1005 * X_s - 0.0151 * X_N \\ - 0.1034 * X_O - 0.0211 * X_{ash} \end{aligned} \quad (2)$$

Where:
X_i: dry mass fraction of Carbon (C), Hydrogen (H), Sulfur (S), Nitrogen (N), Oxygen (O) and Ash.
HHV = higher heating value on a dry basis ($MJ{\cdot}kg^{-1}$);

Through empirical Eq. (2), it is observed that the levels of carbon, hydrogen and sulfur will contribute to the higher heating value of the material, while the levels of nitrogen, ash and oxygen contribute negatively. Although it reduces the higher heating value of solid fuel, organic oxygen is released during thermal decomposition and thus supplies part of the oxygen needed for combustion reactions, thus decreasing the amount of air required in the process.

In **Tables 1** and **2**, data of the heating value of bagasse and sugarcane straw are shown, both lower and higher, respectively, reported in several studies carried out with samples from different countries of origin.

From the data in **Table 1**, it is observed that the values for the higher heating value of bagasse vary from 15.98 to 19.17 $MJ{\cdot}kg^{-1}$, while for straw is about 17 $MJ{\cdot}kg^{-1}$. It is interesting to highlight the differentiation made by [5] in relation to the thermochemical properties relevant to the different constituent parts of the straw.

HHV (MJ·kg^{-1})	LHV (MJ·kg^{-1})	Base	Author
15.98	14.67	Wet base 9.22%	[36]
17.0	—	—	[37]
18.65	—	—	[38]
18.1	—	Dry base	[9]
16.88	—	Dry base	[39]
18.89	17.32	—	[40]
18.90	—	—	[15]
18.61	—	Dry base	[41]
17.23	—	Dry base	[42]
18.59	—	Dry Base	[43]
18.43	—	Dry Base	[43][a]

[a]*Bagasse resultant from a process with dry cleaning system of sugarcane.*

Table 1.
Literature review of the heating value of sugarcane bagasse.

Biomass	HHV (MJ·kg^{-1})	LHV (MJ·kg^{-1})	Author
Green leaves	17.4	—	[9]
Dry leaves	17.4	—	[9]
Tips	16.4	—	[9]
Straw	17.74	16.50	[44]
Dry leaves	16.0	14.8	[41]
Straw	16.347	—	[45]
Straw[a]	16.54	—	[43]
Straw	17.1	—	[10]

[a]*Straw resultant from a process with dry cleaning system of sugarcane.*

Table 2.
Literature review of the heating value on dry basis of sugarcane straw.

In the work of [36], states to the fact that the viability of using sugarcane residues as a fuel in cogeneration processes is directly related to their moisture content, since the heating value is intrinsically linked to fuel's elemental composition and moisture.

As a comparison criterion for this important thermochemical property for the biomass combustion process, the heating value of the wood can be taken as a reference. For this, [46] shows that this traditional biomass can present HHV very close to that found for bagasse and straw, being 18.49 MJ·kg^{-1} for sawdust from Eucalyptus sp.

On the other hand, [37] shows that coal has a calorific value of 29 MJ·kg^{-1}, that is, a heating value about 49% higher than that found for bagasse and straw, mainly due to its greater constituent carbon content.

According to the **Table 3**, vinasse high heating value fluctuates from 12.7 MJ·kg^{-1} to 15.07 MJ·kg^{-1}, when moisture is around 4% and, takes a value of 6.4 MJ·kg^{-1} with 68% of moisture [47, 51]. Hence, vinasse high heating value decreases notably with the increase in moisture content, which must be considered when a thermochemical route is used for energy recovery [52].

HHV ($MJ \cdot kg^{-1}$)	LHV ($MJ \cdot kg^{-1}$)	Author
13.59	—	[47]
14.40	—	[48]
6.4	4.5	[49][a]
13.0	14.0	[50]
12.7	12.6	[51]

[a]*When moisture around 68%.*

Table 3.
Literature review of the heating value on dry basis of sugarcane vinasse.

