Impact of Bagasse Water Content on the Energy Efficiency of a Gas Boiler

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Manuscript received January 3, 2026; revised February 18, 2026; accepted March 3, 2026; published April 17, 2026

***Abstract*—The increasing energy consumption in industry is forcing each sector to exploit all forms of renewable energy from its waste.In sugarcane industry boiler are used for burning bagasse and produce electricity. The aim of this study is to identify optimal value of bagasse moistureto optimize efficiency of energy of the BABCOCK & WILCOX boilers working with sugarcane bagasse. Approximately 20 bagasse samples were collected monthly from October 2022 to April 2023. For each sample, the moisture content, fumes heat at the boiler outlet, and energy output were measured. Other parameters, such as the lower heating value and efficiency, were also calculated. The results indicate that the optimal moisture for bagasse is 47% on a wet basis.Concerning outlet fumes of boiler heat should be approximately 320 kcal/kg for an optimal efficiency of 78%. However, a moisture content of approximately 45% results in significant heat loss, with a high outlet fumes heat of nearly 340 kcal/kg.Based on these results, we propose that the heat output of the boiler be taken into account for efficiency assessment, and that the optimum moisture content of the bagasse should be close to 47% for efficiency tests.**

***Keywords*—boiler, energy efficiency, humidity, sugarcane bagasse, drying, heat**

I. Introduction

A. Context

Energy production in the agri-food sector must take into account the energy that can be captured during the process. One of the major developments in this field dates back to 1867, when George Herman Babcock and Stephen Wilcox [1] developed the water-tube boiler capable of operating at high pressure and high temperature, while offering increased thermal efficiency. This type of boiler is now widely adopted in the food processing industry for its performance and its ability to adapt to modern energy and environmental requirements.For example, in the sugarcane sector, bagasse is generally used. Consequently, the combustion of bagasse was rethought, no longer considering it as waste but as a fully-fledged biofuel. Simultaneously, the growing demand for bagasse for other industrial uses, particularly the manufacture of paper, fiberboard, and furniture, reinforced the importance of this resource in the sugarcane industry. The energy recovery of bagasse thus became a major issue for stakeholders in the sugar industry. However, too low a moisture content reduces the amount of energy that can be extracted, and too low a value presents a risk of fire in the installation. Determining an optimal value is therefore essential and must consider both color intensity and moisture content, as indicated in the literature. But considering the heat produced in the combustion chamber is also crucial, as shown in this study.

B. Literature Review

The population growth projection for 2050 will increase the demand for food products, and the resulting pollution will increase. Furthermore, the global energy consumption in the agri-food sector is currently approximately 200×10^{18} J, representing 12% of the industrial sector's energy consumption [2]; this energy is derived primarily from conventional sources. This sector is therefore moving toward energy efficiency in its processes and equipment [3]. However, given the enormous quantities of energy involved, it is difficult for these industries to transition to renewable energy sources. Consequently, some companies determine the optimal temperature and heat of the outlet fumes and the combustion air fraction for their boilers [4]. For others, the residues of their production are transformed into a source of energy by adapting the operation of equipment or processes to optimize boiler efficiency [5]. This is the case for the palm oil and sugarcane industries. In the sugar industry, bagasse is considered a fossil fuel [6, 7].

To determine the optimal moisture content for high-energy bagasse without compromising the integrity of the equipment, two bagasse boilers at a sugar refinery in northern Côte d'Ivoire were studied over oneyear. Thermal performance tests were conducted on the boilers in operation, starting with the moisture content of the bagasse entering the process. The experiment was carried out over several harvests during the 2022–2023 season.

Using the thermal performance test method for a bagasse boiler, the fumes heat output of the boiler was evaluated, the bagasse moisture content was averaged monthly, the monthly energy output was assessed, and the efficiency of each boiler was also evaluated. After describing the tools and methodology, we present the results and discussions arising from this energy analysis before concluding.

II. Materials and Methods

A. Materials

The experiments took place in northern Côte d'Ivoire, a sugar company, during the 2022–2023 harvest. They consisted of sugar and bagasse production data collected from October 2022 to April 2023.

