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Thermogravimetric Evaluation of Coal–Bagasse Blends for Co-Gasification Applications: Effects of Operating Parameters on Thermal Conversion and Kinetic Behavior

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Abstract

This study evaluates the co-gasification suitability of coal–bagasse blends through thermogravimetric analysis under non-isothermal conditions. Unlike studies that focus mainly on single coal–biomass pairs, this work first screens multiple indigenous Pakistani coal samples and agricultural residues and then evaluates the selected Chamalang coal–bagasse blends under different operating conditions to identify a TGA-based optimum composition and operating window. Indigenous coal and biomass samples were first characterized using proximate analysis, ultimate analysis, and higher heating value determination, after which Chamalang coal and bagasse were selected for blend preparation. Coal–bagasse blends of 94:6, 91:9, and 85:15 were examined to determine the effects of operating conditions, including heating rate, feed composition, and equivalence ratio, on thermal conversion behavior and kinetic characteristics. Thermogravimetric experiments were conducted from ambient temperature to 950°C. The thermograms showed clear differences in the conversion behavior of coal, biomass, and blended fuels, confirming the strong influence of volatile matter, fixed carbon, ash content, and inherent oxygen on reactivity. Among the tested blends, the 91:9 coal–bagasse blend exhibited the most favorable overall performance. The highest overall conversion was obtained at an equivalence ratio of 0.30 and a heating rate of 20°C min^{-1}. Kinetic analysis further supported this result, with activation energies for the 91:9 blend reported as 26.75, 26.54, and 25.64 kJ mol^{-1} at ER values of 0.25, 0.30, and 0.35, respectively. These findings demonstrate the potential of optimized coal–bagasse blends for efficient co-gasification system design.

Keywords: Coal–biomass blends; Coal–bagasse co-gasification; Thermogravimetric analysis; Kinetic behavior; Biomass utilization; Thermal conversion.

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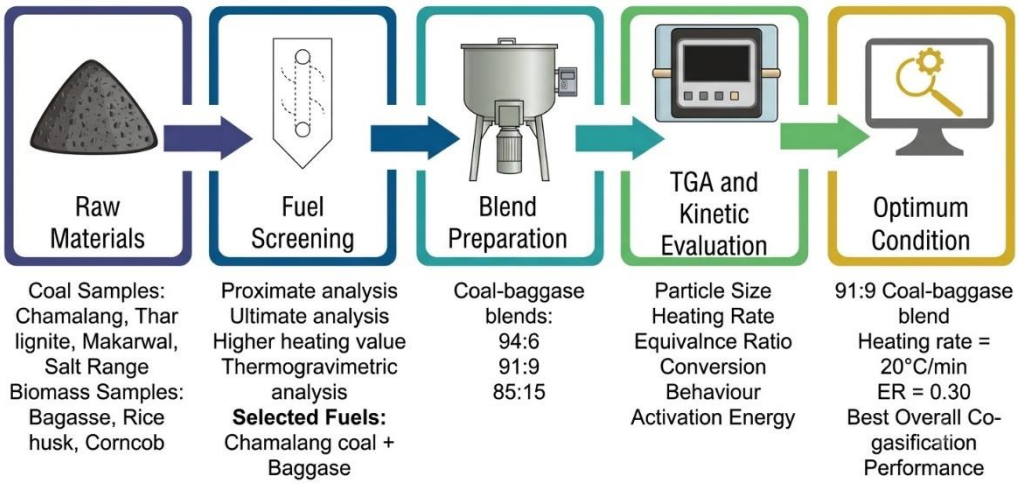
Graphical abstract



1. Introduction

Renewable energy has emerged as a key component of sustainable energy systems because it offers a promising pathway to reduce dependence on fossil fuels, enhance energy security, and mitigate environmental impacts (Ali *et al.*, 2025; Ansari *et al.*, 2026; Habib, 2026). The growing demand for affordable and reliable energy, together with concerns over fossil fuel depletion and environmental impact, has renewed interest in the thermochemical conversion of solid fuels (Abedin *et al.*, 2025; Ansari *et al.*, 2026; Quan *et al.*, 2026). Among the available options, gasification offers an attractive route for converting low-grade solid feedstocks into useful gaseous products while providing greater flexibility than direct combustion (Pribadi and Noble, 2026; Ungureanu *et al.*, 2025). Coal remains an important energy resource because of its large reserves and established availability, but the direct use of low-rank coal is often limited by high moisture or ash content and lower fuel quality (Balaram and Manikyamba, 2026; Lei *et al.*, 2026; Nussipov *et al.*, 2026). In this context, gasification presents a more suitable pathway for utilizing such resources efficiently (Inayat *et al.*, 2025). At the same time, biomass has gained attention as a renewable and widely distributed energy source that can partially substitute fossil fuels and improve the sustainability of thermal conversion systems (Luo and Zhou, 2025).

Pakistan possesses substantial coal resources and also generates large amounts of agricultural biomass residues, making coal–biomass co-gasification a practically relevant research direction (Luo and Zhou, 2025). In particular, bagasse, rice husk, and corncob are available in appreciable quantities and are already used to some extent as low-cost fuels in local industries (Jamil *et al.*, 2026; Mohlala *et al.*, 2016). However, the direct use of biomass is often constrained by low bulk density, variable moisture content, and lower energy density compared with coal (Bajwa *et al.*, 2018; TUMULURU and WRIGHT, 2010). Blending biomass with coal can therefore provide a useful compromise by combining the higher volatile and oxygen content of biomass with the higher fixed carbon and more stable feeding characteristics of coal (Bajwa *et al.*, 2018; TUMULURU and WRIGHT, 2010).

The performance of a fuel in gasification depends strongly on its physicochemical and thermal characteristics. Properties such as volatile matter, fixed carbon, ash content, sulfur content, oxygen content, heating value, and particle size influence ignition and devolatilization behavior, char conversion, heat transfer, and the overall reactivity of the feedstock (Yadav *et al.*, 2023). For blended fuels, these effects become even more important because interactions between coal and biomass components may alter the thermal response of the mixture (Si *et al.*, 2024). For this reason, careful characterization of candidate fuels is necessary before selecting a feedstock for gasification or co-gasification applications (Awais *et al.*, 2022).

Thermogravimetric analysis (TGA) is a useful technique for evaluating the thermal conversion behavior of coal, biomass, and their blends because it provides continuous mass-loss information as a function of temperature and time under controlled operating conditions (Yao *et al.*, 2023; Zhang *et al.*, 2023). It is widely used to investigate decomposition behavior, thermal stability, reactivity, and kinetic parameters of solid fuels (Gong and Yang, 2024). While many earlier studies focused on pyrolysis and combustion, comparatively less attention has been given to blended fuels under gasification or sub-stoichiometric conditions, particularly with respect to the influence of operating parameters on both conversion behavior and kinetics (Koyunoğlu and Tolay, 2025; Wang *et al.*, 2025; Zein, 2026). Non-isothermal TGA is especially attractive for such analysis because it enables comparison of thermal responses under practical heating programs and allows estimation of kinetic parameters from conversion data (de Oliveira *et al.*, 2022; Tarani and Chrissafis, 2024).

In coal–biomass co-gasification, operating conditions play a decisive role in determining fuel behavior. Parameters such as particle size, heating rate, blend composition, and equivalence ratio affect devolatilization, char conversion, heat transfer, and the apparent kinetics of the process (Tian *et al.*, 2023). A systematic investigation of these variables is therefore essential for identifying suitable feed blends and favorable operating windows for co-gasification applications (Adeoye *et al.*, 2026).

Unlike studies that focus mainly on single coal–biomass pairs, this work first screens multiple indigenous Pakistani coal samples and agricultural residues and then evaluates the selected Chamalang coal–bagasse blends under different operating conditions to identify a TGA-based optimum composition and operating window. Therefore, the aim of this study is to evaluate the suitability of selected indigenous coal, biomass, and coal–bagasse blends for co-gasification using thermogravimetric analysis under non-isothermal, air-assisted conditions. The novelty of this work lies in the integrated screening and optimization approach. First, four Pakistani coal samples and three agricultural biomass residues were characterized through proximate analysis, ultimate analysis, higher heating value determination, and thermogravimetric behavior. Second, Chamalang sub-bituminous coal and sugarcane bagasse were selected based on their combined fuel properties and thermal conversion performance. Third, coal–bagasse blends were investigated at different blend ratios, heating rates, and equivalence ratios to determine their effects on conversion behavior and apparent kinetic parameters. In this way, the study provides a feedstock-specific and operating-condition-based assessment of indigenous coal–bagasse blends, offering a clearer basis for selecting local fuels and identifying favorable operating windows for further co-gasification development.