As showed in **Table 4**, sugarcane Filter-cake have around 17 $MJ \cdot kg^{-1}$ of high heating value, which is proximate to the results reported for straw and bagasse in **Tables 1** and **2**. This indicates a high energy potential in filter cake, which could be related to a high content of proteins, sugar and fibers, giving a possibility to use this by-product for energy as with other sugarcane and woody biomasses which is normally used for thermochemical processes [56, 57].

Taking into account the energy potential of the sugarcane industry residues, there is a possibility to use it as the coal. One favorable way to increase residues potential could be to use a blend of them. Residues as the vinasse and filter cake, which have a high availability, would present more heating value compensate by add straw and bagasse [51].

3.2 Ultimate analysis

An ultimate analysis of biomass offers the contents of Carbon, Nitrogen, Hydrogen, Oxygen and Sulfur, which together with moisture and ash, are the main components of biomass. With the results of this analysis, it is possible to estimate the amount of products that will generated in combustion or gasification, as well as the amount of oxidant needed. The nitrogen content is useful for assessing the amount of nitrogen oxide (NO_x) transport in combustion or ammonium (NH_4) in gasification. The sulfur content is necessary to calculate the possible dates of sulfur dioxide (SO_2) or hydrogen sulphide (SH_2) and with chlorine, to assess corrosion of the equipment [54].

The elementary analyses of sugarcane bagasse and straw found in the literature of recent years are summarized in **Tables 3** and **4**.

Regarding the properties of wood, the sawdust of Eucalyptus sp., it has a carbon content of 46.80%, oxygen of 46.61% and hydrogen oxygen of 6.59% [46]. Therefore, it can be noted that bagasse and cane straw have an ultimate composition similar to wood, ancient biomass used in thermochemical processes.

In addition, bagasse and sugarcane straw have a 39% lower carbon content compared to coal [37]. Even so, it can be said that these by-products of the sugar and alcohol sector have combustible characteristics, since carbon and hydrogen are responsible for more than 50% of their composition, which will undergo oxidation in the presence of air during combustion, releasing heat.

In addition, from the results showed in **Table 5** and form other authors [60–63], bagasse and straw have a high oxygen content (from 39 to 50%), when compared to coal, which may have 7.4% oxygen content, according to [37], which implies low heating value of bagasse and straw compared to coal. However, the high content of constituent oxygen reduces the amount of oxygen required in the combustion process, since organic oxygen is released during thermal decomposition and provides part of the oxygen needed for combustion reactions (**Tables 6** and 7) [33].

HHV ($MJ \cdot kg^{-1}$)	LHV ($MJ \cdot kg^{-1}$)	Author
17.05	14.6	[53]
17.0	—	[54]
17.1	—	[55]
14.9	13.8	[50][a]
8.57	7.79	[56]

[a]*Wet basis.*

Table 4.
Literature review of the heating value on dry basis of sugarcane filter cake.

C (%)	H (%)	O (%)	N (%)	S (%)	Cl (%)	Author
44.8	5.40	39.60	0.4	0.01	—	[58]
44.8	5.4	38.1	0.4	0.03	0.02	[37]
50.3	6.3	43.1	0.3	0.07	—	[38]
44.6	5.8	44.5	0.6	0.1	0.02	[9]
44.31	5.73	49.11	0.63	<0.1	0.13	[39]
43.6	5.52	50.63	0.25	0.07	—	[59]
45.48	5.70	45.21	0.40	0.06	—	[15]

Table 5.
Ultimate composition of sugarcane bagasse reported by different authors.

