Sugarcane Bagasse and Cane Trash as a Fuel

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Abstract

Sugarcane bagasse is a by-product milling sugarcane and it is an important fuel resource for the sugar industry. Bagasse is a fibrous, has low density material and has a wide range of particle sizes with high moisture content. Sugarcane bagasse (SCB) is among the most abundant agricultural residues globally in sugar producing countries. Bagasse is mainly used as a fuel for cogeneration by the sugar factories, but has other applications like ethanol production, paper and pulp manufacture, biogas production and charcoal briquettes manufacture. The falling electricity prices and reducing global sugar prices due to excess sugar stock in the world market have made bagasse a very attractive fuel for grid-based electricity generation and supply making it a feasible diversification pathway for sugar factories. This study identifies the various physical, chemical, and thermodynamic properties of bagasse and sugar cane trash as fuels in the sustainable energy transition. The study recommends various policy initiatives to promote the use of bagasse and cane trash as a fuel particularly in heat and power generation. Proposed measures include attractive feed in tariffs for cogenerated heat and power, tax incentives and measures to encourage investment, and a flexible power purchase agreement that recognizes the unique challenges facing the sugarcane manufacturing like unsteady supply of cane and hence inconsistent milling and fuel supply. Bagasse has various pathways for exploitation as an energy resource i.e., direct combustion in boilers to produce heat for steam and power generation, anaerobic digestion to produce biogas and pyrolysis and gasification to produce syngas. Syngas and biogas can further be upgraded to produce biomethane which has significant energy and process applications as a substitute of natural gas. Bagasse has got three e major components, namely pith, fiber, and rind,
Key Words: bagasse; cane rash; bagasse cogeneration.

Introduction

Sugarcane is a major crop in many countries globally grown commercially for the production of sugar abundant. Sugarcane plant has one of the highest bioconversion efficiencies with ability to efficiently fix solar energy, to yield up to 55 tons of dry matter annually per hectare of land under cultivation. The harvested sugarcane leaves behind cane trash as the cane is transported to a sugar factory where it is crushed to extract juice at the mills or the diffuser leaving behind energy rich fibrous bagasse as the sugar is taken to the process house for sugar making(M. Kabeyi & O. Olanrewaju 2021; Kabeyi 2020; Kabeyi 2022). Sugarcane bagasse is a renewable feedstock used for power generation and manufacturing cellulosic ethanol in among other applications(Kabeyi 2020) . The energy potential of bagasse produced is more than enough to meet the heat and electricity energy needs of a traditional as well as modern sugar factory, making sugar factories ideal for grid based decentralized power generation. The main challenge facing many traditional sugar factories is that the existing technology adopted is inefficiently designed maximize bagasse burning as a disposal strategy and energy supply limited energy for the factory use (Ike 2013; M. J. B. Kabeyi & O. A. Olanrewaju 2022c).

The global price of sugar and petroleum products have shown variations since 1973, but the long term outlook shows a gradual increase fossil fuel prices and stagnation, in the price of sugar(Paturau, 2012). This scenario explains, to a large degree, global interest in diversification by the sugar industry which shows that optimal use of sugar production byproducts can support the sugarcane industry, which cannot redress the difficult situation by relying on sugar alone as the product(Kabeyi 2022; Paturau 2012). Bagasse is a pulpy fibrous material that remains after crushing sugarcane and in some cases sorghum stalks for juice extraction. Bagasse is used as a biofuel for the production of ethanol. It is also used as heat and electricity production, and as a feedstock for manufacture of paper and pulp and as building material (M. J. B. Kabeyi & O. A. Olanrewaju 2022e).

Bagasse is said to be a carbonaceous byproduct of sugar cane milling by sugar factories usually combusted in boiler furnaces to generate steam for power production and process steam and electricity generation to support the sugar factory processes(Kabeyi & Oludolapo, 2021). Efficient and economical use of bagasse is essential to for economic manufacture of sugar and production of excess electricity for export to generate extra revenue(Mtunzi et al. 2012). Generally, a ton of sugarcane ground for sugar and ethanol production contains on average , 50% moisture, 250–270 kg of bagasse, and more than 200 kg of straw. Bagasse has been used for many years in the production of steam and electricity needed for sugar and ethanol production, hence energy self-sufficiency of sugar factories (de Souza, 2020). Advances in technology and efficiency enhancement have made it possible for sugar factories to produce excess electricity for supply to the grid as an additional revenue stream(de Souza, 2020; M. Kabeyi & O. Olanrewaju 2021). The primary use of bagasse is heat and electricity generation to meet the energy needed for sugar and ethanol production in sugar factories. In many cases, bagasse is found in excessive supply for traditional sugar factories leading to challenges in waste disposal and storage for future use. It is for this reason the sugar factories are designed to deliberately burn the sugar cane bagasse at low efficiency for disposal. The highest producing sugar cane nations are Brazil (33%), India (23%), and China (7%). Sugar cane crushing produces about 30% mass bagasse. Five million tons of bagasse burned brings about one million tons of fuel oil saved. Therefore, bagasse is an ideal renewable biomass energy source with zero net greenhouse gas emissions(M. J. B. Kabeyi & O. A. Olanrewaju 2022f; Rakhoh Industries Pvt Ltd. 2022)**.**

Bagasse Production

Generally, each ton of sugarcane ground generates, on an average, 50% moisture, 250–270 kg of bagasse, and more than 200 kg of straw. Bagasse has been used since the industrial revolution, in the production steam and electricity thus guaranteeing the energy self-sufficiency of sugar factories (de Souza, 2020; M. J. B. Kabeyi & O. A. Olanrewaju, 2022a, 2022c). The manufacture of sugar from sugarcane has four main byproducts i.e. cane tops, bagasse, filter muds and molasses(Paturau, 2012). Assuming the world sugarcane production of about 60 million tons of sugar cane, table 1 shows the summary of the main byproducts of sugarcane crop

Table 1. Products of the sugar cane crop

Cane tops	200 million tons	(fresh weight)
Bagasse	60 million tons	(bone dry weight)
Filter muds	5 million tons	(air dried weight)
Molasses	16 million tons	(at 80 percent DM)

From table 1, it is noted that the main products of sugar cane factory are cane tops, bagasse, molasses, and filter mad or cake. It is also noted that for the kg of sugar produced, almost a similar amount of bone-dry bagasse is produced and about 3.3 times more of fresh cane tops are available