2. Materials and Methods

2.1. *Materials*

Four indigenous coal samples, namely Chamalang sub-bituminous coal (CHSB), Thar lignite (THLig), Makarwal sub-bituminous coal (MAsub), and Salt Range sub-bituminous coal (SAsub), were collected from coal-bearing regions of Balochistan, Sindh, and Punjab, Pakistan. Biomass samples including bagasse, rice husk, and corncob were collected from local industrial sources where these materials were being used as boiler fuel. All sample preparation and characterization work was carried out at the Coal Research Centre, NFC Institute of Engineering and Technology, Multan. Based on the initial fuel characterization, Chamalang coal and bagasse were selected for blend preparation. Coal–bagasse blends were prepared in mass ratios of 94:6, 91:9, and 85:15 for subsequent thermogravimetric evaluation under different operating conditions.

2.2. *Sample preparation and particle size classification*

The as-received coal samples were first crushed using a jaw crusher and then ground using a mortar grinder. The ground coal was sieved into particle sizes of 710, 500, and 355 µm using a sieve shaker. Bagasse was milled, dried, and subjected to sieve analysis to determine its average particle size, which was found to be approximately 490 µm. On the basis of the preliminary evaluation, coal of particle size 710 µm and bagasse of average particle size 490 µm were selected for blend preparation and co-gasification analysis. The prepared samples were then used for proximate analysis, ultimate analysis, heating value determination, and thermogravimetric testing.

2.3. *Physicochemical characterization*

2.3.1. Proximate analysis

Proximate analysis of coal, biomass, and coal–bagasse blend samples was carried out using a thermogravimetric analyzer (TGA-701). Approximately 80–110 mg of each sample was used for analysis. All samples were prepared in triplicate, and the analyses were performed according to ASTM D5142. The measured parameters included moisture content, volatile matter, fixed carbon, and ash content. Average values of the three runs were reported and used to compare the fuel characteristics of the investigated materials.

2.3.2. Ultimate analysis

Ultimate analysis was performed using a LECO TruSpec CHNS analyzer to determine the elemental composition of the coal and biomass samples. Carbon, hydrogen, and nitrogen were measured using approximately 10 mg of sample, while sulfur determination was carried out separately using larger sample quantities placed in ceramic crucibles. The CHNS analyzer was operated with blank and standard runs between samples to ensure measurement reliability. Each sample was analyzed in triplicate, and average values were reported on an as-received basis. Oxygen content was determined by difference. The elemental composition data were later used to interpret the thermal conversion behavior and kinetic characteristics of the fuels.

2.3.3. Higher heating value determination

The higher heating value (HHV) of coal, biomass, and coal–bagasse blend samples was measured using an automatic bomb calorimeter (LECO AC-500) according to ASTM D5865. Approximately 100 mg of each sample was used, and all measurements were performed in triplicate. During each test, a measured quantity of sample was placed in the combustion vessel under pressurized conditions and ignited. The temperature rise of the surrounding water was recorded by the microprocessor-controlled calorimeter, and the corresponding HHV was determined. In addition to the experimental measurements, the heating values of selected coal and biomass samples were also estimated using Dulong's formula for comparison.

For proximate analysis, ultimate analysis, and higher heating value determination, repeated measurements were performed and the average values were used for comparison of fuel properties. However, the present study reports average values without standard deviation because the complete replicate datasets were not available in a consistent form for all reported parameters. Therefore, the reported values should be interpreted as representative

average values for comparative evaluation of the investigated fuels.

2.4. *Thermogravimetric analysis under co-gasification conditions*

Thermal conversion behavior of the prepared coal–bagasse blends was investigated using a thermogravimetric analyzer operating in non-isothermal mode under controlled air atmosphere. The blended samples were placed in ceramic crucibles and heated from ambient temperature to 950°C. The effects of operating variables including feed composition, heating rate, and air flow rate were studied systematically. Blend ratios of 85:15, 91:9, and 94:6 were tested. Heating rates of 15, 20, and 40°C min^{-1} were employed, while air flow rates of 3.5 and 5.0 L min^{-1} were used to generate equivalence ratio (ER) values of 0.25, 0.30, and 0.35. Air was selected as the reaction atmosphere in this study to represent air-assisted, sub-stoichiometric gasification conditions, particularly for low-cost and decentralized gasification applications where air-blown operation is commonly preferred because of its operational simplicity and lower oxidant cost. However, it is recognized that industrial gasification systems may also employ steam, oxygen-enriched air, oxygen–steam mixtures, or CO_2-containing atmospheres depending on the target syngas composition and process design. Therefore, the present thermogravimetric results should be interpreted primarily as a comparative evaluation of coal–bagasse blend behavior under air-assisted conditions rather than as a complete representation of all industrial gasification atmospheres. During each run, the initial sample mass and the corresponding mass loss with time and temperature were recorded continuously throughout the thermal conversion process. It should be emphasized that the thermogravimetric approach used in this study records only sample mass loss as a function of temperature and time. Therefore, the results provide information on apparent thermal conversion behavior, mass-loss stages, and kinetic response, but they do not directly quantify gasification product quality. Parameters such as syngas composition, H_2/CO ratio, gas heating value, tar concentration, carbon conversion to gas, and cold gas efficiency were not measured in the present work. Consequently, the findings should be interpreted as a preliminary thermogravimetric screening of coal–bagasse blend reactivity rather than a complete assessment of gasification product performance. The operating conditions used for the thermogravimetric experiments are summarized in **Table 1**.

Table 1. Operating conditions used for non-isothermal thermogravimetric analysis of coal–bagasse blends from ambient temperature to 950°C.

Run#	Sample	Sample weight(g)	Ramp rate(°C min^{-1})	Air flow(L min^{-1})	ER=Actual air/stoichiometric air
1	91:9	2.092	40	3.5	0.30
2	85:15	3.5	20	5	0.25
	91:9	3.0			0.30
	94:6	2.5			0.35
3	85:15	2.5	20	3.5	0.25
	91:9	2.092			0.30
	94:6	1.80			0.35
4	91:9	2.092	15	3.5	0.30

Note: ER = equivalence ratio, defined as the ratio of actual air supplied to stoichiometric air requirement. Coal blend ratios are expressed on a mass basis. The temperature range for all TGA runs was from ambient temperature to 950°C.

The thermogravimetric experiments were used to compare the relative conversion behavior of the selected coal–bagasse blends under controlled operating conditions. The TGA results are presented as representative conversion profiles for each condition. Since complete repeated TGA datasets were not available for every blend ratio, heating rate, and equivalence ratio, error bars and standard deviations were not included for the conversion curves. This limitation should be considered when interpreting small differences between operating conditions; therefore, the main conclusions were drawn from consistent overall trends in conversion behavior and kinetic response rather than from minor point-to-point variations.

2.5. *Conversion calculation*

The extent of thermal conversion of the coal–bagasse blends during thermogravimetric analysis was determined from the mass-loss data using the following expression:

$$\alpha = \frac{W_i - W_t}{W_i - W_\infty} \quad (1)$$

where W_i is the initial sample mass, W_t is the sample mass at time t, and W_∞ is the final residual mass after completion of the thermal conversion process. This expression was used to compare the conversion behavior of the blended fuels under different operating conditions.

2.6. *Kinetic modeling*

2.6.1. Kinetic assumptions

The kinetic analysis of thermal conversion was carried out using thermogravimetric mass-loss data. For the purpose of kinetic modeling, the following assumptions were adopted: the reaction was considered to be kinetically controlled, the thermal decomposition process was approximated by a first-order reaction model, and the influence of heat-transfer limitations was neglected because of the relatively small particle size of the samples. These assumptions were used to simplify the estimation of the apparent kinetic parameters from the non-isothermal thermogravimetric data. It should be noted that the first-order Arrhenius-based model used in this study provides

apparent kinetic parameters for comparative purposes. Solid-fuel co-gasification is a complex process involving overlapping devolatilization, char conversion, mineral-catalyzed reactions, and possible heat- and mass-transfer effects. Therefore, the assumption of a single first-order reaction does not fully represent the complete reaction mechanism. The activation energies reported in this work should be interpreted as model-dependent apparent values rather than intrinsic kinetic constants.

2.6.2. Arrhenius-based non-isothermal kinetic model

Using the conversion term defined in Eq. (1), the general rate equation for solid-state thermal conversion can be written as

$$\frac{d\alpha}{dt} = k(T) f(\alpha) \tag{2}$$

Where $k(T)$ is the temperature-dependent rate constant and $f(\alpha)$ is the reaction model function. According to the Arrhenius relation,

$$k(T) = A \exp\left(\frac{-E_a}{RT}\right) \tag{3}$$

Substituting Eq. (3) into Eq. (2) gives

$$\frac{d\alpha}{dt} = A \exp\left(\frac{-E_a}{RT}\right)(1-\alpha)^n \tag{4}$$

Where A is the pre-exponential or frequency factor, E_a is the activation energy, R is the universal gas constant, T is the absolute temperature, and n is the reaction order.

