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Co-Gasification of Sugarcane Bagasse and Coal: A Study on Thermal Characteristics and Efficiency

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Abstract

Biomass fuels offers sustainable alternative to traditional energy sources, mitigating pollution and landfill disposal challenges. This work aim at identifying an optimal blend for enhancing gasification efficiency, operational stability and reduced emissions. Ultimate analysis was adopted for elemental composition determination, proximate analysis for physical and chemical properties while the energy content was determined through calorimetry and thermal degradation behavior using the thermo-gravimetric analysis. Elemental analysis of coal, sugar cane bagasse and their blends revealed principal chemical constituents of carbon, hydrogen and oxygen, with coal demonstrating higher carbon content. Nitrogen composition is negligible for pure and blended samples. Results indicate that coal provide more energy than bagasse owing to its lower ash content and higher carbon concentration. Conversely, calorific value of blends increased with proportion of bagasse, likely due to its high reactivity, which catalyzes coal combustion. Thermo-gravimetric analysis (TGA) displays maximum de-volatilization at 900°C, with rapid weight loss between 300-550°C for all blends. Derivative (DTG) profiles of blends exhibit two peaks: first peak at 320-350°C, with second peak at 400-800°C representing sub-bituminous coal de-volatilization. This study concludes that blending 10% coal with 90% sugarcane bagasse optimize calorific values, thermal stability, efficiency and minimizes environmental pollution.

Keywords: *Co-gasification, sugarcane bagasse, coal, thermal characteristics.*

1.0 Introduction

Biomass is not only of interest as a fuel source but also readily becoming a raw material option for power and bio-based products such as chemicals, building materials and plastic production (Messay *et al.,* 2021). The use of waste biomass as fuel avoids pollution and other landfill disposal problems. Lignite is often used for electricity generation and heat, besides producing various refined chemicals **(**Samuel *et al.,* 2021)**.** The properties of coal are broadly classified as chemical and physical with chemical composition having strong influence on its combustibility **(**Vassilev *et al.*, 2010). Structural characterization of lignite coal is reported to present major challenges because of the extreme complexity and heterogeneity of low ranked coal**.** Biomass-coal co-combustion has potentials as a short term option as a renewable fuel source for existing coal-fuelled power generation stations with little modifications. The extremely volatile matter yield of biomass fuels is central to the co-gasification process for the utilization of residual fuels (Abid *et al.,* 2022). Vardhan (2020) research aimed to have a comparison of thermodynamic efficiency of bagasse with hard coke, a commonly used fuel in generators and turbines. The work proves bagasse, a waste product of sugarcane can have a lesser price when sundried than that of hard coke. Bemgba (2020) examined the fuel properties and energy recovery potential of the newly discovered Obomkpa coal in Delta State of Nigeria. Physicochemical, calorific, and thermal degradation properties characterization using ASTM standards revealed its prospective feedstock for coal-fired electricity production. Based on the standard specification of solid fuels for households, Mandasini *et al.,* (2018) characterized coal-biomass charcoal bio-briquettes fit as a combustible solid fuel. The study of Samuel *et al.,* (2021) illustrated the potential of sugarcane bagasse and coal mixture as a possible replacement of fossil fuels often utilized for injection into coke blast furnaces. Messay *et al.,* (2021) concluded briquettes derived from sugar cane bagasse can be a quality source of energy. Abid *et al.,* (2022) found that bagasse and co-firing of coal-bagasse feed-stocks could provide a better quality of syngas relative to coal feedstock in a combined cycle power plant. The work of Rizka *et al.,* (2023) indicated that the addition of sugar bagasse on rice husk charcoal for briquette could increase the calorific value and improve briquette quality fulfilling standards for commercial sales. Plants for utilizing blended sugarcane bagasse and coal is reported in Mauritius for cogeneration of 35MW, while Indian examples include those at sugar mills in Maharashtra with 22.5 MW bagasse-based cogeneration plants, Birla Sugar Company with six plants with

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combined capacity of 112 MW (Salman, 2023; Salman, 2024). Blend ratios are function specific and 25:75, 50:50 75:25, 70:30 are reported to have been investigated for co-gasification (Hameed *et al.,* 2024). For better understanding of the co-gasification process, there is need to interpolate existing ratios.