Bagasse as an Energy Resource

Sugarcane is an efficient converter of the solar energy into biomass through photosynthesis with the main components of sugarcane being sucrose, and fiber. Bagasse is combusted in boilers to produce thermal energy while carbon dioxide produced being absorbed in the next generation making it a carbon neutral process(M. Kabeyi & O. Olanrewaju, 2021; Moses Kabeyi & Oludolapo Olanrewaju 2022; M. J. B. Kabeyi & O. A. Olanrewaju 2021; Mtunzi et al. 2012). Therefore, countries producing more sugarcane produce more bagasse, cane tops and trash, filter muds and molasses which have significant energy potential that can be exploited. An important characteristic of bagasse is its high moisture content of 45-50% depending on milling quality. This complicates its combustion and energy value by lowering it (M. Kabeyi & O. Olanrewaju 2021; Moses Kabeyi & Oludolapo Olanrewaju 2022). Figure1 one shows the physical appearance of bagasse.

Figure 1. Physical appearance of bagasse

From figure 1, it is noted that bagasse is a fibrous form of biomass consisting of fibers of different sizes and shape The main elements of bagasse include potassium and sodium which are present in biomass ash in the forms of oxides. Their presence can lead to fouling and ash deposition on the convective parts of the boiler. The presence of Alkali chlorides also contribute to slagging, fusion and sintering of ash particles which leads to to solid deposits on boiler tubes and leading to increased corrosion and cost of operation and maintenance(Rakhoh Industries Pvt Ltd. 2022).

Bagasse is the fibrous residue of the cane stalk left after crushing and extraction of the juice. It consists of fibers, water and relatively small quantities of soluble solids - mostly sugar(Paturau, 2012). The fiber consists mainly of cellulose (27 percent), pentosans (30 percent), lignin (20 percent) and ash (3 percent). The calorific value (CV) of bagasse is given by the formula: Net CV = 18 309 - 31.1 S - 207.3 W - 196.1 A (expressed in kJ/kg). where, S= soluble solids %, W is moisture %bagasse and A= Ash% bagasse(Kabeyi, 2022; M. J. B. Kabeyi & O. A. Olanrewaju, 2022e).

If W = 0, S = 2 and A = 3, then the net CV of bone-dry bagasse = 17 659 kJ/kg.

If W = 50, S = 2 and A =1 1/2 then the net CV of mill-run bagasse = 7 588 kJ/kg.

Bagasse is used for the generation of steam and power required to operate the sugar factory. A typical factory producing raw sugarcane require, about 35 kWh of electricity per ton of cane and 450 kg of exhaust steam. Much progress has been achieved lately and, with continuous operation of the pans, crystallizers and centrifuges and an efficient evaporation station, a modern raw sugar factory can now operate with 30 kWh and 300 kg of exhaust steam per ton of cane. Such a factory can save 50 percent of the bagasse it produces and this bagasse can be used to produce electricity for the grid or saved as raw material for the production of paper, board, furfural, etc.(Kabeyi 2020; Paturau, 2012).

Physical Properties of Bagasse

Bagasse from sugarcane is a fibrous material that is left after juice extraction at the cane sugar factory. Bagasse is s mainly used as a fuel by sugar factories to generate steam in boilers for process heating and electricity production. Sugarcane bagasse is the fibrous waste that remains after the recovery of sugar juice via crushing and extraction. It also has been the principal fuel used around the world in the sugarcane agro-industry because of its well-known energy properties(Pippo & Luengo 2013). The sugar making process normally converts over 25% of the initial weight of sugarcane bagasse. The combustion of bagasse produces about 3–5% of the its weight as sugarcane bagasse ash (SCBA)(Prabhath et al., 2022). Bagasse is rich in moisture whose composition varies between 45 and 55%. In a typical Brazilian scenario 280 kg of wet bagasse is from a tone of milled cane making it a significant byproduct of a sugar cane factory(Prabhath et al., 2022), (Pippo & Luengo, 2013).

Bagasse produced by a traditional factory is in excess of the energy requirement of the factories and often cause a disposal nightmare. For this reason, the traditional sugar mail is design to inefficiently burn off bagasse a waste disposal strategy. It is estimated that use of more efficient bagasse boilers can reduce bagasse consumption by up to 36%. Which can be used for more steam and power generation or can be used as feedstock for other processes like bioethanol production(M. Kabeyi & O. Olanrewaju, 2021),(Kabeyi & Oludolapo, 2021).

Composition of Dry Bagasse

Sugarcane consists of dissolved solids called brix, water, and fiber. Fiber is an important component, of sugarcane that determines the quantity of bagasse produced. Generally, in sugarcane consists of 11 to 16% sucrose content, while bagasse levels range from 27 to 38%(Reddy & Yang 2015). In a typical sugar factory, every 10 tons of sugarcane milled generates about 3 tons of sugar cane bagasse. Bagasse as a fuel has sufficient energy that can be used to supply the entire energy needs of a factory for steam and power generation thus making the industry self-reliant with respect to steam and power needs and export the excess energy and earn extra revenue (Bartens 2017). According to (Wibowo, 2022) Bagasse is a heterogeneous fibrous residue formed after juice extraction from sugar cane at the mill. Generally, milling 100 tons of sugarcane generates 30–34 tons of bagasse of which 22–24 tons is used to supply energy for sugar production with about 8–10 remaining as excess in a conventional sugar factory. According to (Reddy & Yang, 2015) 30–32 % of the weight of the cane is generated as coproducts. Bagasse consists of 45–55 % cellulose, 20–25 % hemicellulose, and 18–24 % lignin.

According to (Hajiha & Sain, 2015) sugarcane bagasse is composed of approximately 50% cellulose, 25% hemicellulose and 25% lignin (Huang *et al*. 2012, Xu *et al*. 2010). The high cellulose content makes bagasse ideal for use as composite reinforcement material. Multiple researches have recorded different chemical compositions for bagasse. The crystallinity in sugarcane bagasse is about 47% and most of the cellulose in bagasse is in a crystalline structure. An elemental analysis of bagasse shows that it is composed of 45.5 wt% C, 5.6 wt% H, 45.2 wt% O and about 0.3 wt% N (Bilba *et al*. 2003). Additionally, the metal elemental analysis of bagasse shows that it contains 3.89 wt% Al^{3+}, 3.87 wt%; Ca^{+}, 1.32 wt% Mg^{+}, 0.97 wt% Na^{+} and 27.0 wt% Si^{4+} (Jústiz-Smith *et al*. 2008). It should be noted that the presence of these metals in the fibers increases the brittleness of bagasse(Hajiha & Sain, 2015).The composition of bagasse is summarized in table 2.