Biomass	C (%)	H (%)	O (%)	N (%)	S (%)	Cl (%)	Author
Green leaves	45.7	6.2	42.8	1.0	0.1	0.4	[9]
Dry leaves	46.2	6.2	43.0	0.5	0.1	0.1	[9]
Tips	43.9	6.1	44.0	0.8	0.1	0.7	[9]
Straw	44.7	5.8	—	0.45	0.08	—	[44]
Straw	43.42	5.71	49.64	1.23	—	—	[10]
Straw	42.5	6.02	50.2	0.6	0.24	0.44	[10]

Table 6.
Ultimate composition of sugarcane straw reported by different authors.

Considering that sugarcane vinasse is obtained in the final stages of bioethanol production, their composition is highly heterogeneous, which may explain why the nitrogen content is approximately three times higher than in straw and bagasse. The high Carbon and Oxygen content verify residual sugars and acids from the sugarcane process. On the other hand, sulfur content can be explained by the presence of SO_2 residue from sulphitation in cane juice treatment [57].

According to **Table 8**, the high content of oxygen and carbon suggests the presence of organic groups characteristic of lignocellulosic materials, which may indicate their use as solid biofuel or for obtaining bio-oil [68]. In addition, as an important part of the filter cake is obtained in the sulfite and clarification processes, a high sulfur content may result when compared to other sugar cane residues. Although the presence of Nitrogen and Sulfur in most of the residues studied is low, when compared to other biomasses, they are undesirable because they can reduce

C (%)	H (%)	O (%)	N (%)	S (%)	Cl (%)	Author
41.2	5,0	20.8	5.0	5.0	—	[49]
32.9	4.5	36.4	1.0	2.7	6.2	[50]
31.87	6.13	28.26	1.69	2.32	—	[51]
39.7	8.6	—	1.65	0.12	—	[64]

Table 7.
Ultimate composition of sugarcane vinasse in dry basis reported by different authors.

C (%)	H (%)	O (%)	N (%)	S (%)	Cl (%)	Author
32.5	2.2	—	2.2	—	—	[65][a]
42.9	5.3	24.99	1.8	3.1	—	[53]
33.73	3.92	—	2.36	0	—	[54]
37.1	—	—	2.3	—	—	[66]
29.6	3.9	46.0	0.9	0.5	0.3	[50]
21.5	3.33	18.34	0.81	0.13	—	[56]
34.4	—	—	2.07	9.93	—	[67][b]

[a]*Wet basis.*
[b]*Dry basis.*

Table 8.
Ultimate composition of sugarcane filter cake reported by different authors.

the calorific value, at the same time as they decrease combustion efficiency by promoting the formation of nitrogen oxides (NO_x) and sulfur oxides (SO_x) [51, 57].

It is also important to take into account that the chemical composition of sugarcane residues depends on the locality, cane variety, land conditions, nutrients applied to the field, milling efficiency and method of clarification [54, 57].

3.3 Proximate analysis

The proximate analysis establishes the contents of moisture, ash, volatile material and fixed carbon of the fuels, with which it is possible to estimate the behavior of the biomass during the combustion process.

The moisture content can determine the most suitable energy conversion process for biomass, since for materials with moisture content greater than 50%, biological routes are generally applied, such as anaerobic decomposition, while for biomasses with moisture content of up to 50% (wet basis), thermochemical processes are more used [69–72].

The fixed carbon indicates the carbon content that still remains in the biomass used as fuel, after the volatilization of the volatile compounds. An indicative relationship can be established between these two levels, in which materials with a higher volatile content in relation to the fixed carbon content will be combustible with greater ignition ease. Finally, ash is the inert material that results from combustion, so the higher the ash content, the less energy is available in the fuel [69].

The moisture content of straw depends, in general, on the time that this material is deposited in the field. At the time of harvest, the straw can contain up to 50% moisture (w.b.). This moisture content can drop to 30% (w.b.) in 2 to 3 days and to 15% (w.b.) in two weeks, which can represent an energy gain in its burning [9]. For bagasse, the moisture content in the juice extraction outlet at the plants, whether by milling or diffusion, is in the range of 47 to 52% (w.b.) [33].