This work seeks to investigate the potential of sugarcane bagasse and lignite coal blends as a viable energy source. Findings derived from this study aim to provide valuable insights into the potential benefits and challenges of co-processing sugarcane bagasse and lignite coal, including the effects of different blend ratios on the energy content, thermal stability, and combustion characteristics. Furthermore, the results of this investigation will inform the design optimization techniques of systems that can convert energy and can efficiently process sugarcane bagasse and lignite coal blends, thereby supporting the transition towards a more sustainable and environmentally friendly energy future.

2.0 Materials and Methods

2.1 Materials, sample preparation and briquetting

The sugarcane bagasse was obtained from Mudal Lawa market in the metropolitan area of Bauchi, Nigeria, while lignite coal which is of low ash composition was sourced from Ashaka cement at Gombe state. Samples of sugarcane bagasse and lignite coal were milled to powder form using a ball mill as required by the analytical instruments in the range of 25 μm to approximately 1mm. The blends of sugarcane bagasse, SB with lignite coal, CL were prepared in the ratios of; 90% SB:10% CL, 80% SB:20% CL, 70% SB:30% CL, 60% SB:40% CL, 50% SB:50% CL, 40% SB:60% CL, 30% SB:70% CL, 20% SB:80% CL, 10% SB:90% CL. The briquette samples were prepared at a pressure of 120 Mpa with 100 seconds as the holding time. A standard die forms the briquettes with a diameter of 3 cm at an ambient temperature of 27°C. A hand-push manual pressure-based die compressor was adopted for the compaction process. Produced briquettes were stored in a closed container until further characterizations. World outlook of sugarcane bagasse production suggest a sustainability of this environmentally clean form of energy production. Top world potential producer of bagasse is Brazil with estimated 188-225 million tons followed by India with 101-121 million tons and Thailand having 32-39 million tons, while China has estimated of 27-33 million tons and Pakistan with 16-20 million tons. Other notable nations ranking in tens of millions of tons include the United States, Indonesia, Guatemala, Mexico, Colombia and Australia.

2.2 Methods

2.2.1 Ultimate and proximate properties

The ultimate analysis of pure and sugarcane bagasse blends were determined by the element analyzer (CHNS analyzer ASTM D5291 Method). The proximate analysis of the coal and briquette was determined mainly on ash content, and the presence of volatile matter, fixed carbon, and moisture content of the briquettes. The proximate analysis results of the various biomass and coal including their blends were obtained from a series of TGA plots. These were measured on a dry basis according to the European standards (EN 15148, EN 14775 and EN 14774-3). The content of fixed carbon (char) was calculated by subtracting from 100 the weight composition of the other three components (ash content, volatile matter and moisture content).

2.2.2 Calorific value of sugarcane bagasse and coal blends

An oxygen calorimeter (CAL2K model) was employed to identify the energy value of the sugarcane bagasse and the blends after calibration with a 0.5g of benzoic acid before taking measurements. The vessel for the calorimeter was pressurized to 3000 Kpa using oxygen. This experiment was repeated in triplicate and average value of the calorific value calculated and recorded.

2.2.3 Thermo-gravimetric analysis

Thermo-gravimetric analyzer was used to study the thermal degradation behavior of blends of sugar cane bagasse/coal. A 5.08 mg of each sample were heated over a temperature range of 20ºC-1000ºC under a nitrogen atmosphere at 20°C/min heating rate. This heating rate was applied because it is a typical gasification heating rate.

3.0 Results and Discussion

3.1 Proximate analysis

The properties of the blended samples vary according to the ratio of blends (Table 1). Variation in ash content of coal could be primarily due to foreign materials in the blends or during coal formation. Pure samples in comparison to blends indicate high ash content in coal to sugarcane bagasse. The influence of extraneous mineral matter introduced during mining operations could be responsible. Ash composition of blends are quite high except for 90:10 (SB:CL) where the ash composition is 7.5%. This relatively high amount of ash content is due to the composition of both feedstock which are dependent on factors such as source and type of sugarcane bagasse, coal type, bio factors of growth processes, and as mining operations for coal. High amount of ash is undesirable as it could cause agglomeration, slagging and fouling as well as deposition and corrosion during co-gasification of