During the campaign, more than 1 million tons of cane were harvested to produce more than 105,000 tons of sugar.

1) Characteristics of bagasse

In practice, the quantity of bagasse produced varies from approximately 24–28% of the sugarcane weight. Bagasse contains between 42% and 48% water. Other components include woody matter (L) at approximately 47% to 56% and dissolved solids (composed of sugars and impurities) at approximately 2% to 5%. These dissolved solids are grouped together in the extraction indicator, which is the Brix (B) of bagasse.

2) Chemical composition

Bagasse is composed of Carbon (C), Hydrogen (H), Oxygen (O), and ash [8]. The chemical composition of dry bagasse varies slightly from one author to another (Table 1).

Table 1. Chemical composition of bagasse according to different authors

	Constituents and holders of the bagasse						
	Value 1	Value 2	Value 3	Value 3	Value 4	Value 5	
% C	46.5	44	48.5	47.5	47.9	49	48.1
% H	6.5	6	6	6.1	6.7	7.4	6.1
% O	46	48	43.3	44.4	45.4	41.8	43.3
% Ash	1	2	2.2	2	Traces	1.8	2.5

Table 2. Average chemical composition of dry

Constituans	C	O	H	Ash	Sulfur	Total
Contents (%)	47	44	6.5	2.5	Traces	100

However, we use the following standard average composition of our calculation's values in Table 2.

3) Boiler characteristics

The boiler analyzed in this study is a water-tube boiler manufactured by BABCOCK & WILCOX CO-USA with a working pressure of 31 bars.

Table 3. Characteristics of turbo-alternators

Units		°C	MW	rpm	LHV/Bar	kVA	V
GTA1	**TURBO 1:**	371	7565	5200	425/31	/	/
	Alternator 1	/	7.5	1500	/	9375	5500
GTA2	**TURBO 2:**	371	7.5	5133	425/31	/	/
	Alternator 2	/	7.5	1500	/	9375	5500

It was built in 1973 and has a test pressure of 54 bars. Fluid circulation is natural, and it can handle mixed solid–liquid fuel. The average power output of this boiler is 62 MW, with a flow rate of 70 tons per hour. The outlet steam is superheated to 31 bar and 371 °C. Bagasse is injected into the combustion chamber by a fan. Other technical specifications are presented in Table 3.

4) Combustion smoke

During combustion, every 2 h, a portable probe (Sauermann) is inserted into the chamber to measure the levels of CO (carbon monoxide), CO_2 (carbon dioxide), NOx, O_2 (excess air in the combustion gases), and H_2O (water content of the gases). This process is repeated throughout the day, resulting in 12 measurements. A scale provided by the manufacturer is then used to interpret the values (Table 4).

Table 4. Combustion flue gas analysis scale

Measured Quantities	Content (manufacturer's standard)	Unit	Comments
Flue gas T °C	220–250	°C	boiler is losing energy through the chimney [9]
CO_2	14 to 18	%	A low CO_2 indicates more air is being used; excessive CO_2 indicates insufficient combustion air.
CO	400-500	ppm	A low or excessive CO content clearly shows us that combustion is incomplete due to insufficient air.

5) Fluid flow rate (steam, juice)

The evaluation of circulating fluids such as steam and juice, leaving or entering the boiler, will be assessed with differential pressure mass flow meters from the manufacturer Endress + Hauser ranging from 0 to 500 mbar.

6) Energy consumed

The energy produced by the boiler's turbo-alternator is measured by a Schneider Electric Sepamie 080 (sep080). The difference in daily readings on the monitoring screens determines the energy produced by the turbines.

B. Method

1) Moisture in a bagasse base

A 100 g bagasse sample was placed on a 250 mm diameter sieve with 250 µm mesh. The assembly was incubated at 105 °C ± 3 °C for 4 h, and the mass loss was measured every 30 min. When this mass loss exceeds 0.2 g, the process in the oven (Fisher Bioblock Scientific; 160 L) continues. Conversely, when the mass loss falls below 0.2 g, the process is stopped. The final mass was quickly measured using the same 0.2 g precision balance. The water content is determined via the following formula [10]:

$$\%w = \left(\frac{m_2 - m_3}{m_2 - m_1}\right) * 100 \quad (1)$$

The determination of each parameter of Eq. (1) is performed in the following way.