Under a constant heating rate condition,

$$\beta = \frac{dT}{dt} \tag{5}$$

Where β is the heating rate. Substituting Eq. (5) into Eq. (4) gives

$$\frac{d\alpha}{dT} = \frac{A}{\beta} \exp\left(\frac{-E_a}{RT}\right)(1-\alpha)^n \tag{6}$$

Rearranging and integrating Eq. (6) yields

$$\int_0^{\alpha} \frac{d\alpha}{(1-\alpha)^n} = \frac{A}{\beta} \int_{T_0}^{T} exp\left(\frac{-E_a}{RT}\right) dT \tag{7}$$

For n≠1, the integral form becomes

$$\frac{1-(1-\alpha)^{1-n}}{1-n} = \frac{A}{\beta} \int_{T_0}^{T} exp\left(\frac{-E_a}{RT}\right) dT \tag{8}$$

and for the first-order model (n=1),

$$ln\left[\frac{1-(1-\alpha)^{1-n}}{(1-n)T^2}\right] = \ln\left(\frac{AR}{\beta E_a}\right) - \frac{E_a}{RT} \tag{9}$$

Since the temperature integral has no exact analytical solution, an asymptotic approximation was used. Accordingly, the linearized form for $n \neq 1$ can be expressed as

$$ln\left[\frac{1-(1-\alpha)^{1-n}}{(1-n)T^2}\right] = \ln\left(\frac{AR}{\beta E_a}\right) - \frac{E_a}{RT} \tag{10}$$

For the first-order reaction model used in this study, the final linearized form becomes

$$ln\left[\frac{-\ln(1-\alpha)}{T^2}\right] = \ln\left(\frac{AR}{\beta E_a}\right) - \frac{E_a}{RT} \tag{11}$$

In the present work, the reaction order was assumed to be unity for all operating conditions in order to simplify the analysis and to enable direct comparison among coal, biomass, and coal–bagasse blend samples.

2.6.3. Determination of kinetic parameters

For the first-order model, the kinetic parameters were determined from the linear relationship given in Eq. (11) by plotting

$$ln\left[\frac{-\ln(1-\alpha)}{T^2}\right] versus \frac{1}{T} \tag{12}$$

The slope of the straight line is equal to $-E_a/R$, while the intercept is equal to $\ln(AR/(\beta E_a))$. Therefore, the activation energy (E_a) and frequency factor (A) were calculated from the slope and intercept of the fitted line. The values of conversion α and absolute temperature T obtained from the thermogravimetric curves were used in the analysis, and the best acceptable kinetic parameters were selected on the basis of the linear correlation coefficient.

3. Results and Discussion

3.1. *Physicochemical characterization of coal and biomass samples*

The physicochemical properties of the selected coal and biomass samples were evaluated through proximate analysis, ultimate analysis, and higher heating value determination in order to identify suitable feedstocks for co-gasification. The results show clear differences between the indigenous coal samples and biomass materials in terms of volatile matter, fixed carbon, ash content, elemental composition, and calorific value. These variations are important because they directly influence fuel reactivity, devolatilization behavior, char conversion, and the overall suitability of the feedstock for thermochemical conversion. These fuel-property results support the later selection of Chamalang coal and bagasse for blend preparation.

The proximate analysis and experimentally measured higher heating values of the coal and biomass samples are presented in **Table 2**. Among the biomass samples, bagasse exhibited the highest volatile matter and the lowest ash content, indicating favorable reactivity and cleaner thermal conversion behavior. Corncob also showed appreciable volatile matter and fixed carbon, whereas rice husk had comparatively lower volatile matter and higher ash content, which may limit its suitability for gasification applications. Among the coal samples, Chamalang sub-bituminous coal showed the most balanced fuel

characteristics, with moderate volatile matter, high fixed carbon, low ash content, and a favorable heating value. In contrast, Salt Range coal contained very high ash, which may adversely affect reactivity and increase the possibility of ash-related operational problems during thermal conversion. Thar lignite exhibited a lower heating value, while Makarwal coal, although having relatively high volatile matter and heating value, contained more ash than Chamalang coal. These results indicate that Chamalang coal is the most suitable coal sample among those investigated for subsequent co-gasification studies.

Table 2. Proximate analysis and measured higher heating values of indigenous coal and biomass samples, with selected literature comparisons.

Characteristics	Volatile(%)	Fixed Carbon(%)	Ash (%)	HHVMJ kg^{-1}	References
Bagasse	81.33	12.28	5.35	17.88	This study
Bagasse	83.2	10.06	6.9	17.06	(Vamvuka *et al.*, 2003)
Bagasse	79.90	18.00	2.20	(db)18.	(Rodrigues *et al.*, 2011)
Corncob	60.04	29.85	6.61	16.41	This study
Corncob	83.5	15.5	1.0	17.9	(Zakaria *et al.*, 2010)
Rice husk	48.21	31.86	10.31	14.29	This study
Rice husk	68.0	17	15	16.2	(Youssef *et al.*, 2009)
Rice husk	62.95	13.49	18.15	14.80	(Youssef *et al.*, 2009)
Low Rank (ar)CH_{SB}	39.8	51	8.3	22.20	This study
Low Rank (ar) MA_{Sub}	46.95	28.56	14.42	28.56	This study
PRB Coal	40.83	50.34	8.83	26.60	(Wang *et al.*, 2012)
Low Rank (ar) SA_{Sub}	35.03	30.48	33.34	19.82	This study
Low rank (ar) THLig	22.93	39.25	4.95	13.25	This Study
Lignite (ar)TH	23.96	40.14	14.28	15.53	(Sarwar *et al.*, 2012)
Thailand Low rank Coal	36.68	19.24	25.70	---	(Rodjeen *et al.*, 2006)
Low rank Malaysian Coal	43.0	53.3	3.7	25.2	(Youssef *et al.*, 2009)
Medium Rank coal	25.1	68.5	6.4	32.0	(Youssef *et al.*, 2009)
Low rank	45.4	45.3	9.3	28.7	(Youssef *et al.*, 2009)

Note: CHSB = Chamalang sub-bituminous coal; MA_{sub} = Makarwal sub-bituminous coal; SA_{sub} = Salt Range sub-bituminous coal; THLig = Thar lignite; ar = as-received basis; db = dry basis; HHV = higher heating value. Biomass abbreviations: BG = bagasse, CC = corncob, RH = rice husk

Table 3. Ultimate analysis and higher heating values estimated using Dulong's formula for coal and biomass samples, with selected literature comparisons.

Samples	N(%)	C(%)	H(%)	S(%)	O(%)(By diff)	HHV BY Dulong's Formula(Mj/Kg)	Ref
TH_{Lig} (ar)	0.98	31.90	7.17	0.99	54.01	11.41	Present study
Lignite (daf)	3.88	58.0	11.18	0.68	25.16	14.17	(Senneca *et al.*, 1999)
(ar) CH_{SB}	1.409	59.08	5.60	2.79	22.82	24.22	Present study
Sub- bit coal (daf)	1.95	72.98	7.01	0.71	17.00	20.50	(Senneca *et al.*, 1999)
Wyoming Sub- bit coal (daf)	1.07	75.68	4.43	0.45	18.37	27.11	(Fryda *et al.*, 2006)
Colombia bituminous coal (dry)	1.58	75.69	5.29	1.57	7.91	30.634	(Preciado *et al.*, 2012)
Coal	1.89	75.8	4.40	1.22	16.7	-	(Puig-Arnavat *et al.*, 2010)
(ar)SA_{Sub}	1.57	43.64	3.93	13.12	4.4	20.79	Present study
(ar)MA_{Sub}	1.56	71.79	6.04	0.77	5.43	31.99	Present study
Ba	1.41	43.07	6.6	0.16	43.41	16.22	Present study
Bagasse	0.16	49.86	6.02	0.17	40.19	18.53	(NREL, 1995)
Bagasse	0.60	44.60	5.80	0.10	44.50	18.00	(Rodrigues *et al.*, 2011)
Ch	1.37	42.85	5.4	0.15	45.54	14.03	Present study
Corncob	0.64	45.04	5.79	-	48.53	--	(Rodjeen *et al.*, 2006)
Rh	1.39	36.45	5.43	4.82	41.59	13.07	Present study
Rice Husk	0.14	37.85	5.20	0.61	27.65	-	(Youssef *et al.*, 2009)

Note: N = nitrogen; C = carbon; H = hydrogen; S = sulfur; O = oxygen calculated by difference; HHV = higher heating value estimated using Dulong's formula. THLig = Thar lignite; CH_{Sb} = Chamalang sub-bituminous coal; SASub = Salt Range sub-bituminous coal; MASub = Makarwal sub-bituminous coal; Ba = bagasse; Cc = corncob; Rh = rice husk; ar = as-received basis; daf = dry ash-free basis.