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coal/sugarcane bagasse blends. Combustion temperature significantly affects the total yield of ash as its yield is determined at a relatively high temperature of 100-1300°C lowering the amount of ash produced during co-gasification as reported by Vassilev *et al.*, (2010). Ash composition in any feedstock is required to be between 5-6% for avoidance of slagging problems and for the smooth running of the gasifier. The difference in volatile matter content between coal and sugarcane bagasse could also stem from the difference in properties between the two feed-stocks. Fuels with high volatile matter content are always better for gasification due to their tendency to vaporize before combustion, thus affecting the easy of ignition during gasification compared to fuels with low volatile matter content which burns primarily as glowing chars. The amount of volatile compounds in typical biomass material and coal ranges from 60 to 90% and 20 to 35% respectively. High moisture content in the feedstock will lowers combustion unit temperature and lead to an increased fuel throughput, thereby increasing the volume of flue gas released. Moisture content of pure coal is relatively low, while it varies in the sugarcane bagasse (Table 1). It also varies in the blends in the range of 2.5-7.6% which is termed low and suggests supporting gasification. This was because samples were dried before analysis. The fixed carbon of coal is higher (24%) than that of sugar cane bagasse and comparatively constant across the blends in a range of 20-22%. Volatile content differs across the blends with peak display observed in the 90:10 blend (68%). The ash content increases as the quantity of coal in the blend upsurges with 30:70 (31.1%) blend exhibiting the highest value. Blends such as 90:10 and 80:20 with more proportion of sugar cane bagasse are possibly more appropriate for gasification owing to their favorable combination of high volatile matter content and moderately low ash content, while those of 30:70 and 20:80 with increased amount of coal requires precise control operation in gasification systems due to their elevated ash content, which increases the risk of slagging and fouling problems.

Table 1: Proximate analysis of pure samples of sugar cane bagasse and coal

	Coal				Sugarcane bagasse			
Property	**MC**	**VM**	**FC**	**AS**	**MC**	**VM**	**FC**	**AS**
(%)	0.2	25	24	50.8	8.7	75.3	19.3	3.3

Table 2: Proximate analysis of pure and blended samples of sugar cane bagasse and coal

Ratio	MC	VM	FC	AS
90:10	2.5	68	22	7.5
80:20	2.6	54	21	22.4
70:30	3.1	23	49	24.9
60:40	3.4	56	20	20.6
50:50	4.2	59	21	15.8
40:60	5.4	61	20	13.6
30:70	5.9	42	21	31.1
20:80	6.5	48	20	25.5
10:90	7.6	45.1	22	25.3

Note: MC = Moisture content, VM = Volatile matter, FC = Fixed carbon, AS = Ash.

3.2 Ultimate analysis

The elemental analysis of coal, sugar cane bagasse and their blends indicate carbon, hydrogen and oxygen as major elements demonstrating organic nature of the feed stocks. Pure coal exhibits higher carbon levels with percentage composition of approximately 70% which implies that it is the primary constituent in coal compared to the sugar cane bagasse enriched with carbon content of less than 50% (table 3). However, the oxygen composition of pure sugar cane bagasse is quite higher (45.5%) compared to that of pure coal (27%). This difference in oxygen composition is due to the carbohydrate nature of sugar cane bagasse. Hydrogen in the sugar cane bagasse was found to be higher than in the pure coal, which can be attributed to the difference in chemical properties between sugar cane bagasse and coal. The carbon content in all of the blends is quite lower than that of the pure coal with carbon content (table 4). This stems blend ratio as the blends with a higher ratio of coal have higher carbon content. There is an insignificant decrease in the carbon-oxygen composition as the ratio of sugar cane bagasse increases in the blends. Carbon and hydrogen in the blends are oxidized during co-gasification by the exothermic reactions forming carbon dioxide and water. The carbon and hydrogen content has a positive contribution to the calorific value of the fuel and the carbon dioxide formed is emitted as a major product of complete combustion because incomplete combustion in the oxidation zone of the gasifier can lead to emissions of unburnt carbon based pollutants such as hydrocarbons, polycyclic aromatic hydrocarbons, tar and soot (Ewa and Anna, 2024). The variation in the composition of oxygen for blends is due to the ratio of biomass in the blends. Oxygen will reduce the energy density of the fuel but is essential to start the syngas formation process as it reacts with carbon and hydrogen in the feedstock to form carbon dioxide and water (Bingxin, 2024). The disparity for nitrogen composition for pure and blended samples is found to be insignificant. The nitrogen is completely transformed into gaseous nitrogen and nitric oxides (NO, NO_x, NO_2) during co-gasification (Peng *et al.,* 2022). Studies have indicates that emission of NOx is a primary environmental consequence of using coal and biomass (Mohammed *et al.,* 2025). Key factors affecting formation include air supply, combustion zone design, temperature, and gasification technology (Nazli *et al.,* 2017). It is evidently that the blends composition is negligible and does not raise environmental concerns during co-gasification.