Table 2. compositing of dry bagasse(Nikodinovic-Runic et al., 2013)

	Constituent	Composition %
1	Cellulose	45-55
2	Hemicellulose	20-28
3	Lignin	18-24
4	Minerals	1
5	Ash	1
6	Sugar	5
	Total	100

From table 2, it is noted that dry bagasse consists of about 28% hemicellulose, 45% cellulose, 1% minerals, 20% lignin, 5% sugar, and 1% ash. The composition of bagasse is similar to wood but it contains higher moisture content. This makes bagasse ideal for manufacture of paper and pulp, biofuel, filler for building materials and as a substrate for the growing of mushrooms. The fact that bagasse available is more than what is needed for the energy needs of the sugar factories makes it a candidate for value addition(Nikodinovic-Runic et al. 2013).

Sugarcane bagasse has two major types of fibers i.e. rind and the inner pith. The fibers in rind are useful because of their longer length and relatively better mechanical properties compared to fibers from inner pith which have wide applications but have inferior mechanical properties due to short lengths (Mahmud & Anannya 2021).The stems of cane contain mainly pith (5 %), fibers (73 %), and the rind (22 %) (Becharry, 1996; Bressanin et al. 2021).. Pith and the outer rind are sources for fibers in sugar cane. Pith is lighter with a considerably lower density of about 220 kg/m^3 and made up of coarse fibers and large cavities compared to rind whose density is density 550 kg/m^3(Reddy & Yang 2015).

Thermodynamic properties of Bagasse

The main application of bagasse is as fuel for steam and power generation for process consumption in juice treatment, fermentation, drying and other thermal applications and can use a minimum of 50% of the bagasse generated, with the remaining bagasse or excess bagasse requiring some form of disposal or alternative application and may lead to safety and health issues like spontaneous combustion, and fermentation. It is for this reason that sugar factories deliberately burn excess bagasse mainly through deliberate inefficient combustion at the boilers(Prabhath et al. 2022), (Pippo & Luengo 2013).

The calorific value and humidity of biomass are the main determinants of the cogeneration potential of bagasse and another biomass. The average caloric value of dry bagasse is about 18 MJ/kg as compared to other fuels e.g. bituminous coal has 30.2 MJ/kg, while dry wood is 19.8 MJ/kg (Morales-Guilléna et al. 2022). According to (Morales-Guilléna et al. 2022), the use of bagasse as a fuel can reduce carbon dioxide emissions by about 8% and meet the entire energy demand of the sugar industry.

Bagasse with 50% moisture content has a gross calorific value (GCV) of about 8,816kj/kg to 9,600 kJ/kg while the net caloric value is about 7,600 kJ/kg. The gross calorific value of dry ash free bagasse is about 17,632 kJ/kg -19,400 kJ/kg(Hugot, 1986; Kabeyi 2020). Sugar cane crop has fiber content of 10- 17% by mass which forms bagasse on milling. About 24 -30% i.e. about is about one quarter of the weight of sugar cane milled is bagasse (M. Kabeyi & O. Olanrewaju 2021; Moses Kabeyi & Oludolapo Olanrewaju 2022; Kabeyi 2022). The calorific value of the various bagasse constituents is shown in table 3

Table 3. Calorific value of different bagasse constituents (Hugot 1986; Kabeyi 2020)

Item	Constituent	Calorific Value (kJ/kg)
1	Fiber	19,320
2	Sugar	16,611
3	Impurities	17,220
4	Water	0

From table 3, it is noted that the main components of bagasse are water, fiber, sucrose/sugar, and impurities. However, water is the non-combustible component as the rest i.e. and noncombustible elements of bagasse fuel while fiber, sucrose/sugar, and some impurities are the combustibles.

The physical properties of bagasse from different sugar cane varieties may vary slightly but, the gross calorific value of dry bagasse is almost constant different varieties and from different countries. Table 4 below shows a summary of the gross calorific value of bagasse from different countries.

Table 4. GCV of bagasse by state/Country(Hugot 1986; Kabeyi 2020)

Country	GCV of Dry Bagasse (Kj/kg)
Australia	19,076
South Africa	19,257
Hawaii	19,412
Cuba	19,702
Puerto Rica	19,295
Average	19,488

From table 4, it is observed that the average (GCV) 19,488 kJ/kg of dry bagasse. However, since dry bagasse has about 6-7% moisture content, or an average of 6.5%, the gives net calorific value of NCV is about 17,850kj/kg.

Emissions from Bagasse

The main pollutants from bagasse fired boilers is the particulate matter caused by the turbulent movement of flue gases from bagasse combustion and the resultant ash. Bagasse has low levels of sulfur and nitrogen compared to conventional fossil fuels hence the low sulfur dioxide (SO_2) and nitrogen oxides (NOx) in bagasse combustion. Dirty cane influences the bagasse's ash content while neglecting combustion conditions increases emissions of unburned organics and carbon monoxide (CO), expressed as volatile organic compounds (VOCs) and total organic compounds (TOCs)(Rakhoh Industries Pvt Ltd. 2022).