The ultimate analysis results and heating values estimated using Dulong's formula are summarized in **Table 3**. The biomass samples contained higher oxygen and lower carbon contents than the coal samples, which is consistent

with their generally lower heating values but higher expected reactivity. Bagasse showed a favorable combination of carbon, hydrogen, and oxygen contents, supporting its selection as the biomass component for blend preparation. Among the coal samples, Chamalang and Makarwal coals showed comparatively higher carbon contents and higher calculated heating values than Thar lignite and Salt Range coal. Thar lignite contained lower carbon and higher oxygen, while Salt Range coal exhibited an unfavorable sulfur and ash profile. These elemental trends complement the proximate analysis results and further support the selection of Chamalang coal and bagasse as suitable fuels for co-gasification.

Overall, the combined results of proximate analysis, ultimate analysis, and heating value determination indicate that Chamalang coal and bagasse are the most appropriate coal and biomass samples, respectively, for preparing blended fuels. Chamalang coal was preferred because of its relatively high fixed carbon, low ash content, and acceptable heating value, whereas bagasse was selected because of its high volatile matter, low ash content, and favorable elemental composition. These properties make the selected pair suitable for investigating the thermal conversion behavior of coal–bagasse blends under different co-gasification operating conditions.

3.2. *Thermogravimetric behavior of individual coal and biomass samples*

The thermogravimetric behavior of the individual coal and biomass samples was evaluated under non-isothermal heating conditions in order to compare their conversion characteristics and identify the most suitable feedstocks for subsequent co-gasification studies. As shown in **Figure 1**, the thermograms of both coal and biomass samples can be broadly divided into three main stages: initial moisture release, devolatilization, and subsequent conversion of the residual char.

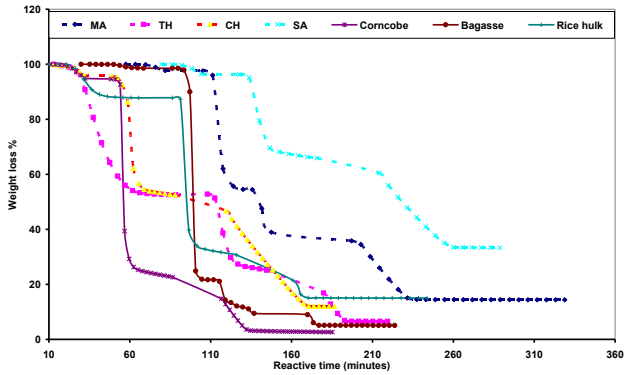


Figure 1. Thermogravimetric conversion behavior of individual coal and biomass samples under non-isothermal heating conditions from ambient temperature to 950°C.

In the first stage, the initial mass loss corresponds primarily to moisture removal from the fuel matrix. This stage was more pronounced for fuels with higher inherent moisture, particularly Thar lignite, which is consistent with its lower thermal conversion efficiency during later stages. The second stage represented devolatilization, where the release of volatile compounds occurred more rapidly in biomass than in coal. The biomass thermograms were steeper in this region, indicating faster conversion and greater reactivity. This behavior is consistent with the higher volatile matter and oxygenated organic fractions of biomass, which promote decomposition at relatively lower temperatures. The stronger devolatilization behavior of biomass can be attributed to its higher content of thermally reactive constituents, and the biomass samples showed higher overall conversion than coal under the same conditions.

Among the biomass samples, bagasse and corncob exhibited the highest overall thermal conversion, while rice husk showed comparatively lower conversion. The overall conversion values are reported as approximately 98% for bagasse, 96% for corncob, and 84% for rice husk. The comparatively lower conversion of rice husk can be linked to its higher ash content, whereas the superior behavior of bagasse reflects its high volatile matter and lower ash fraction. These results are consistent with the fuel-property trends already discussed in Section 3.1 and provide further support for the selection of bagasse as the biomass component for blend preparation.

The coal samples showed slower and less extensive conversion than the biomass samples, particularly in the devolatilization region. Among the coals, Chamalang sub-bituminous coal exhibited the most favorable thermal behavior. Although Thar lignite is inherently more reactive than higher-rank coals, its elevated moisture content reduced its effective conversion performance under the tested conditions. Salt Range coal showed the poorest suitability because of its very high ash content, which can suppress reactivity and may also promote ash-related operational problems during co-gasification. Makarwal coal exhibited comparatively high volatile matter and heating value, but its ash content remained higher than that of Chamalang coal.

The third stage of the thermograms corresponded to the conversion of the residual char at higher temperatures. This region is important because it reflects the ability of the remaining carbonaceous material to continue reacting after the devolatilization phase. In general, the coal samples retained more residual mass than the biomass samples, which is consistent with their higher fixed-carbon content and lower overall conversion under the same non-isothermal conditions. Therefore, the thermogravimetric analysis of the individual fuels confirms that bagasse and Chamalang coal are the most suitable biomass and coal feedstocks, respectively, for investigating coal–bagasse blends under co-gasification conditions.

3.3. *Physicochemical characterization of coal–bagasse blends*

Based on the physicochemical characterization and thermogravimetric behavior of the individual fuels, Chamalang coal and bagasse were selected for the preparation of blended feedstocks for co-gasification analysis. Coal–bagasse blends were prepared at mass ratios of 94:6, 91:9, and 85:15 in order to examine the effect of biomass addition on the fuel properties of the parent coal.

The visual appearance of the prepared blends is shown in **Figure 2**, while their proximate analysis and higher heating value data are summarized in **Table 4**.

Figure 2. Physical appearance of coal–bagasse blends prepared at selected mass ratios

The progressive addition of bagasse to Chamalang coal altered the physicochemical characteristics of the blended fuels in a systematic manner. As shown in **Table 4**, increasing the biomass fraction increased the volatile matter content of the blends while reducing the fixed carbon content relative to the parent coal. This behavior is expected because bagasse is more volatile and more oxygen-rich than coal. The moisture content also showed a slight increase with biomass addition, reflecting the more hygroscopic nature of bagasse. In contrast, the ash content remained within a comparatively moderate range, indicating that the selected biomass did not introduce the high ash burden typically associated with less favorable agricultural residues such as rice husk. These trends are important because higher volatile matter can enhance ignition and devolatilization, whereas excessive ash can hinder reactivity and reduce conversion efficiency during thermochemical processing.

Table 4. Proximate analysis and measured higher heating values of Chamalang coal and coal–bagasse blends prepared at different mass ratios.

Sample Coal:Bagasse	Moisture (%)	Volatile matter (%)	Fixed Carbon (%)	Ash (%)	Calorific value. MJ/kg
94:06	0.917	42.2918	48.6768	8.123	21.9408
91:09	0.920	43.5377	47.5152	8.0345	21.8112
85:15	0.928	46.0295	45.192	7.8575	21.552

Note: Coal blend ratios are expressed on a mass basis. HHV values are reported in MJ kg^{-1}. Moisture, volatile matter, fixed carbon, and ash contents are reported as weight percentages.

The higher heating values of the blends remained reasonably close to that of the parent coal, despite the addition of biomass. This indicates that partial substitution of coal by bagasse did not cause a severe reduction in energy content within the investigated blending range. Among the tested mixtures, the 91:9 blend provided the most favorable balance between volatile matter enhancement and acceptable calorific value. Thus, the blend-property data provide an important preliminary indication that moderate bagasse addition can improve the reactive characteristics of the fuel without significantly compromising its energy value.

The observed property changes in the blended fuels are consistent with the individual characteristics of Chamalang coal and bagasse discussed in Sections 3.1 and 3.2. Chamalang coal contributed relatively high fixed carbon and stable fuel value, while bagasse contributed higher volatile matter and improved reactivity potential. Therefore, blending these two fuels offers a practical route for producing a composite feedstock with more favorable characteristics for co-gasification than the raw coal alone. On this basis, the prepared coal–bagasse blends were selected for detailed evaluation of the effects of operating conditions on thermal conversion behavior in the following section.

3.4. *Effect of operating parameters on conversion behavior*

3.4.1. Effect of particle size

Particle size is an important fuel parameter because it affects surface area, heat transfer, release of volatile matter, and the accessibility of the solid matrix to reacting gases. As the coal particle size decreased from 710 to 355 µm, the release of sulfur and ash changed noticeably, and the heating value of most coal samples improved. The decreasing particle size increased the release of ash and sulfur and generally improved the heating value for all coals except Salt Range coal. This behavior was attributed to enhanced reactivity resulting from the larger surface area and higher porosity of smaller particles (**Figure 3**).