Table 3: Ultimate analysis of pure samples of sugar cane bagasse and coal

	Coal				Sugarcane bagasse			
Element	**C**	**H**	**O**	**N**	**C**	**H**	**O**	**N**
(%)	69.5	1.7	26.9	1.7	39.6	6.7	45.5	0.1

Note: C = Carbon, H = Hydrogen, O = Oxygen, N = Nitrogen.

Table 4: Ultimate analysis of blended samples

Ratio	C	H	O	N
90:10	63.6	4.0	30.9	1.6
80:20	61.3	4.1	32.9	1.6
70:30	60.7	4.5	33.0	1.7
60:40	57.4	4.9	36.0	1.7
50:50	54.6	5.1	38.7	1.6
40:60	51.6	5.4	41.3	1.7
30:70	48.3	5.8	44.1	1.8
20:80	45.2	5.8	47.5	1.5
10:90	43.5	6.5	48.5	1.5

Note: C = Carbon, H = Hydrogen, O = Oxygen, N = Nitrogen.

3.3 Calorific value of pure and blended samples of sugarcane bagasse and coal

The pure coal sample has a much higher calorific value than that of sugar cane bagasse (Table 5). The difference in calorific values of the two feed stocks is attributed to the ash content as well as the quantity of carbon and oxygen in each of the material. A 1% increase in carbon concentration will elevate the calorific value by approximately 0.39 MJ/kg. Generally, coals have calorific values greater than biomass due to their lower degree of oxidation (Kalpesh *et al.,* 2024). The calorific values for the blends range from 16.97 MJ/kg to 23.49 MJ/kg for the 90:10 and 10:90 respectively increasing as the coal fraction surges. Calorific value of 18.75 MJ/kg is exhibited by the 70:30 blend shows a 10.5% more than that from 90:10 blend while the 50:50 indicate moderate increment for energy density with calorific value of 19.77 MJ/kg. Blend ratios of 40:60, 30:70, 20:80, and 10:90 demonstrate uppermost values for energy content signifying the dominance of coal in the blends (Table 6). Blends of 90:10, 80:20, 70:30, and 60:40 will experience reduction in thermal stability owing to considerable amount of bagasse reactivity and moisture content, whereas higher quantities of coal in blends could enhance thermal stability portraying coal's higher thermal resistance. The combustion characteristics of the blends are also affected, with higher bagasse proportions potentially leading to faster ignition and improved combustion efficiency, while higher coal proportions may result in slower ignition and reduced combustion efficiency. Increased combustion efficiency will be more pronounce for blends with substantial amount of bagasse in comparison to coal in contrast to low ignition for blends having relatively higher coal than bagasse. Busiso *et al.,* (2012) found bagasse for cogeneration purposes from Hippo Valley Estates (HVE), a sugar manufacturing company in Zimbabwe could satisfactorily met the firm power requirement and also generate an annual surplus of 2.8 million dollars from the sale of excess power.

Table 5. Calorific values of pure samples of sugar cane bagasse and coal

Coal (MJ/kg)	**Sugarcane (MJ/kg)**
22.8	16.1

Table 6: Calorific values of blended sugar cane bagasse and coal samples

Ratio	Values (MJ/kg)
90:10	16.97
80:20	17.80
70:30	18.75
60:40	19.43

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Ratio	Values (MJ/kg)
50:50	19.77
40:60	20.22
30:70	21.41
20:80	23.01
10:90	23.49

3.4 Thermal investigation of coal/ sugarcane bagasse blends

Figure 1 show the weight loss of coal/ sugar cane bagasse blends obtained using a thermo-gravimetric analyzer, carried out under a nitrogen atmosphere at 10, 15 and 20°C/min heating rates. The maximum temperature reached was 900°C. It can be observed that initial mass loss occurred at 105°C temperature for all samples. This initial mass loss arises from evaporation of moisture from the samples. Rapid weight loss due to de-volatilization in the 100% sugar cane bagasse started at 400°C which is considerably lower than the temperature corresponding to the start of the de-volatilization of 100% coal at 530°C. At all mix ratios, the curves corresponding to the blends maintained essentially the same shape and position and displayed three stage of weight losses with the last stage of de-volatilization occurring at a much higher temperature (600-800°C) due to char oxidation except for the 70% SB: 30% CL blend which is characterized by four weight loss stages due to much higher volatile matter content of sugarcane bagasse in the blend, with last stage of weight loss occurring at 715°C. The de-volatilization behavior of the blends as revealed by TGA analysis implies that during co-gasification, the maximum expected temperature for complete de-volatilization of all materials would occur at about 900°C characterized by rapid weight loss between 300-550°C for all blends.