Bagasse power installations mainly use wet scrubbers and mechanical collectors to control the particulate emission from boilers. The impingement and venturi scrubbers are the types of wet scrubbers primarily applied in bagasse boilers. Impingement scrubbers are installed on the gas-side and have the benefit low energy requirements and relatively low maintenance problems and incur pressure drop of 5 to 15 inches of water. For venturi scrubbers, the pressure drop is over 15 inches of water. Both scrubbers have collection efficiency of over 90 %(Rakhoh Industries Pvt Ltd., 2022). Mechanical collectors may be installed as a single cyclone, double cyclone, or multiple cyclone dust collector and have collection efficiency of between 20 to 60 %. The performance of the mechanical collectors may negatively impacted over time due to the abrasive nature of bagasse fly ash and the erosion if the system (Rakhoh Industries Pvt Ltd., 2022)

Bagasse Ash

Leading sugar-producing nations have been generating high volumes of sugarcane bagasse ash (SCBA) as a by-product. SCBA has the potential to be used as a partial replacement for ordinary Portland cement (OPC) in concrete, from thereby, mitigating several adverse environmental effects of cement while keeping the cost of concrete low. The majority of the microstructure of SCBA is composed of SiO_2, Al_2O_3, and Fe_2O_3 compounds, which can provide pozzolanic properties to SCBA. In this paper, literature on the enhancement of the mechanical properties of SCBA-incorporating concrete is analyzed. Corresponding process parameters of the SCBA production process and properties of SCBA are compared in order to identify relationships between the entities. Furthermore, methods, including sieving, post-heating, and grinding, can be used to improve pozzolanic properties of SCBA, through which the ideal SCBA material parameters for concrete can be identified. Evidence in the literature on the carbon footprint of the cement industry is utilized to discuss the possibility of reducing CO_2 emissions by using SCBA, which could pave the way to a more sustainable approach in the construction industry. A review of the available research conducted on concrete with several partial replacement percentages of SCBA for OPC is discussed.(Prabhath et al. 2022).

There can be a high variability in the ash content of sugarcane bagasse. This is in large part due to variations in the practices used for harvesting the sugarcane. In some cases, the harvested crop can contain a significant proportion of soil, a trend that will lead to increased ash in the bagasse. Figure 2 shows the various applications of ash from bagasse fuel combustion.

Figure 2. Production of ash and use in cement manufacture(Prabhath et al. 2022)

Figure 2 shows the process of ash production and feasible applications. Sugar cane ash can be used in manufacture of cement with additional value addition to the sugar industry, low cost concrete and lower emissions as benefits.

Sugar cane Trash as Fuel for Cogeneration

Properties of sugar cane trash

Sugarcane consists of clean stalk (72%), GSTs (8%) and DSLs (20%) while the amount of trash that remain in the field after harvesting depends on the harvesting method, cane variety, and moisture content (MC) of trash. The moisture content GSTs and DSLs are about 65% and 15% weight basis respectively. Since DSLs has about three times more silica than GSTs, the high silica content (2.76%), makes the fodder not recommended for the livestock. The lignin content in GSTs is about 60% higher than DSLs. The high lignin and silica restricts the application of sugarcane trash (ST) for fuel purpose and use as livestock fodder(Gonçalves et al. 2021). The sugarcane tops and dry leaves have differences in nutrients content and moisture content. About 80 % of N, P and K is derived from the sugarcane tops hence more nutritive and valuable to the soil leading to use of less mineral fertilizers for sugarcane cultivation. Additionally, the tops have about seven times more moisture than dry leaves and also have higher levels of extractives organic compounds of low molecular weight. It is predicted in studies that dry leaves are more viable for production of second generation ethanol production compared to tops due to better results of yield in the pretreatment steps for dry leaves although glucose yields obtained in the enzymatic hydrolysis step were similar (Gonçalves et al. 2021),(Franco et al. 2013).

The chemical composition of sugarcane trash in terms of average per cent ash, lignin, cellulose and hemicellulose is about 7.17 ± 1.65, 20.18 ± 5.75, 44.55 ± 4.70 and 27.44 ± 2.54, respectively. The carbohydrate and silica content in sugarcane trash is about 57.5% and 6.96%, respectively. This shows that trash has potential applications in biochemical conversions like anaerobic digestion for biogas production, biofuel processing and ethanol production(dos Santos & Ricardo A. V. Ramos, 2020). Therefore, trash has significant potential for power generation, production of 2nd generation ethanol and production of other biochemical products(Franco et al. 2013).

Energy potential of trash

Sugarcane has emerged as an interesting complementary fuel for the sugar cane factories. Trash is the residue usually left in the sugarcane field in quantities representing about 125 kg trash/ton of cane harvested. Possible pathways in the use of trash for energy purpose conversion to syngas mixed with the bagasse or co-firing with natural gas at the gas turbines or can be used in an afterburner to supply extra/ additional energy directly to the HRSG(Ensinas et al. 2006). It is however operationally easier to transport straw along with sugarcane in the same truck which increases handling costs (dos Santos & Ricardo A. V. Ramos 2020).

Sugar cane trash has got same energy as bagasse but it is wasted during open burning at the farms. It is estimated that trash contains about one-third of total energy contained in sugarcane. Sugar factories and sugar producing nations can realize some sustainable and socioeconomic development by harnessing energy in sugarcane trash through creation of. extra employment opportunities and conservation of the environment and further contribute to profitability and sustainability of sugar factories. The main limitation is the technological and economic challenges to utilize in commercial exploitation of sugar cane trash. for steam and power production. Specific constraints include lack of technological awareness, lack of incentives, poor purchasing power of the farmer and lack of market for the trash or energy (Gonçalves et al. 2021).(Powar et al. 2022).

Besides bagasse as a boiler fuel, trash is a significant material that can be used as boiler fuel. Trash is the residue left in the field after sugarcane is harvested, comprising mainly of leaves and the tops of the plant; cane portions with low or insufficient sucrose content hence not worthy for juice extraction in milling(Prabhakar et al., 2010). On average basis, every ton of sugar cane harvested yields about has, 140 kg of trash. However, this only applies in the case of mechanically cane harvesting which involves the trash being blown back onto the field during harvesting as opposed to manual harvesting where the crop is burnt prior to harvesting by workers who chop the stems. This burns leaves and only leaves the stems and roots as trash. Manual harvesting is a common practice in developing countries including Brazil which had set a targeted 2020 for all harvesting to be mechanical(Prabhath et al. 2022), (Pippo & Luengo 2013),(Kabeyi 2020).

Dry sugarcane trash contains about 28% of the total energy content in the sugarcane crop. In the study by(Prabhakar et al., 2010), it was noted that in India alone, if all the cane trash is utilized for energy purpose, the national energy deficit can be cut by 50% and the sugar industry can generate additional 110% power for export.. Sugarcane trash contains more silica and alkali making it undesirable as a boiler fuel directly(Kabeyi, 2020),(Prabhakar et al., 2010). Therefore, trash processed with the cane supply should be thoroughly washed at mills to reduce the alkali and silica content of resultant bagasse for cases where trash is harvested together with sugar cane and delivered to the factory(Prabhakar et al. 2010).