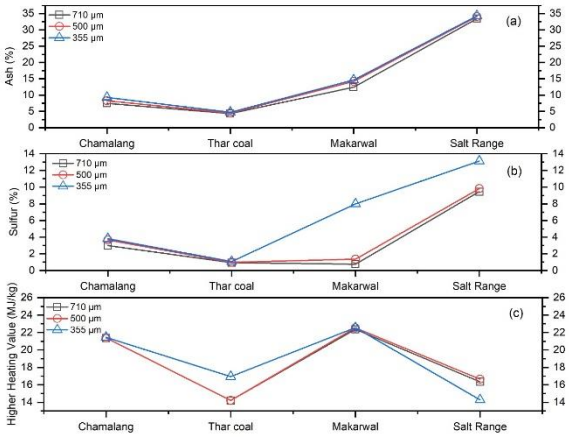


Figure 3. Effect of coal particle size on fuel properties of the investigated coal samples: (a) ash content, (b) sulfur content, and (c) higher heating value.

The improvement associated with smaller particles is also relevant from a process standpoint. Reduced particle size promotes faster heating and more efficient removal of volatile products from the particle surface, which can improve the thermal conversion performance of the fuel. In addition, smaller particles are more compatible with fluidized-bed operation because they help maintain more stable fluidization and reduce the tendency for excessive inert ash accumulation. However, the response was not identical for all coal types. Salt Range coal showed a

reduction in heating value after size reduction, which attributes to the release of inorganic combustible sulfur with the ash fraction. Therefore, although particle size reduction generally improved fuel behavior, the extent of the benefit depended on the mineral and sulfur characteristics of the individual coal. Overall, the particle-size analysis supports the use of suitably reduced coal size for co-gasification applications. Since smaller particles provide faster heat transfer and greater reactivity, they are expected to favor improved gasification performance. On this basis, the selected coal size was considered appropriate for subsequent blending and thermogravimetric conversion experiments.

3.4.2. Effect of heating rate

The effect of heating rate on thermal conversion was investigated using the 91:9 coal–bagasse blend under otherwise fixed conditions. The thermograms showed that changing the heating rate altered both the position and the shape of the conversion curves. Increasing the heating rate from 15 to 40°C min^{-1} caused a shift in the thermograms, with the curves requiring different times to reach the main devolatilization region. The reported times to attain approximately 700°C were 48.88, 37.25, and 18.72 min for heating rates of 15, 20, and 40°C min^{-1}, respectively.

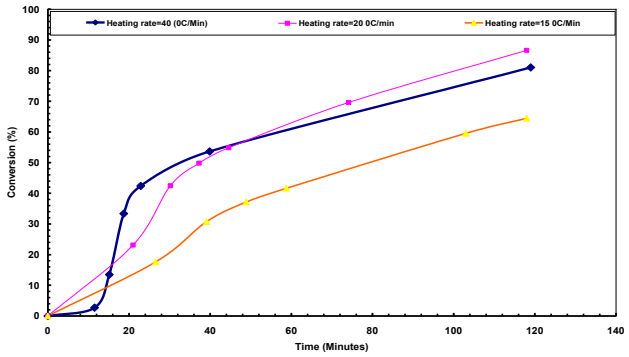


Figure 4. Effect of heating rate on the conversion behavior of the 91:9 coal–bagasse blend under air-assisted conditions at ER = 0.30.

It is to be noted that within the lower temperature range, up to about 700°C, the highest conversion rate was observed at 20°C min^{-1}, with a value of 49.82%, whereas corresponding values at 40 and 15°C min^{-1} were 37.49% and 37.16%, respectively. At higher temperatures, between 700 and 950°C, the conversion behavior changed because the remaining char underwent further thermochemical reactions. In this region, the 40°C min^{-1} condition showed a stronger instantaneous conversion contribution, but the highest overall conversion was still obtained at 20°C min^{-1}. These results indicate that an intermediate heating rate provided the best balance between devolatilization and subsequent char conversion.

This behavior can be explained by the competing effects of heat supply and thermal uniformity. At very low heating rate, the process becomes slower and the conversion remains limited. At very high heating rate, heat is supplied rapidly, but local non-uniformity and incomplete utilization of the volatile-release stage may reduce the overall effectiveness of the process. Therefore, the results suggest that 20°C min^{-1} is the most suitable heating rate among the tested values for coal–bagasse co-gasification under the present thermogravimetric conditions.

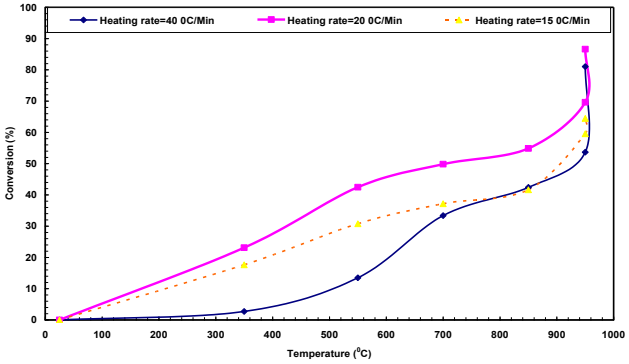


Figure 5. Thermogravimetric curves of the 91:9 coal–bagasse blend at heating rates of 15, 20, and 40°C min^{-1} under air-assisted conditions.

3.4.3. Effect of feed composition

The feed composition had a clear influence on the thermal conversion behavior of the coal–bagasse blends. Increasing the fraction of bagasse increased the oxygen availability and volatile matter content of the feedstock, while lowering the fixed carbon and slightly reducing the heating value, as already seen in Table 4. The higher oxygen content of biomass can reduce the effective oxidant demand of the mixture and promote the partial oxidation reactions involved in gasification (**Figures 4–6**).

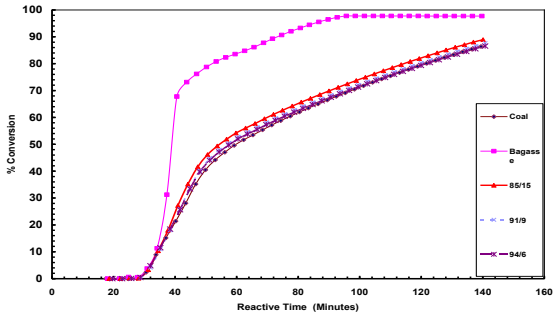


Figure 6. Effect of coal:bagasse blend ratio on thermal conversion behavior at a heating rate of 20°C min^{-1} and ER = 0.30.

As shown by the conversion curves, increasing the biomass fraction enhanced the reactivity of the blend. With increasing biomass content from 94:6 to 91:9 and 85:15, the reactivity of the feedstock increased due to the higher volatile fraction, greater inherent oxygen availability, and lower ash content. At the same time, heating value decreased with increasing biomass fraction, which means that reactivity enhancement must be balanced against the decline in fuel energy density. This is an important practical observation because excessive biomass addition may improve conversion but reduce the calorific strength and bulk handling quality of the feed.

It should be noted that the improved conversion behavior observed after bagasse addition represents the apparent co-conversion performance of the blended fuels under the investigated thermogravimetric conditions. In this study, a formal quantitative synergy index was not calculated

because rigorous synergistic or antagonistic interaction analysis requires complete conversion profiles of the individual coal and biomass samples under exactly the same operating conditions as each corresponding blend. Therefore, the observed enhancement in reactivity should be interpreted as an indication of improved blend performance rather than direct quantitative proof of synergistic interaction. Future work should include theoretical additive conversion analysis, in which the experimental blend conversion is compared with the weighted conversion of individual coal and bagasse, to quantify the degree of synergy or antagonism during co-gasification.

Therefore, feed composition must be optimized rather than simply maximizing the biomass fraction. The results suggest that moderate addition of bagasse improves conversion behavior without causing an excessive penalty in heating value. This later supports the selection of the 91:9 blend as the most suitable composition for further operating and kinetic analysis.

The enhanced conversion behavior of the coal–bagasse blends can also be interpreted from a micro-mechanistic perspective. During heating, bagasse decomposes earlier than coal because of its higher volatile matter and oxygenated organic structure. The rapid release of volatiles from biomass can contribute to the formation of additional pores and channels within the blended char matrix, thereby improving heat transfer and increasing the accessibility of reacting gases to the remaining carbonaceous material. Similar effects of biomass addition on volatile release, char structure, and coal–biomass interaction have been reported in previous studies on coal–biomass thermal conversion (Vamvuka *et al.*, 2003; Wang *et al.*, 2012; Tian *et al.*, 2023).

In addition, biomass-derived ash may contain mineral species that can influence char conversion reactions. Alkali and alkaline earth metals present in biomass ash are commonly considered to promote carbon conversion by increasing active reaction sites and facilitating oxygen transfer during thermochemical reactions (Puig-Arnavat *et al.*, 2010; Yadav *et al.*, 2023). The oxygen-rich structure of bagasse may also promote the formation of oxygenated volatiles and surface functional groups during decomposition, which can improve the local reactivity of the coal–biomass matrix. Therefore, the improved performance of the coal–bagasse blends may be associated not only with bulk fuel properties such as volatile matter, ash content, and heating value, but also with pore evolution, catalytic mineral effects, and oxygen-assisted reaction pathways. However, these mechanisms are inferred from the observed thermogravimetric behavior and literature evidence; direct confirmation would require additional char characterization.