The values of the contents of fixed carbon, volatile matter and ash for bagasse and straw, determined by different authors, are shown in **Tables 9** and **10**.

The proximate analysis data for the bagasse and straw are somewhat similar in terms of variation: the fixed carbon is within the range of 6.9–18% and the volatile material is 73–89%. These variations in values may be related to the varieties of sugar cane, as well as the presence of impurities.

Fixed carbon terminology refers to the fuel fraction of coal or any bituminous material after removal of moisture, volatile and ash content. Or it can also be defined as the elemental carbon content constituting coal and bituminous materials added to the fraction of carbonaceous residue formed under the rate of heating of the material [75]. In the case of the methodology described by ASTM E872–82, this heating is done at 950°C for 7 minutes [76].

However, according to [75], biomass does not have elemental carbon, unlike coal, since its carbon fixation occurs through photosynthetic fixation to form the main macromolecules that make up biomass, such as carbohydrates, lipids and proteins. Thus, the term fixed carbon is not adequately used in biomass and its corresponding fraction refers more to a content of pyrolytic carbon (carbon formed at a temperature of approximately 100°C). In addition, the pyrolytic carbon content will directly depend on the temperature rate used for the determination of volatile material in the biomass, as already described.

The content of volatile materials, in turn, refers to the amount of material that will detach from the fuel in gaseous form, undergoing combustion first. Thus, the higher the content of volatile materials in biomass, the better its combustion. In relation to this, it is observed that both straw and bagasse have a high content of

Fixed carbon (%)	Volatile matter (%)	Ash (%)	Author
11.95	85.61	2.44	[73]
14.9	73.8	11.3	[51]
18.0	79.9	2.2	[20]
13.1	86.0	0.9	[54]
9.3	88.7	2.0	[33]
—	—	3.1	[74]
—	—	2.4	[74]
12.4	81.8	5.8	[74]

Table 9.
Proximate analysis for sugarcane bagasse on a dry basis reported by different studies.

Biomass	Fixed carbon (%)	volatile matter (%)	Ash (%)	Moisture (%)	Author
Green leaves	15.7	80.6	3.7	67.7*	[9]
Dry leaves	11.6	84.5	2.7	13.5*	[9]
Tips	16.4	79.3	4.3	82.3*	[9]
Straw	6.9	81.55	11.57	9.92	[44]
Straw	17.46	78.64	4.32	—	[45]
Straw	10.1	82.5	7.5	—	[10]

**Moisture of fresh samples.*

Table 10.
Proximate analysis for sugarcane straw reported by different studies.

volatile materials (about 80%), when compared to coal (34%), which indicates that they are easily combustible fuels [36, 37].

On the other hand, wood residues present volatile material contents of 88.27% (sawdust from Eucalyptus sp.) And 80.73% (sawdust from Pinus sp). Therefore, it is noted that the residues of the sugar and alcohol sector show similar behavior to wood during direct combustion, considering the high content of volatiles [46].

Regarding the ash content, it is noted that the sugarcane straw has a higher ash content compared to the bagasse, since for the bagasse the ash content is between 0.9 and 11.57% and for the straw this variation ranges from 2.7% to 11.3%.

The analysis of the ash content of the sugarcane residues at the sugar and alcohol plant is of paramount importance as regards the use of these materials in thermochemical conversion processes, considering that the lower the ash content, the less the problems in the boilers such as scale, deposits and corrosion.

In this sense, the ash values found for bagasse and straw are close to those found for wood sawdust, which may vary from 0.46% for sawdust from Eucalyptus sp. to 7.88% for sawdust from Pinus sp. Regarding mineral coal, both straw and bagasse have much lower ash contents, which can reach a difference of 13.8%, according to [37].

Tables 11 and **12** reports the proximate composition of vinasse and filter cake, respectively, according to different studies from literature.