Cogeneration System

In the 1970s and 1980s, sugar factories were designed to consume all the bagasse in production of steam and electricity for internal use. The systems were so inefficient that some factories needed additional fuel from elsewhere(Kabeyi 2020; Pellegrini et al. 2010). In the 1990s and early 2000s, the sugarcane industry faced an open market perspective, hence more need to reduce operating and production costs. Additionally the economic value of the factory by-products i.e. bagasse, molasses, etc. increased while decentralization of generation and the quest for renewable energy sources created a possibility of selling power to the public grids. These development led to a search for more advanced cogeneration systems, using higher steam parameters, while in future, even more advanced systems like biomass integrated gasification combined cycles may be adopted by the sugar mills (Moses Kabeyi & Oludolapo Olanrewaju 2022; Pellegrini & de Oliveira Junior 2011). These cogeneration systems can attain 35–40% efficiency in power generation .Supercritical steam cycles can also realize such efficiency values, making them attractive alternative to gasification-based systems(Pellegrini et al. 2010).

The boilers in traditional sugar mills generally operate at steam temperature of 300 °C and pressure of 21 bar used to generate electricity using backpressure turbines, with backpressure steam pressure of 2.5 bar for factory thermal applications in processes while the condensate of good quality is fed back to boiler(Pellegrini et al., 2010). Modern mills use boilers with higher parameters of 40 –120 bar, and produce excess electricity for sale to the using backpressure and condensing-extraction steam turbines (Pellegrini & de Oliveira Junior, 2011). Much higher generation promise to be generated in future by adopting more efficient configurations like Biomass Integrated Gasification Combined Cycles (BIGCC), Supercritical Steam Cycles (SuSC) and other advanced gasification based systems. (Pellegrini & de Oliveira Junior, 2011; Pellegrini et al.2010).

There are different options for use by sugar factories to simultaneously generate electricity, sugar and ethanol(Pellegrini & de Oliveira Junior, 2011). The different cogeneration options are;

Conventional Backpressure Steam Systems (BPST)

The back-pressure steam turbine (BPST) systems involves use of a back-pressure turbine with exhaust pressure above atmospheric pressure normally 2 To 2.5 bar for process use. These are the most common configuration in many sugar factories. The back pressure system can still generate excess electricity through process modernization to reduce steam consumption as well as steam and power generation efficiency improvement. (Pellegrini & De Oliveira 2007).

Condensing-Extraction Steam Systems (CEST)

The condensing extraction steam turbine system is applied as an option in which a condensing-extraction turbine is used to supply low pressure steam extracted from the expansion for process application while the excess is exhausted to the condenser. Other measures to improve performance compared to the back-pressure steam turbine is to reduce process steam consumption from average of 500 kg/tc to about 400 kg/tc, (Kabeyi & Oludolapo, 2021; Pellegrini & De Oliveira, 2007). Both BPST and CEST can use different steam generation temperatures and pressures were used e.g. 42 bar/400 ºC, 42 bar/ 450 ºC, 67 bar/480 ºC, 67 bar/515 C, 80 bar/520 ºC, 100 bar/520 ºC and 120 bar/540 ºC (Pellegrini & De Oliveira, 2007).

Supercritical Steam Systems (Susc)

The supercritical steam system is an improvement of the condensing extraction steam system. The system used very high steam parameters and regenerative heat exchangers for preheating boiler feed water which effectively improves the cycle efficiency. There is also a possibility of applying gas turbine for power generation thus a biomass gasification-based system is a possible option. Bagasse and cane trash is dried and sent to a gasifier, to produce producer gas which is used as a fuel in the gas turbine system while turbine exhaust gases are passed through a Heat Recovery Steam Generator (HRSG) to generate steam for use in a condensing-extraction turbine for extra power generation(Kabeyi, 2020; Pellegrini et al., 2010).

Biomass Integrated Gasification Combined Cycles (BIGCC)

There are two main configurations for BIGCC technology. They are low pressure air-blown and high-pressure air-blown (Pellegrini et al., 2010; Pellegrini & De Oliveira 2007). The BIGCC is made up of four major subsystems, namely; fuel system for handling and feeding fuel to the BIGCC system, the gasifier, the gas clean-up unit (GCU), and combined cycle system. The gas turbine system and steam turbine system are integrated together (Pellegrini & de Oliveira Junior 2011; Pellegrini et al. 2010).

Cogeneration Potential of Sugar Factories

Cogeneration in sugar factories involves simultaneous production of thermal energy and electricity with bagasse as a fuel. With cogeneration, the total efficiency of the sugar factory increases to about 50%(M. J. B. Kabeyi & O. A. olanrewaju 2022b, 2022f). The traditional factories generate just enough electricity and steam for factory internal use while high efficiency cogeneration sugar mills have boilers with high thermal efficiency, more efficient condensing extraction steam turbines or other efficient turbines to produce excess electricity and have modernized process equipment and drive systems that consume less steam and electricity to maximize the power production and export. Bagasse cogeneration is the use of the fibrous sugarcane waste called bagasse to produce electricity and heat by sugar factories.((WADE) 2004; Kabeyi 2020; Kabey, 2022). The energy potential of bagasse is determined mainly by the moisture content and the energy generation technology applied in power generation and steam generation. The electric power output is fundamentally dependent on market rules and incentives available like feed in tariffs and other drivers of production efficiency ((WADE) 2004; Kabeyi 2022).

Bagasse fiber accounts for 25 to 30% of the weight sugar cane milled factory with 50% being the moisture content (da Silva et al. 2017; Kabeyi 2020). The thermodynamic performance of a bagasse cogeneration facility can be expressed in the form of energy utilization factor, heat-to-electricity ratio, fuel saving ratio exegetic efficiency, and electricity produced per ton of cane. Cogeneration plants using high pressure, Rankine cycle steam turbine generally produce 115–120 kWh/tc, while BIG-GT and BIG-STIG very high generation potential of 270–275 kWh/tc. Cogeneration with the backpressure and condensing steam turbines have energy and exegetic efficiencies of about % and 22–25%, and 60–70% respectively. Other important parameters for the sugar factory and bagasse cogeneration power plant is the steam consumption which varies between 480–550 kg/tc milled. The electricity demand of a sugar factory varies between 16–22 kWh/tc for mill turbine driven mills and 32–40 kWh/tc for electrified mill drives(Kabeyi 2022; Kabeyi & Oludolapo 2021).