The sample holder (250 mm diameter sieve with a 250 µmmesh opening) previously dried in the oven was weighed, and the mass (m_1)was noted to the nearest 0.1 g.

Approximately 100 g of bagasse or prepared cane was added to the empty sample holder, and the mass of the sample holder (m_2) with the bagasse was noted to the nearest 0.1 g.

After placing the sample holder with the prepared bagasse or cane in the drying oven, it was dried at 105°C ± 3°C for 4 h. After 30 min, the mass loss was confirmed to be well below 0.2 g; if not, drying was continued until a constant weight was reached.

For the last parameter determination, the sample holder with the bagasse sample or prepared hot dry cane was weighed, and its mass (m_3) was recorded to the nearest 0.1 g.

2) Calorific value of bagasse

For wet fuel, the amount of water present in the product just before combustion must be considered. For bagasse containing a certain amount of water and sugar, several formulas have been proposed to correlate the Lower Heating Value (LHV) in Eq. (2) and the Higher Heating Value (HHV) in Eq. (3) of wet bagasse with its various constituents. The formulas we use for our calculations are from internal sources and are based on scientific work [11].

$$LHV = 4250 - 12S - 48.5W(\text{kcal/kg}) \quad (2)$$

where, W isthe moisture content of bagasse in %;S is the Pol bagasse or sugar content in bagasse in %.

With the mechanization of harvesting, the addition of soil and other insoluble materials tends to reduce the calorific value of bagasse. All insoluble and noncalcinable matter was determined in the laboratory under the heading of ash% bagasse [12].

$$HHV = 19605 - 196.05W - 196.05C - 31.14B(\text{kJ/kg}) \quad (3)$$

where, C is % of ash in bagasse; B is Brix % bagasse (sucrose + other soluble matter).

3) Heat lost at the chimney of the boiler

The heat lost by the boiler is related to the quality of combustion. The values of outlet fumes heat (Q) were determined via Eq. (4) and Eq. (5).

$$Q = T \times (1 - W) \times \left(1.4 \times m + \frac{0.5}{1 - W} - 0.12\right) \quad (4)$$

$$m = \frac{0.1955}{Y} + 0.0126 \quad (5)$$

In this equation, the significance of each parameter is as follows.

Q is sensible heat lost at the chimney, in calories; T is outlet boiler gas temperature, °C; W is bagasse humidity; Y is CO_2 content of the flue gases (from combustion gas analysis); m is excess combustion air (the ratio of the weight of air used to the theoretical weight strictly required).

4) Boiler energy efficiency

The boiler efficiency on Eq. (6) represents the ratio between the energy produced (useful energy, output) and the energy consumed (energy input). In this case, it is the percentage of energy recovered from the Lower Heating Value (LHV) of the bagasse.

$$\eta = 100 \times \frac{boilet\ outlet\ energy}{LHV of bagasse} \quad (6)$$

III. Result and Discussion

The monthly average values presented are derived from approximately 20 measurements taken during the operation of the production equipment. These results therefore represent more than 100 samples. These samples were used simultaneously in two of the company's boilers.

A. Moisture Content of Bagasse at the Boiler Inlet

The evolution of the water content during the sugarcane harvest months is shown in Fig. 1, and the values were calculated via Eq. (1). Each value is an average of several water contents measured during the month in question. The average value is 47%. The value of 48% is derived from a sample of 2 values at the end of October. However, a lower peak is observed in November because of the technical adjustment of the mills at full capacity [10].