Considering **Tables 11** and **12**, information for filter-cake and vinasse moisture fluctuate according to the sample utilized for the study, but normally the sample need to be dried. *In natura* conditions, these by-products have a moisture around 90%, which may imply low yields in thermochemical transformation processes, but is an important design parameter for assessing the need for a previous drying step and estimating the energy consumption involved [72].

Analyzing the volatile material, it can be observed that the vinasse and the filter cake have a lower content, compared to the bagasse and straw, indicating a lower reactivity and the need of high temperatures to achieve its thermal degradation. Considering the diversity in the composition of vinasse and filter cake, the content of volatile materials probably corresponds to the evaporation of low molecular weight compounds such as lactic acid, phenolic compounds and, finally, to the partial release of combustible (CxHy gas, CO and H_2) and non-combustible (CO_2, SO_x, NO_x H_2O) products as well as straw and bagasse. Thus, the organic composition (Volatile Material) of vinasse and filter-cake and the predominance of inorganic composition (Ashes), reduces the energy that can be released [51, 52, 73, 78].

In **Table 11**, fixed carbon presented for vinasse may indicates longer combustion and a higher thermochemical conversion rate compared with filter-cake, as showed in **Table 12**. Considering the ash content, vinasse has a value in the range of feedstock material normally used for pyrolysis and gasification processes [50]. On the other hand, filter-cake present highest ash content than vinasse, which may adversely affect

Fixed carbon (%)	Volatile matter (%)	Ash (%)	Moisture(%)	Author
18.95	69.31	11.73	—	[74]
—	32,3	9,7	58	[49]
—	—	34.1	—	[50]
3.55	63.06	29.35	4.05	[51]
12.18	61.66	20.56	5.6	[56]

Table 11.
Proximate analysis for sugarcane vinasse reported by different studies.

Fixed carbon (%)	Volatile matter (%)	Ash (%)	Moisture(%)	Author
25.95	56	15.55	—	[53]
—	61.2	25.9	3.52	[54]
—	—	23.32	73.13	[77]
—	—	42.6	—	[50]
—	80.8	19.2	73.3	[75]
3.45	40.67	45.83	2.06	[56]
—	—	20.6	10.5	[67]

Table 12.
Proximate analysis for sugarcane filter cake reported by different studies.

the high heating value, important in a thermochemical process, but this high mineral measure and possibly sugar and protein content, according ultimate analysis, indicates filter cake can be used in the biogas production [79]. Likewise, these ash contents in sugarcane waste increase the sintering potential and the possibility of fouling and corrosion in combustion reactors or boilers, as well as operating costs [80].

4. Conclusions

Sugarcane industry residues presents a feasibility to be used in energy conversion process, as indicated by the physicochemical properties showed in this chapter.

The high heating value is the principal parameter to analyze the energy that can be liberated by a biomass in a thermochemical process. Most of the uncommon sugarcane residues heating values were proximate, which if compared with woody biomass or bagasse, normally used in a combustion process, allows to demonstrate the potential for energy recovery in the sugarcane industry.

However, vinasse and filter cake present high moisture and ash contents, which indicates that these residues must present better yield in biochemical processes of energy conversion instead of the thermochemical ones. The high ash concentration is related to a good performance of the biofertilizer obtained after the biogas production, which can be used for fertilizing sugarcane crops. The high concentration of carbon, in appropriated ratio with nitrogen, indicates that good yields of methane gas can be obtained.

On the other hand, the production of biogas requires the construction of an appropriate system for anaerobic biodigestion, which requires investment by the plants in new facilities and processes. In this case, the joint use of residues in thermochemical processes can be considered, causing a compensatory effect of the straw and bagasse with the properties of the vinasse and filter cake, mainly when it is required to improve the negative effects related to the ultimate and proximate composition, to increase the energy potential of the waste.

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Appendices and nomenclature

MY	marketing year
TWh	terawatt hour
DCR	dry cleaning system residue
COD	chemical oxygen demand
BOD	biological oxygen demand
LHV	lower heating value
HHV	higher heating value
w.b.	wet basis

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