The conventional sugar mills with no power export generally produce 10-20 kWh electrical energy/tc and consume 480-550 kg steam/tc, while modern mills applying efficient conversion systems produce electrical energy in the range of 115-120 kWh/tc. Application of steam saving measures in the sugar factory releases steam from process and milling application to production of extra power. From various studies on bagasse cogeneration, it was established that reducing steam consumption from 500 by 30% to 350 kg/tc increases power generation by 24% while partial use of cane of cane trash can increase excess power generation by or two folds(Birru 2016; M. Kabeyi & O. Olanrewaju, 2021; Kabeyi 2020).

There are many benefits that come with investment in export cogeneration by sugar factories as a diversification strategy. They include revenue diversification, stabilization of the sugar industry, job creation and extra revenue and stable revenue for sugar cane farmers(Kabeyi & Olanrewaju 2021). Cogeneration experience from countries like India, Réunion, Mauritius, Brazil and Cuba have has proved that the sugar industry can supply significant electricity to the grid which helps in mitigating the greenhouse emissions and help countries realize their emissions and climate targets(Gonçalves et al. 2021; Prabhath et al. 2022).

Sugar production is an energy intensive undertaking which requires energy mainly in the form of heat/steam and electricity. In the conventional or traditional factory, a back-pressure turbine supplies electricity and steam from its exhaust for process use. The modern sugar mills generally use the condensing extraction (CEST) which is more efficient to generate electricity in excess for internal use and sale to the grid while extracted/bled off steam is used for process thermal applications. The main sugar factory energy consuming equipment are the cane knives, cane carrier elevators, the gantry cranes at cane yards, the mill drives, conveyers, pumps, evaporators, pans, centrifuges, and mills have either electric drives of steam turbine drives(Hugot 1986; Kabeyi & Olanrewaju 2021). The mills and cane knives are driven by either steam turbines or electric motors although electric motors are considered to be more energy efficient (M. J. B. Kabeyi & O. A. Olanrewaju 2022e).

The efficiency of conventional cogeneration systems using back pressure turbines have efficiency of about 25% at steam pressures of 20-30 bars. For systems using pressure of 45-66 bars, the electricity potential is about 100 kWh per ton of milled. For high pressure boilers of average of 82 bars, the generation capacity is about 110-130 kWh per ton of cane crushed based on experience from Reunion, Mauritius, India and Brazil. There are their basic bagasse cogeneration configurations applied, namely; intermittent generation in which the power generation is based on sugar production needs, continuous cogeneration power plants that are designed operate continuously during the sugarcane crop season with bagasse as main fuel and the firm power plants which operate throughout the year except for planned maintenance. Firm power normally operates for 300 days and are stopped for 65 to 66 for routine maintenance. (M. J. B. Kabeyi & O. A. Olanrewaju 2022e). The characteristics of the three types of bagasse cogeneration power plants are shown in table 5.

Table 5. comparison of the three cogeneration setups that can be adopted by sugar mills.

	Parameter	Intermittent Generation	Continuous Generation	Firm power Generation
1	Power generation capacity (kWh/ton)	10	60	110-130
2	Cane milling rate	10 TCH or 240 TCD	150 TCH or 3,600 TCD	230 TCH or 5600 TCD
3	Load factor and availability	Intermittence allowed	Continuous at 90% load factor	Continuous at 90% load factor, 300 milling days or 7200 hours a year and 65-66 days for maintenance.
4	Ratio of Steam to bagasse	1.8:2.2	2.5	2.5
5	Steam pressure (bars)	25 to 30	30-45	82
6	Type of turbine used	Back pressure	Condensing	Condensing type
7	Boiler capacity (tons/hr)	40	120	140-150
8	Steam consumption	500-600 kg/ton of cane crushed	400 kg/ton of cane milled	400 kg/ton of cane milled

9	Electricity consumption	25 kWh/ton of cane crushed	30% internal consumption	Not more than 30% internal consumption
10	Turbine capacity	0.5-3 MWe	At least 15 MW	At least 30 MW

From table 5, it is noted that firm power plants have the highest generation capacity and use boilers with highest steam pressure of 82 operate at high load factors of 90% followed by the continuous power plants which also operate at a load factor of about 90% bars and use boilers with medium pressure range of 30 to 45 bars. The intermittent power plants usually use low pressure boilers of pressure 25 to 30 bars which are associated with the traditional sugar factory conditions.

The internal electricity consumption is limited to 30% for the continuous and firm power plants while the intermittent power plants generally consume 25 kWh/ton of cane milled. The steam to bagasse ratio is 2.5 for the continuous and firm power plants hence more efficient than the intermittent whose ratio is 1.8:2.2. on average basis. Another indicator of steam efficiency is the steam consumption which is 400 kg/ton of cane for continuous and firm power plants and 500-600 kg/ton for the intermittent mills. The average turbine capacity for an intermittent power plant is 0.5 to 3 MWe for intermittent power plants, 15 MWe for continuous and 30 MWe for the firm power plants. However, we have several cases of capacities beyond the stipulated range(Kabeyi 2020; M. J. B. Kabeyi & O. A. Olanrewaju, 2022c 2022d).

Investment Costs for Bagasse Cogeneration

The investment cost for bagasse cogeneration power plants depends on the net export capacity and technology adopted. Low pressure plants cost about $1.4 million/MW, mid-range pressure systems cost about $1.8 million/MW while the high pressure at the top end cost about to $3.1 million/MW. These costs compare favorable against heavy fuel plants which cost about $1.1 million/MW, geothermal at $2.25 million/MW and $2.5 million/MW for hydroelectric power plants. The advantage of bagasse power plants over the thermal power plants is that they do not have a fuel cost assuming bagasse is waste product or byproduct of sugar production process but the thermal power plants have significant fuel costs that are passed directly to consumers in addition to the electricity or energy costs(Dantas et al. 2013).