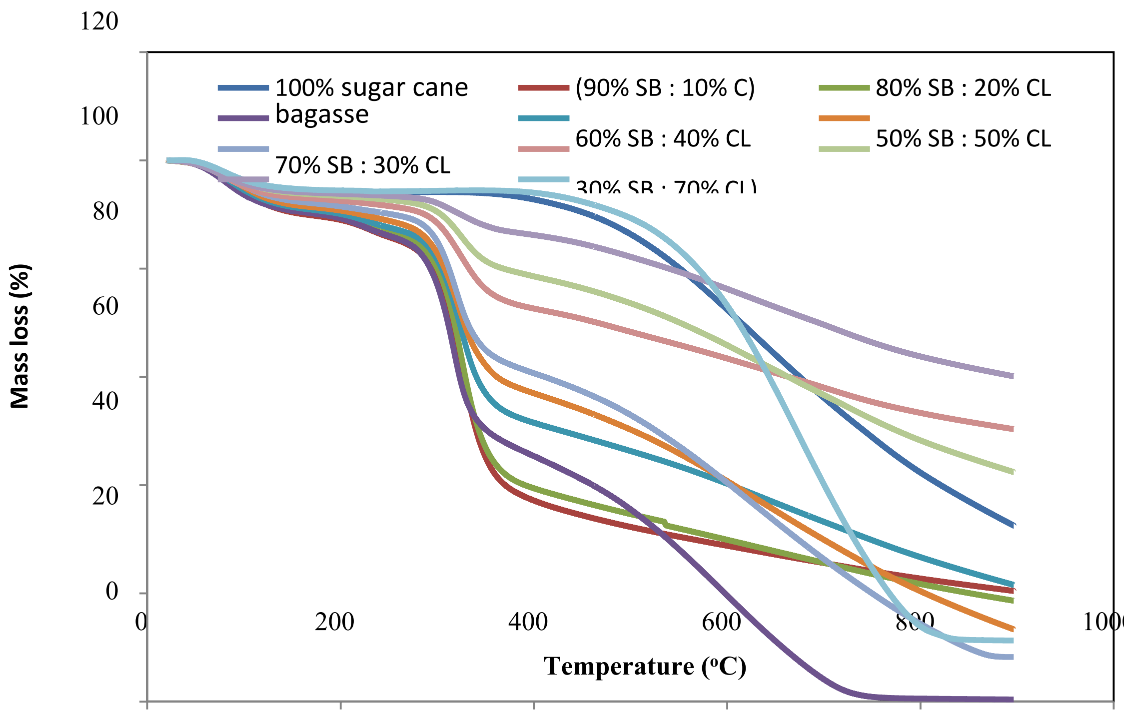

Figure 1: TGA curves of pure sugar cane bagasse and coal as well as their blends

3.5 DTG evaluation of coal evaluation of coal/sugarcane bagasse blends.

The DTG plot of coal/sugarcane bagasse blends, a derivative of the TGA plot shown in figure 2 is used in assessing the thermal degradation rate for blends in the temperature range of 0 to 900°C. As observed, samples exhibited peak for temperatures less than 108°C representing moisture removal. Temperature distribution of 350 to 800°C, indicate thermal evolution profile for the release of carbon encompassing volatiles from coal with estimated maximum temperature of 660°C for pure coal, the thermal evolution profile of all blends displayed another major peak over a wide temperature distribution 350-800°C. These peaks represent the release of carbon containing volatiles from coal. The maximum peak temperature for the pure coal is approximately 660°C. It is worth noting that the maximum weight loss rate of the pure sugar cane bagasse sample is much lower than that of the pure coal. This is due to the fact that sugar cane bagasse contains much higher content of volatile matter than the coal. The thermal decomposition profile for sugar cane bagasse falls in a much narrower temperature range compared to that for coal (220-650°C). This is mainly due to the high volatile matter and lower fixed carbon contents of sugar cane bagasse as compared to that of coal. This difference is also attributed to the