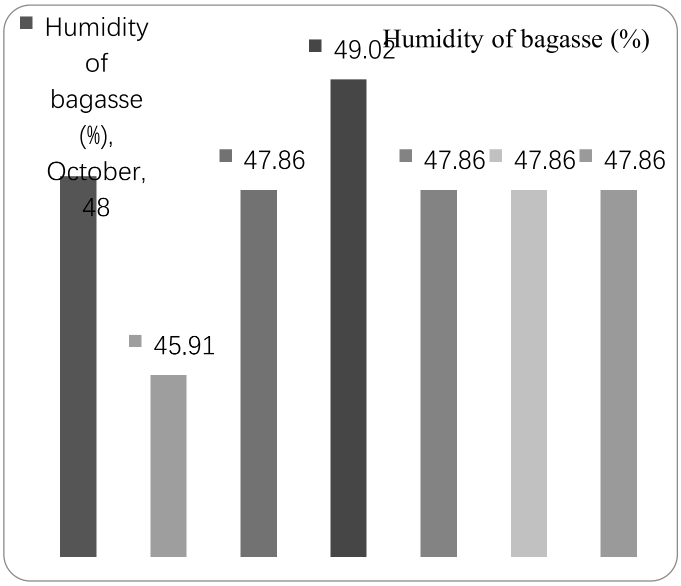

Fig. 1. Average monthly moisture content of bagasse during a sugar campaign.

While the January peak on Fig. 1 can be attributed to the quality of the sugarcane itself, from February onward, the value stabilizes for the remainder of the season. This situation can be explained by the variability in sugarcane quality from one harvest to another, as observed in other studies on sugarcane [13, 14]. The humidity of the bagasse, which is too low, can cause fires during its transport to the boiler. Therefore, a low and safe value must be found. To achieve this optimal moisture content in the bagasse, it would be possible to use the heat coming out of the chimney for a preheating process [15].

B. Lower heating value of bagasse

The curve in Fig. 2 below shows the evolution of the calorific value (LHV) of sugarcane bagasse. The value was determined via equation 1 (Eq. (2)). The maximum peak is observed in November. This value is consistent with the lowest water content occurring in the same month [16, 17]. From February onward, the value stabilized.

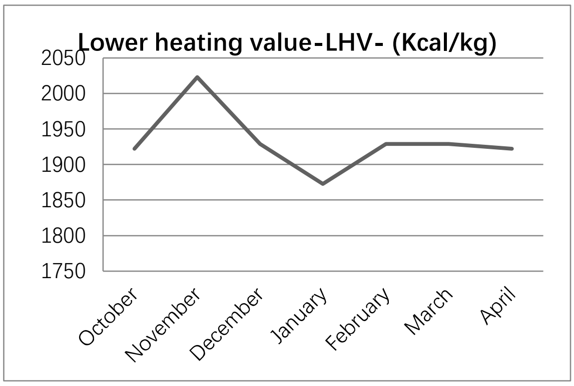

Fig. 2. Average monthly calorific value of bagasse during a sugar campaign.

Considering the moisture content of bagasse, the highest water content corresponds to the lowest calorific value, as has also been observed for sorghum [18]. Indeed, some of the combustion energy will be used to evaporate the water contained in the bagasse, thus inducing a decrease in energy.

C. Heat loss at the outlet of each chimney during boiler operation

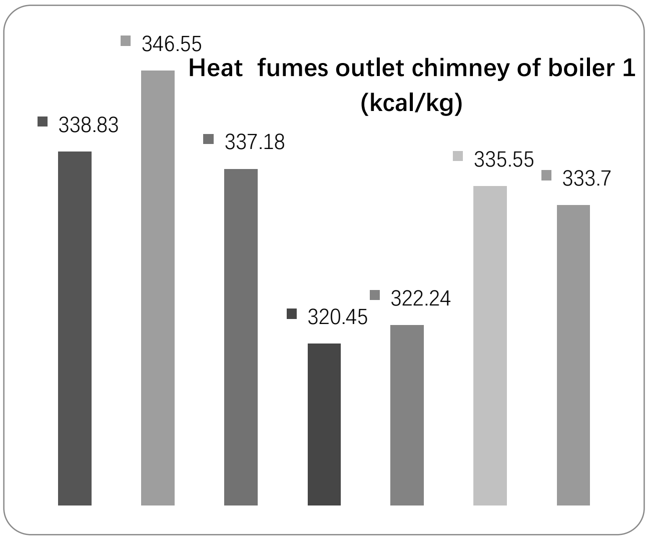

Fig. 3. Average monthly heat output from boiler 1.