Investment Options for Bagasse Cogeneration

Experience from past bagasse cogeneration projects around the world the following design specifications for a 5000TCD (tones per day sugar factory) in terms of bagasse consumption, generation capacity, investment capital and actual electricity generation for 45, 60 and 82 bars boiler steam configurations. Table 6 is the summary of the various parameters

Table 6. Investment guidelines for bagasse cogeneration projects(Kabeyi 2020)

Component	Possible plant options		
Boiler pressure (bar)	45	60	82
Recommended plant capacity (tons of cane per day)	5000	5000	5000
Boiler capacity (tons of steam per hour)	140	140	140
Bagasse feed rate (tons per hour)	58	62	70
Turbine capacity (MW)	25	30	50
Daily power generation, gross (MWh)	420	550	820
Equivalent capacity (MW)	18	24	40
Daily export power, net (MWh)	260	330	550
Equivalent export capacity (MW)	12.5	14	24
Total capital investment ($ million)	18	25	75
Estimated local component ($ million)	4	5	12

Estimated annual revenue from electricity ($ million)	4	5	8.3
Simple payback period (years)	4.5	5	8.8

From table 6, it is noted that, based on factory size and choice of technology, there are three types of boilers that can be selected for generation of steam based on a 5,000 TCD sugar factory. The steam pressure ranges from 45 to 82 bars or closer denominations. The annual electricity revenue is between USD4 and USD 8.3 million dollars and payback period ranges between 4.5 years and 8 .8 years based on experience from similar projects.

Bagasse To Energy Conversion Pathways

Biomass energy resources in energy crops, animal waste, wood waste and crop residues can be extracted by direct combustion or conversion into gaseous fuels like biogas and syngas and then combustion of the intermediate energy carriers to release energy. Anaerobic digestion of biomass involves bio-digestion of biomass with high moisture content in oxygen deficient to produce biogas. Gasification on the other hand is ideal for conversion of particularly for low-moisture biomass into syngas in as environment with limited amount of air at high temperatures(Nguyen & Hermansen 2015).

As a conservation measure, the non-energy by-product of gasification and direct combustion i.e. ash and the digestate from anaerobic digestion should be applied appropriately to the agricultural soils for nutrient to recycle farm nutrients and reduce the use of commercial fertilizers. For fly ash, which is a product of direct combustion and gasification, the presence of heavy metals may exert toxicological effects to the soil and by a good practice should not be applied to the soil 40],(Nguyen & Hermansen, 2015). The main challenge bagasse use as an energy resource is the high moisture content and low calorific value, high oxygen content, the hygroscopic nature of bagasse, and heterogeneous properties which causes challenges in handling, storage, transportation, and combustion or conversion [36].

4.1. Direct Bagasse Combustion

In direct bagasse conversion to energy, bagasse in its raw form which is solid state is burned in an excess of air in boiler furnaces to produce heat which is used to generate steam. The produced steam is used to run steam turbines for power generation as well as prime movers for sugar factory plant and equipment like for mill drives as well as cane knife turbines(M. J. B. Kabeyi & O. A. Olanrewaju, 2022c, 2022d). Efficient combustion may need extra drying process to reduce to to an optimum level except for anaerobic digestion(Nguyen & Hermansen 2015).

4.2. Bagasse Gasification

Biomass gasification is an important technology for wider use of biomass as a source of energy. Gasification is a thermochemical conversion process done in limited supply of oxygen to produce a gaseous mixture called syngas. Syngas consists of mainly of hydrogen and carbon monoxide(Nguyen & Hermansen, 2015). Carbon conversion rate is the key measure of the efficiency of gasification process. For a circulating fluidized bed gasifier, maximum carbon conversion reported is 98–99%(Nguyen & Hermansen 2015). Gasification is a mature technology used to convert carbon-rich biomass to useful combustible gas mixtures e.g. carbon monoxide, hydrogen, and methane. Conversion is achieved by reacting biomass with oxygen in air steam, and carbon dioxide at temperatures higher than (>600 °C)(Jenkins 2015). Gasification is classified as a thermochemical conversion process carried out in a limited supply of oxygen to produce a gaseous mixture called syngas made up hydrogen and carbon monoxide. Carbon conversion is a key measure of the gasification efficiency. Maximum carbon conversion of a circulating fluidized bed gasifier can be as high as 98–99%(Nguyen & Hermansen 2015; Stevens 2001).

Gasification systems can supply clean products for use as fuel or synthesis gases in an environmentally friendly processes(Stevens 2001). The similarity between gasification and direct combustion is that they perform better with low moisture content of biomass unlike for anaerobic digestion(Nguyen & Hermansen 2015). Gasification provides a pathway towards sustainable renewable energy sources by converting organic, or fossil based carbonaceous materials to produce hydrogen, carbon monoxide, methane and carbon dioxide. The reaction in gasification normally takes place at high temperatures, usually above 1000°Cin limited supply of oxygen and/or steam. The product of gasification is syngas or producer gas whose heating value is 4-6 MJ/kg. Use of syngas is potentially more efficient than direct combustion of the original like bagasse. Bagasse gasification generates some CO_2 but it is the CO_2 consumed during the growth of the crop rendering the process a carbon neutral process (Anukam et al. 2020).

Gasification of bagasse produces synthesis gas (syngas) and some smaller capacity of environmental contamination. Heat produced during gasification can be employed for steam production , and a gaseous fuel from the direct biomass combustion can be used as a fuel and can also be upgraded to biomethane(Figueroa et al., 2012). Bagasse is a suitable material for gasification because it has low ash content and has high content of volatile matter. The main limitation of bagasse as a gasification feedstock is the high moisture content which reduces volume of the syngas and its heating value. It also reduces the conversion efficiency of the gasifier because the heating value is directly proportional to the conversion efficiency of the gasifier(Anukam et al. 2020).

For sugarcane bagasse, gasification starts with pyrolysis, then gasification of the char formed. The properties of syngas produced depends strongly on the heating rate and temperature of the sample. Pyrolysis involves a series of hydrocarbons breakdown, fragmentation, isomerization and repolymerization. For high heating rates and high reactor temperatures, the gasification and steam reforming reactions happen parallel with some of the pyrolysis reactions (Ahmed & Gupta, 2012). Some end use technologies like turbines or synthesis gas systems demand high quality gases. Although boilers too have fuel quality requirements, the quality is not as stringent as the gas turbines. Gas from biomass gasifiers have some impurities in form of particulates, tars, and other constituents that may go beyond minimum recommended limits. Therefore, gas cleaning and conditioning becomes a necessary investment(Stevens 2001).