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strength of the molecular structure of the fuels. As observed, the DTG profile of sugar cane bagasse results in a split peak in the temperature range of 220-350°C. As for the blends, the DTG evolution profiles showed two distinct peaks in the temperature range of approximately 130-800°C. The first peak occurs at a maximum peak temperature of approximately 320-350°C representing the de-volatilization of sugarcane bagasse while the second peak occurs at a maximum peak temperature of 400-800°C representing the de-volatilization of the sub-bituminous coal used for this study. It can also be observed that the maximum weight loss rate (%/min) for the sugar cane bagasse de-volatilization profile increased with increasing concentration of sugar cane bagasse in the blends and vice versa for the coal de-volatilization profile, without an apparent change in the shape and position of the peaks when compared to those of the pure samples (Figure 2). This may be attributed to the fact that the release of volatiles containing oxygenated components during the de-volatilization of sugar cane bagasse generally does not affect the de-volatilization of coal at higher temperatures.

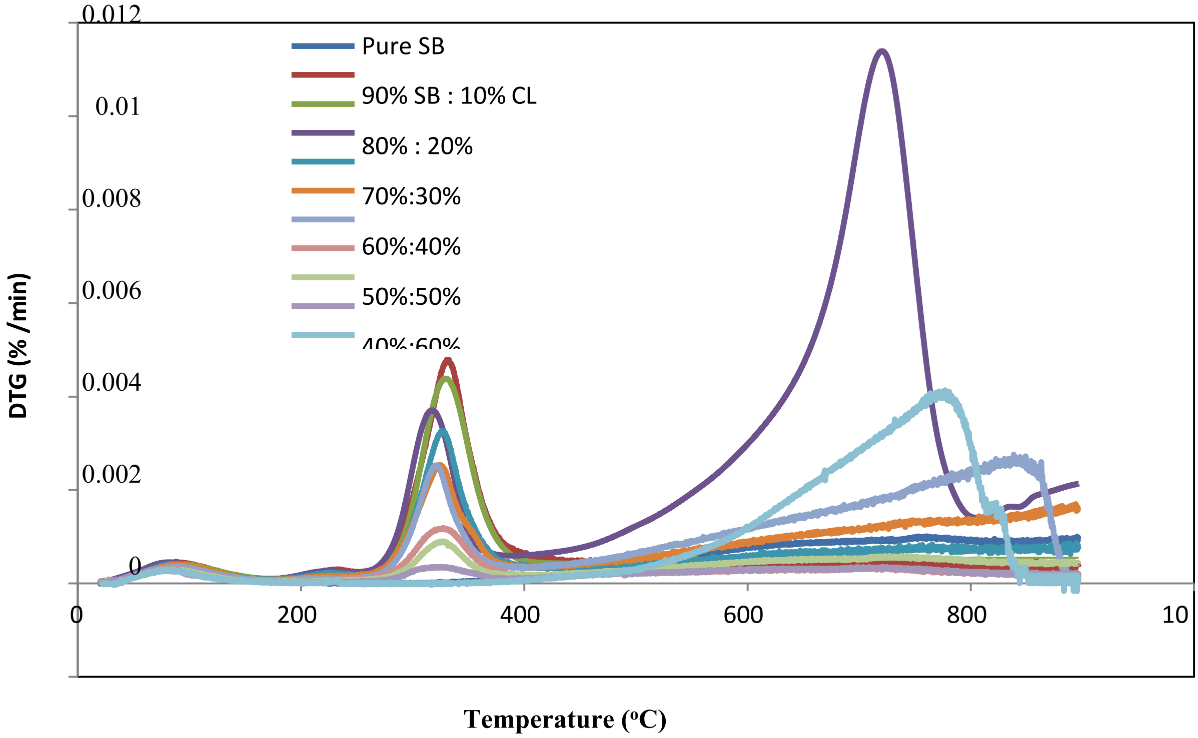

Figure 2: Derivative thermo-gravimetric curves of pure sugar cane bagasse and coal as well as their blend

4.0 Conclusion

The study demonstrates the potential of sugarcane bagasse and coal blends for efficient co-gasification, with blends exhibiting improved properties. Elemental analysis reveals higher carbon content in coal, while nitrogen composition is insignificant in pure and blended samples. Thermogravimetric analysis (TGA) shows maximum weight loss between 300-550°C, with two distinct peaks in DTG profiles corresponding to sugarcane bagasse and coal de-volatilization. The 90% sugarcane bagasse: 10% coal blend (90%SB:10%CL) is identified as the optimal blend for efficient co-gasification, operative stability and reduced emissions. Overall, the results revealed a synergistic effect amid sugarcane bagasse and coal for the gasification process, offering a promising approach for sustainable energy production.

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