3.4.4. Effect of equivalence ratio

Equivalence ratio is one of the most important operating variables in gasification because it controls the amount of oxidant available for combustion and partial oxidation reactions. In the present study, ER values of 0.25, 0.30, and 0.35 were evaluated for the coal–bagasse blends while keeping the other operating conditions fixed. The increase in air supply increased the ER and improved the conversion process. This is reasonable because a higher oxidant supply promotes greater heat release and enhances the conversion of devolatilized and charred material.

Figures 7 to 9 compare the conversion behavior of the three blends at ER values of 0.25, 0.30, and 0.35. The conversion increased as ER increased, which is consistent with the expected role of oxidant supply in raising gasification intensity. However, ER = 0.30 was identified as the best overall condition, rather than ER = 0.35, when conversion performance and kinetic suitability were considered together. This shows that although higher ER promotes conversion, there is still an optimum range beyond which the process may shift away from the desired balance between gasification and partial combustion.

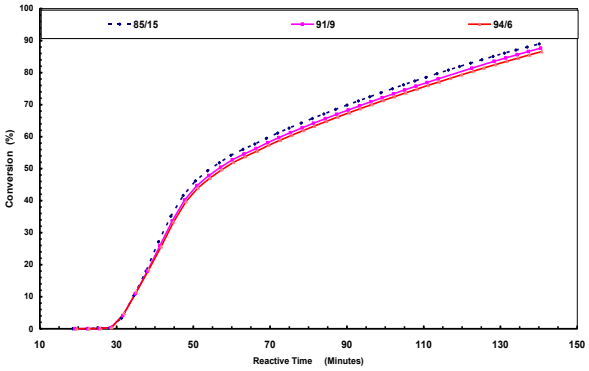


Figure 7. Thermal conversion of coal–bagasse blends at ER = 0.25 and a heating rate of 20°C min^{-1}.

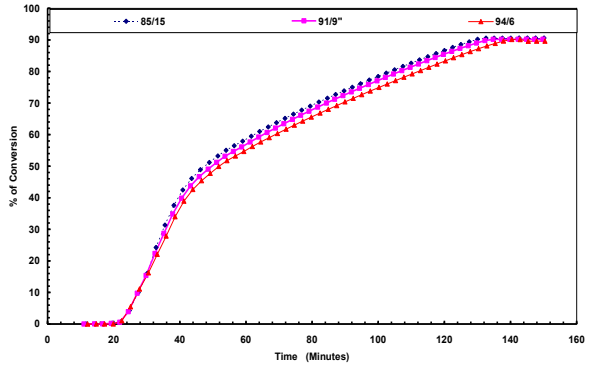


Figure 8. Thermal conversion of coal–bagasse blends at ER = 0.30 and a heating rate of 20°C min^{-1}.

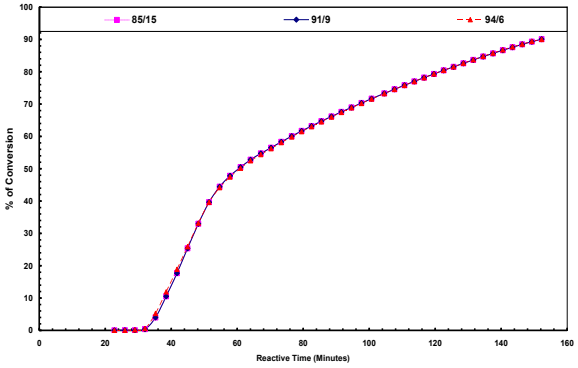


Figure 9. Thermal conversion of coal–bagasse blends at ER = 0.35 and a heating rate of 20°C min^{-1}.

Thus, the ER study demonstrates that oxidant supply strongly affects thermal conversion and must be carefully controlled for efficient co-gasification performance. Within the present operating window, an ER of 0.30 provided the most favorable balance and was therefore selected as the optimum condition for the 91:9 coal–bagasse blend. The use of air as the gasifying atmosphere also means that the observed effect of equivalence ratio reflects the combined influence of oxygen availability and nitrogen dilution under air-assisted conditions. In steam or oxygen-enriched gasification, the reaction pathway and product-gas composition may differ because steam promotes water–gas and water–gas shift reactions, while oxygen enrichment reduces nitrogen dilution and can increase the heating value of the produced gas. Therefore, the optimum ER identified in the present study is specific to the investigated air-assisted thermogravimetric conditions. Further studies under steam, oxygen-enriched air, and mixed gasifying atmospheres are required to extend these findings to broader industrial gasification systems.

3.5. *Kinetic results and discussion*

The kinetic analysis was carried out to further interpret the thermogravimetric conversion behavior of the investigated coal, biomass, and coal–bagasse blends under different operating conditions. Using the first-order Arrhenius-based non-isothermal model described in Section 2.6, the apparent activation energy and frequency factor were estimated from the thermogravimetric data. The resulting kinetic parameters provide an additional basis for comparing the thermal reactivity of the different fuels and for identifying the most favorable operating conditions for co-gasification.

The kinetic results should be interpreted with consideration of the limitations of the adopted model. The first-order Arrhenius approach was selected to provide a simple and consistent basis for comparing the apparent kinetic behavior of the investigated fuels and blends. However, coal–biomass co-conversion usually involves multiple overlapping reaction stages, including moisture release, devolatilization, volatile–char interaction, and high-temperature char conversion. Model-free isoconversional methods, such as Flynn–Wall–Ozawa, Kissinger–Akahira–Sunose, and Starink methods, can provide more detailed information by evaluating activation energy at different conversion levels without assuming a fixed reaction order. Such approaches are particularly useful for complex solid-state reactions and have been recommended for improving the reliability of kinetic interpretation in thermogravimetric studies (de Oliveira *et al.*, 2022; Tarani and Chrissafis, 2024). Since complete multi-heating-rate datasets were not available for all blend compositions and equivalence ratios in the present work, the kinetic analysis was limited to apparent first-order parameters. Therefore, the activation-energy values reported here are used mainly for relative comparison among fuels, blend ratios, and operating conditions.

The lower apparent activation energy observed for bagasse and selected coal–bagasse blends may be associated with microstructural and catalytic effects during thermal conversion. Biomass decomposition generally occurs at lower temperatures than coal decomposition, leading to earlier volatile release and the possible development of a more porous char structure. This can improve gas diffusion and increase the accessibility of reactive sites during subsequent char conversion. Previous studies have also reported that coal–biomass blending can modify volatile-release behavior, char structure, and apparent kinetic response during thermochemical conversion (Zakaria *et al.*, 2010; Wang *et al.*, 2012; Tian *et al.*, 2023).

The presence of biomass-derived mineral matter may also contribute to the improved kinetic behavior of the blends. Mineral species such as potassium, calcium, magnesium, and sodium, which are often present in biomass ash, can act as catalytic species during char conversion and may reduce the apparent energy barrier of the reaction (Puig-Arnavat *et al.*, 2010; Yadav *et al.*, 2023). Furthermore, the higher oxygen content of bagasse can promote oxygen-containing intermediates and surface functional groups, which may enhance the reactivity of the blended fuel. These mechanisms are consistent with the improved apparent conversion and lower activation-energy trends observed for the coal–bagasse blends. However, because the present study did not include SEM, BET, XRD, FTIR, or ash elemental analysis of the residual chars, the proposed mechanisms should be regarded as explanatory interpretations rather than direct experimental confirmation.

The activation energies obtained for the biomass samples are presented in **Figure 10**. Among the tested biomasses, bagasse showed the lowest activation energy, followed by corncob and rice husk. This indicates that bagasse required the least energy input to initiate and sustain thermal conversion, which is consistent with its higher volatile matter content, lower ash fraction, and better overall thermogravimetric performance observed in the earlier sections. Rice husk showed the highest activation energy among the biomass samples, which can be attributed to its comparatively high ash content and less favorable conversion behavior. These results provide kinetic support for selecting bagasse as the biomass component in the coal–biomass blends.

The activation energies of the investigated coal samples are shown in **Figure 10**. Chamalang sub-bituminous coal exhibited the most favorable kinetic behavior among the coals, with lower activation energy than the less suitable alternatives. Salt Range coal showed comparatively less favorable behavior, which is consistent with its high ash content and inferior physicochemical characteristics. Thar lignite and Makarwal coal showed intermediate behavior. The kinetic results therefore complement the proximate, ultimate, and thermogravimetric analyses and further justify the selection of Chamalang coal for preparation of the coal–bagasse blends.