4.3. Anaerobic digestion

This is biological conversion process organic matter is digested in the absence of oxygen to produce biogas. Biogas is a mixture of gases with methane and carbon dioxide as the main components. Perennial crops e.g. miscanthus and willow yield lower specific methane yields than r annual crops like corn e.g. 0.20 m^3 of CH_4 compared to 0.36 m^3 CH_4 per kg volatile solid (VS) in anaerobic digestion, mainly because of the lignocellulosic structure.
The anaerobic biodegradability and methane yield from perennial crops can be enhanced by application of suitable pre-treatment e.g. wet oxidation which is a thermal pre-treatment method done under high pressure and. temperature of between 185 and 220 °C, and oxygen pressure of between 0–12 bar for a period of 15 min. The pretreatment increases methane yield for perennial crops to about 0.36 m^3 CH_4 (or. 0.65 ^{m3} biogas) per kg of VS, considering that about 5% of the organic matter is in the process. Not all methane potential can be extracted at once in anaerobic digestion, because storing digestate uncovered in tanks, leads to methane loss to the atmosphere from spontaneous degradation(Stevens 2001).

4.4. Comparison of Conversion technologies

None of the three feasible bagasse conversion technologies i.e., direct combustion, gasification, and anaerobic digestion is 100% carbon conversion efficient. It is for this reason that there is some amount of residue as ash or the digestate, whose magnitude depends on the carbon conversion efficiency of the process. Biochar carbon is the residue carbon contained in biomass ash from direct combustion especially in gasification. Biochar" is the charred organic materials produced from incomplete of biomass combustion. Sequestration of carbon through production and deposition of biochar has ability to fix 85% of the carbon in the char which is considerably greater than that associated with incorporation of crop residues into the agricultural soil. biochar is highly aromatic structure making it more resistant to microbial degradation than the un-charred biomass. Application of the digestate from anaerobic digestion to the field with residue carbon results in carbon sequestration at a rate of about 12% over 100-year period, if arable land is available for use. However, this carbon sequestration rate is lower than that of biochar, hence anaerobic digestion even with wet oxidation pre-treatment cannot favor the formation of biochar which takes place at higher temperature of about 500 °C (Nguyen & Hermansen 2015; Stevens 2001).

For over the last two decades, sugar factories prefer burning bagasse spreader stokers. Bagasse fuel enters the furnace through a fuel chute. Then it is spread across the furnace by means of charge air allowing part of the fuel to burn in suspension. Heat generated will heat waster in the tubes or water walls to generate steam (Rakhoh Industries Pvt Ltd. 2022).

Results and Discussion

A high ratio of cane crushed (TC)/TS (Sugar made) implies that juice extraction and sugar recovery in processes is inefficient as indicated by high bagasse pol (percentage of dissolved solids in sugar) which also causes undesirable effects to boiler combustion like formation of clinkers on boiler furnace grates during combustion of bagasse which inhibits boiler performance and efficiency by restricting flow of under-grate combustion air. High bagasse moisture content also negatively affects the combustion and steam rate by reducing the heating value of bagasse fuel. Good milling practice produces bagasse with moisture content of 45 to 50% (Kabeyi, 2020),(Powar et al. 2022). Drying bagasse an option that can improve bagasse properties as a fuel but economic sustainability needs further investigation under prevailing circumstances. Dry bagasse has got average universal gross calorific value (GCV) of about 19,488 kJ/kg of dry bagasse. Since dry bagasse has 6-7% moisture content, a working average of 6.5% moisture content gives net calorific value of N.C.V = 17,850kj/kg.

Grid electricity from sugar cane bagasse cogeneration power plants can be applied to complement polluting and expensive fossil fuels electricity and variable sources like hydroelectric power, wind and solar while at the same time provide additional revenue streams from sugar factories. Electric power from bagasse is cleaner compared to both fossil fuels and nuclear power. Since most farmer payment regimes in most countries, is such that farmers are paid for the cane supplied based on sugar content, disregarding the significant energy value of the fiber which produces bagasse fuel, commercialization of electricity and other products from bagasse can generate extra revenue where. the sugar cane farmer is paid for both sucrose and fiber in the cane which will increase the economic value of the sugarcane crop and sugar factories as well (M. J. B. Kabeyi & O. A. Olanrewaju 2022f; Kabeyi & Oludolapo 2020a, 2020b; To et al. 2018).

Bagasse cogeneration is of immense economic value since most sugar producing countries are less developed with high levels of unemployment and low access to grid electricity. Bagasse cogeneration if successfully adopted will accelerate social and economic development for the sugar cane producing nations. Agricultural activities account for about 45% of the Sub-Saharan Africa economy. The Agro-industries need various forms of energy for production and operations, and the employees where over 313 MW of installed generation capacity is installed in five sub-Saharan countries of Kenya, Malawi, Uganda, Tanzania and Ethiopia power capacity in agro-industries with over 270 MW coming from bagasse cogeneration (Kabeyi 2012 , 2022; To et al. 2017).

Conclusion

Bagasse is the most abundant lignocellulose material in tropical countries among many agricultural crop residues found in over 100 countries globally. Sugarcane bagasse is a byproduct of sugarcane milling process for sugar manufacture as well as ethanol production by sugar factories. Bagasse consists of a wide range of particle sizes and contains high moisture content. Bagasse contains three main components, namely, pith, fiber, and rind existing in varying proportions. Bagasse physical properties vary considerably in size and shape of the three components. Bagasse can further be divided into two major parts, namely fibrous outer part and the underlying prit. Prit consists of white, soft, smooth parenchymaton hygroscopic tissue made up of sugars, cellulose. Bagasse yield also varies widely, for example in Brazil, one ton of cane on average yields 280 kg of bagasse, but in Nepal, the average yield is 362 kg of bagasse per ton of cane milled. The average bagasse saving ration is less than 10% for a conventional sugar factory mainly because of inherent combustion inefficiencies of the traditional low pressure and temperature boilers and use of inefficient backpressure steam turbine.

Bagasse has various pathways for exploitation as an energy resource i.e. direct combustion in boilers to produce heat for steam and power generation, anaerobic digestion to produce biogas and pyrolysis and gasification to produce syngas. Syngas and biogas can further be upgraded to produce biomethane which has significant energy and process applications as a substitute of natural gas.

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