The values of heat were calculated via Eq. (3). The average heat values at the boiler outlet, which vary from month to month,are shown in Fig.3. However, they remain above 320 kcal/kg. The lowest values are obtained in January and February, whereas the peak occurs in November. This November value indicates a high energy output from bagasse combustion [19]. This heat value is an indicator of boiler quality, as it helps in understanding energy efficiency [20]. For boiler 2, the results are as follows (Fig. 4).

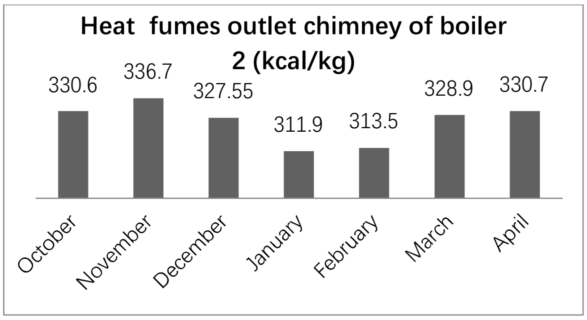

Fig 4. Average monthly heat output from boiler 2.

The observations in Fig. 4 are similar to those of the heat fume outlets of boiler 1 but with slightly reduced average values for boiler 2. This may induce better operation [20, 21] for boiler 2.

D. Quantity of bagasse consumed by all the boilers

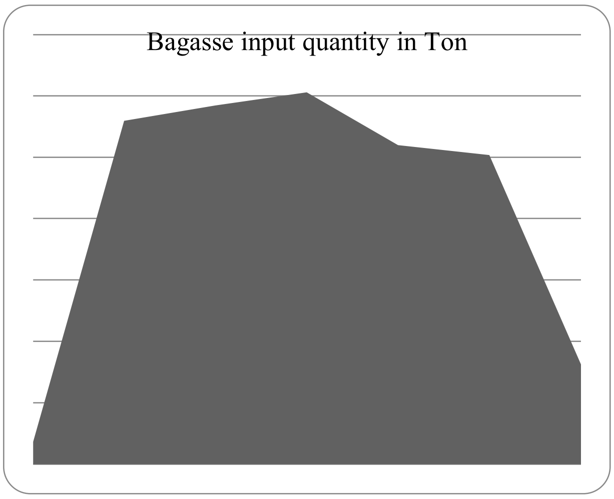

Fig. 5. Total monthly mass of bagasse consumed by the 2 boilers.

Fig.5 shows the total quantity of bagasse consumed by the two boilers each month during the sugar campaign. The peak in consumption occurs in January, followed by a decrease in consumption until the end of the campaign.

E. Energy produced by boilers

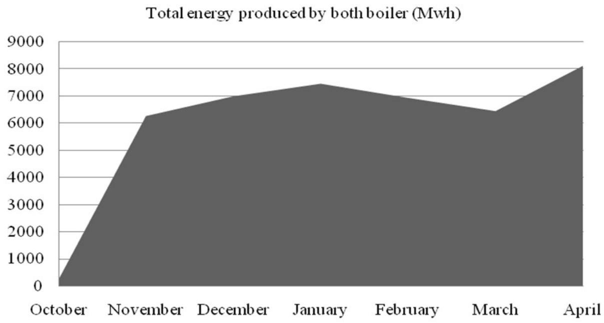

Fig 6. Total monthly energy produced by the two bagasse boilers.