The effect of heating rate on activation energy is illustrated in **Figure 11**. The 91:9 coal–bagasse blend at a heating rate of 20°C min^{-1} exhibited the most favorable overall kinetic response, corresponding to the best conversion performance observed in Section 3.4. Although thermal

conversion can occur at lower and higher heating rates, the kinetic data indicate that the intermediate heating rate provides a more favorable balance between heat supply and effective progression of the reaction. This supports the earlier conclusion that 20°C min^{-1} is the most appropriate heating rate among the tested values for the co-gasification of the selected blend.

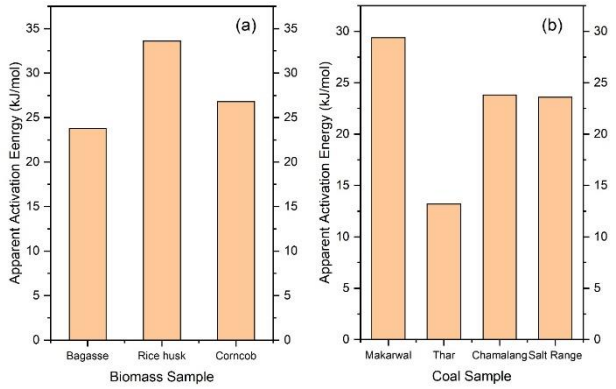


Figure 10. Apparent activation energies of the investigated raw fuels obtained from non-isothermal thermogravimetric analysis: (a) biomass samples and (b) coal samples.

The influence of feed composition on activation energy is presented in **Figure 11.** As the fraction of bagasse in the blend increased, the activation energy generally decreased, reflecting the increasing contribution of the more reactive biomass component. This trend is consistent with the enhanced volatile content and oxygen availability associated with biomass addition. However, although higher biomass addition improved reactivity, it also reduced the heating value of the blend. Therefore, the most suitable feed composition was not simply the one with the lowest activation energy, but rather the one that provided the best overall balance between reactivity and fuel quality. On this basis, the 91:9 blend was identified as the most suitable composition for further co-gasification analysis.

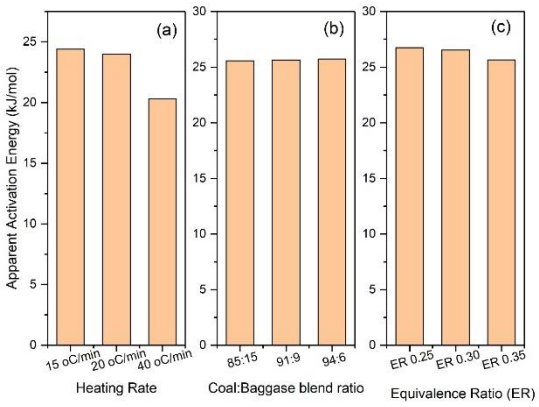


Figure 11. Effect of operating variables on the apparent activation energy of coal–bagasse blends: (a) heating rate, (b) feed composition, and (c) equivalence ratio.

The effect of equivalence ratio on activation energy is shown in **Figure 11**. The activation energies were 26.75, 26.54, and 25.64 kJ mol^{-1} for the 91:9 blend at ER values of 0.25, 0.30, and 0.35, respectively. Although the activation energy decreased slightly with increasing ER, the overall assessment of the process indicated that ER = 0.30 provided the most favorable condition when conversion efficiency and operational suitability were considered together. This suggests that the optimum ER should not be selected solely on the basis of minimum activation energy, but rather on the combined interpretation of conversion behavior, thermal performance, and kinetics.

Overall, the kinetic analysis confirms the trends already observed in the physicochemical and thermogravimetric results. Bagasse was identified as the most reactive biomass, Chamalang coal as the most suitable coal, and the 91:9 coal–bagasse blend as the most favorable feed composition. In addition, a heating rate of 20°C min^{-1} and an equivalence ratio of 0.30 were found to provide the most suitable operating conditions for co-gasification under the present thermogravimetric framework. Thus, the kinetic results not only support the selection of the blend and operating parameters but also strengthen the overall interpretation of the thermal conversion behavior of the investigated fuels.

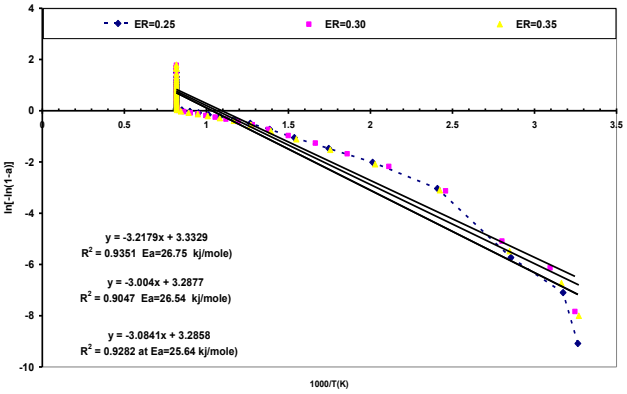


Figure 12. Effect of equivalence ratio on the frequency factor of the 91:9 coal–bagasse blend under air-assisted thermogravimetric conditions.

3.6. *Optimum blend and operating condition*

The selection of the optimum blend and operating condition was based on a combined interpretation of physicochemical properties, thermogravimetric conversion behavior, and apparent kinetic parameters, rather than on a single parameter alone. Among the investigated compositions, the 91:9 coal–bagasse blend showed the most favorable overall balance. Increasing the bagasse fraction enhanced the reactivity of the blend because of the higher volatile matter and oxygen-rich nature of biomass. However, excessive biomass addition also reduced the calorific value of the blended fuel. Therefore, the 91:9 blend was selected because it provided improved conversion behavior while maintaining acceptable fuel quality and kinetic response.

The heating-rate analysis showed that 20°C min^{-1} was the most suitable heating rate among the tested values. At this heating rate, the 91:9 blend exhibited higher overall conversion than the blends tested at 15 and 40°C min^{-1}. This indicates that an intermediate heating rate provided a more effective balance between heat transfer, devolatilization, and subsequent char conversion. At a

lower heating rate, the conversion process progressed more slowly, whereas at a higher heating rate, rapid heating may have increased thermal gradients and reduced the effective time available for complete char conversion.

The equivalence-ratio results also require combined interpretation. For the 91:9 blend, the apparent activation energies were 26.75, 26.54, and 25.64 kJ mol^{-1} at ER values of 0.25, 0.30, and 0.35, respectively. Although ER = 0.35 showed the lowest apparent activation energy, this value alone does not necessarily represent the most suitable gasification condition. Under air-assisted conditions, increasing ER increases oxygen availability, which can promote mass loss and reduce the apparent activation energy. However, excessive oxidant supply may also shift the process toward partial combustion rather than controlled gasification. Therefore, ER = 0.30 was selected as a balanced TGA-based operating condition because it provided favorable conversion and kinetic behavior without relying on the highest oxidant input.

Thus, the optimum condition established in this study corresponds to the 91:9 coal–bagasse blend operated at a heating rate of 20°C min^{-1} and an equivalence ratio of 0.30. This optimum should be interpreted as a thermogravimetric optimum for apparent thermal conversion and kinetic behavior under air-assisted conditions. It should not be considered a universal optimum for industrial gasification performance because final validation requires gasification experiments involving syngas composition, tar content, gas heating value, carbon conversion efficiency, and emission analysis.

4. Conclusions

This study evaluated the co-gasification suitability of selected indigenous coal, biomass, and coal–bagasse blends using physicochemical characterization, non-isothermal thermogravimetric analysis, and kinetic assessment. The results showed clear differences in the thermal conversion behavior of the investigated fuels, confirming that fuel properties such as volatile matter, fixed carbon, ash content, oxygen content, and heating value strongly influence co-gasification performance. Among the individual biomass samples, bagasse exhibited the most favorable behavior because of its high volatile matter, low ash content, and comparatively strong thermal reactivity. Among the coal samples, Chamalang coal was found to be the most suitable because of its balanced fuel characteristics, relatively low ash content, and favorable conversion behavior. These findings justified the selection of bagasse and Chamalang coal for blended-fuel preparation.

The prepared coal–bagasse blends showed that moderate biomass addition improved the reactive characteristics of the parent coal without causing a severe loss in fuel quality. Among the tested blend ratios, the 91:9 coal–bagasse blend provided the most favorable overall balance between conversion performance and calorific value. The operating-condition analysis further demonstrated that thermal conversion was strongly influenced by particle size, heating rate, feed composition, and equivalence ratio. The best overall conversion performance was obtained at a heating rate of 20°C min^{-1} and an equivalence ratio of 0.30.