The energy produced was measured by Schneider Electric equipment. Fig. 6 shows the evolution of the amount of energy produced for both groups. The low value for October indicates the start of bagasse use in the boilers, despite the low stock levels at the beginning of the season. Compared with the value for April, this value is due to the low stock available at the end of the season. The highest values are observed in December, January, and February. However, the peak energy production for all boilers in January corresponds abnormally to the lowest calorific value, probably due to the highest bagasse consumption during that month. Furthermore, the heat at the boiler outlet is the lowest during this period. This suggests that high humidity limits the combustion temperature and therefore also limits the temperature exiting the chimneys. This situation thus results in greater energy production [20] due to low heat losses.

F. Energy efficiency of boilers

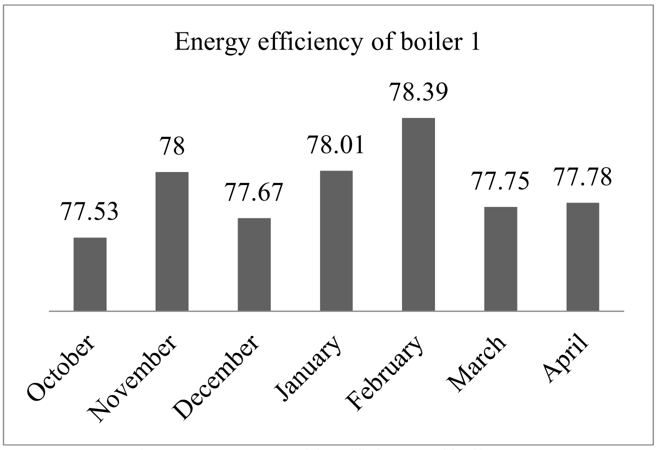

Fig 7. Average monthly efficiency of boiler 1.

The values were calculated via Eq. (4), and Fig.7 shows a highly variable trend in the efficiency value for boiler 1. The highest value is recorded in February, and the heat outlet in that same month is one of the lowest. This helps explain the higher efficiency [21–23]. The lowest efficiency observed in December corresponds to the period when the bagasse moisture content was at its lowest, coupled with the highest outlet fumes heat, which could be attributed to a combustion chamber insulation defect.

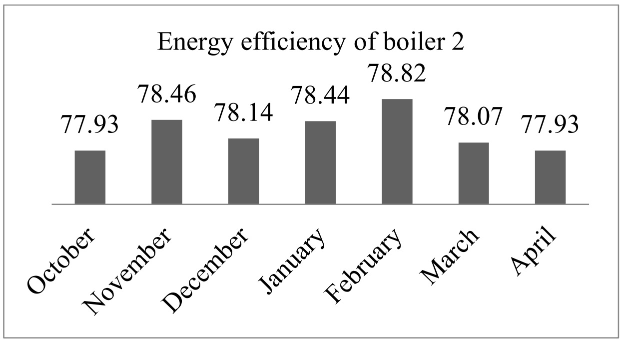

Fig. 8. Average monthly efficiency of boiler 2.

A highly variable trend in the efficiency value for boiler 2 is shown in Fig. 8. This is similar to the values for boiler 1, with a slight difference. This indicates a higher efficiency for boiler 2, a value consistent with the lower temperatures observed in this same boiler.

IV. Conclusion

This study analyzed the energy performance of two boilers fueled by sugarcane bagasse from a processing company. The results revealed that the bagasse moisture content varies between 45% and 49% from one harvest to the next and that at very low moisture levels (45%), the efficiency is low (78.14%) because of excessive heat loss at the combustion outlet (336 kcal/kg). The optimum moisture content, according to our study, is approximately 47%. Furthermore, we observed that to utilize bagasse with a high calorific value (low moisture content), a boiler with good heat shielding is necessary.The future challenges to this work include utilizing the fumes from bagasse combustion or solar thermal energy to dry the bagasse before it enters the boiler. They also include implementing a system for recovering combustion ash, which could be used as fertilizer for sugarcane plantations.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

A.S.Kconducted the research, conceptualization, methodologie, writing original draft preparation; S.J.M.K analyzed the data, writing review and editing; K.E.K wrote the paper, visualization; Z.A.Tvisualization; O.T methodologie, data curation, formal analysis; all authors had approved the final version.

Acknowledgment

The authors wish to thank Department of Technology of UFHB.

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