The kinetic analysis supported the thermogravimetric findings and confirmed the suitability of the selected blend and operating conditions. Bagasse showed the lowest activation energy among the biomass samples, while Chamalang coal exhibited the most favorable kinetic behavior among the investigated coals. For the blended fuels, the 91:9 composition showed the most suitable kinetic response, and the combined interpretation of conversion and activation energy results identified the 91:9 blend operated at 20°C min^{-1} and ER = 0.30 as the optimum condition within the investigated range. Overall, the results demonstrate that partial substitution of Chamalang coal with bagasse can improve the co-gasification performance of the feedstock and may provide a practical basis for the development and optimization of coal–biomass thermochemical conversion systems. The study offers useful guidance for fuel selection and operating-condition optimization in future co-gasification applications involving indigenous coal and agricultural biomass resources.

Although the present study demonstrates improved apparent conversion and kinetic behavior of coal–bagasse blends, quantitative confirmation of synergistic or antagonistic interaction was beyond the scope of the available dataset. Future studies should include matched individual-fuel and blend conversion profiles under identical operating conditions to calculate synergy indices and more clearly distinguish additive, synergistic, and antagonistic effects during co-gasification. The present study was limited to air-assisted thermogravimetric conditions; therefore, future work should investigate coal–bagasse blends under steam, oxygen-enriched air, and mixed gasifying atmospheres to further evaluate their suitability for industrial gasification systems. Since the present work was limited to thermogravimetric mass-loss and kinetic analysis, future studies should evaluate the selected coal–bagasse blends in a lab-scale gasifier with gas-composition and tar-analysis systems to determine syngas quality, tar formation, gas heating value, and overall gasification efficiency.

In practical applications, industries using coal-based thermal systems, such as sugar mills, brick kilns, cement plants, and small-scale gasification units, could consider partial substitution of coal with bagasse at the 91:9 coal–bagasse ratio after pilot-scale validation. Such utilization would provide a productive pathway for consuming sugarcane bagasse residues while reducing the amount of coal required for thermal conversion processes.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used ChatGPT (OpenAI, GPT-4) to improve language clarity, grammar, and readability. The tool was used only for linguistic refinement and not for scientific content generation, data analysis, interpretation, or image creation. The authors reviewed and edited all AI-assisted text and take full responsibility for the content of the manuscript.

No generative AI or AI-assisted tools were used to create, modify, or enhance any figures or graphical materials in this work.

References

Abedin, T., Pasupuleti, J., Paw, J.K.S., Tak, Y.C., Islam, M.R., Basher, M.K., Nur-E-Alam, M., 2025. From waste to worth: advances in energy recovery technologies for solid waste management. Clean Technol. Environ. Policy 27, 5963-5989. https://doi.org/10.1007/s10098-025-03204-x

Adeoye, O.O., Silva Lora, E.E., Andrade, R.V., Pupo, L.P., Jaén, R.L., 2026. Review of Entrained flow Co-gasification Technology of Biomass with Different Fuels. Fuel 404, 136420. https://doi.org/10.1016/j.fuel.2025.136420

Ali, M., Shakaib, M., Zaidi, A.A., Javed, M.A., Khan, S.Z., Aly Hassan, A., 2025. Performance and Environmental Sustainability of Fish Waste Biodiesel on Diesel Engines. Sustainability. https://doi.org/10.3390/su17125385

Ansari, I., Zaidi, A.A., Memon, A.H., Hussain, A., Haleem, A.B., 2026. Valorization of Textile Cotton Waste and Textile Sludge into High-Quality Torrefied Biofuel Pellets: Fuel Characteristics and Optimization. Energies. https://doi.org/10.3390/en19061401

Awais, M., Omar, M.M., Munir, A., li, W., Ajmal, M., Hussain, S., Ahmad, S.A., Ali, A., 2022. Co-gasification of different biomass feedstock in a pilot-scale (24 kWe) downdraft gasifier: An experimental approach. Energy 238, 121821. https://doi.org/10.1016/j.energy.2021.121821

Bajwa, D.S., Peterson, T., Sharma, N., Shojaeiarani, J., Bajwa, S.G., 2018. A review of densified solid biomass for energy production. Renew. Sustain. Energy Rev. 96, 296-305. https://doi.org/10.1016/j.rser.2018.07.040

Balaram, V., Manikyamba, C., 2026. Coal and Coal Combustion Byproducts as Promising Resources for the Extraction of Rare Earth Elements for the Current Energy Transition. Geol. J. n/a. https://doi.org/10.1002/gj.70210

de Oliveira, T.R., Tannous, K., de Lima, E.C.T., 2022. Pyrolysis of the hybrid energy cane: thermal decomposition and kinetic modeling using non-isothermal thermogravimetric analysis. J. Therm. Anal. Calorim. 147, 7431-7448. https://doi.org/10.1007/s10973-021-11028-2

Fryda, L., Panopoulos, K., Vourliotis, P., Pavlidou, E., Kakaras, E., 2006. Experimental investigation of fluidised bed co-combustion of meat and bone meal with coals and olive bagasse. Fuel 85, 1685-1699. https://doi.org/10.1016/j.fuel.2006.01.020

Gong, J., Yang, L., 2024. A Review on Flaming Ignition of Solid Combustibles: Pyrolysis Kinetics, Experimental Methods and Modelling. Fire Technol. 60, 893-990. https://doi.org/10.1007/s10694-022-01339-7

Habib, M.I., 2026. Quantifying Solar Irradiation and Photovoltaic Energy Yield at Optimal Tilt Angles: A Case Study of Gojra, Punjab, Pakistan. J. Energy, Mater. Sustain. 2, 18-38. https://doi.org/10.66173/jenmas.2026.18

Inayat, A., Dafalla, M., Asaad, S., Jamil, F., Al-Haj, L., Shah, F.M., Ghenai, C., Shanableh, A., 2025. Sustainable Energy Production From Waste: A Review of Hybrid Approaches Combining Anaerobic Digestion and Gasification. Int. J. Energy Res. 2025, 6644084. https://doi.org/10.1155/er/6644084

Jamil, R., Zaidi, A.A., Rai, R., Memon, A.H., Aijaz, A., Asif, M., 2026. Chapter 19 - Global market potential and economic aspects of microalgae for biofuel production, in: Özkaya, B., Ali, M., Zaidi, A.A., Naseer, M.N.B.T.-S.P. of M.B. as a B.F. (Eds.), Woodhead Series in Bioenergy. Woodhead Publishing, pp. 535-561. https://doi.org/10.1016/B978-0-443-29269-9.00013-7

Koyunoğlu, C., Tolay, M., 2025. Co-gasification of Turkish lignite and three plastic wastes in a lab-scale updraft gasifier: case-study equilibrium (gibbs free energy), openfoam CFD, analytical validation, and experimental-range benchmarking. Energy Convers. Manag. X 28, 101372. https://doi.org/10.1016/j.ecmx.2025.101372

Lei, S., Xing, B., Lv, B., Fang, J., Zeng, H., Zhang, C., Hou, Y., Wang, X., 2026. Advancements in ultra-low ash coal: preparation techniques, applications, and future prospects for clean and high-value utilization. Int. J. Coal Prep. Util. 46, 931-956. https://doi.org/10.1080/19392699.2025.2484316

Luo, Z., Zhou, J., 2025. Thermal Conversion of Biomass BT - Handbook of Climate Change Mitigation and Adaptation, in: Lackner, M., Sajjadi, B., Chen, W.-Y. (Eds.), Springer Nature Switzerland, Cham, pp. 1233-1289. https://doi.org/10.1007/978-3-031-84483-6_27

Mohlala, L.M., Bodunrin, M.O., Awosusi, A.A., Daramola, M.O., Cele, N.P., Olubambi, P.A., 2016. Beneficiation of corncob and sugarcane bagasse for energy generation and materials development in Nigeria and South Africa: A short overview. Alexandria Eng. J. 55, 3025-3036. https://doi.org/10.1016/j.aej.2016.05.014

NREL, 1995. Alkali Deposits Found in Biomass Power Plants: A Preliminary Investigation of Their Extent and Nature. Volume 1 [WWW Document]. URL https://digital.library.unt.edu/ark:/67531/metadc664004/ (accessed 4.25.24).

Nussipov, D., Akimbekov, N., Tastambek, K., Digel, I., Aimagambetov, A., Xiangrong, L., Yaya, W., Ackley, L., Zhailauova, G., 2026. Resource recovery from low-rank coal and livestock manure for sustainable agroecosystems: a review. Arch. Microbiol. 208, 204. https://doi.org/10.1007/s00203-026-04758-0

Preciado, J.E., Ortiz-Martinez, J.J., Gonzalez-Rivera, J.C., Sierra-Ramirez, R., Gordillo, G., 2012. Simulation of Synthesis Gas Production from Steam Oxygen Gasification of Colombian Coal Using Aspen Plus®. Energies. https://doi.org/10.3390/en5124924

Pribadi, G.A.D., Noble, A., 2026. Gasification of Indonesia's Low-Rank Coal: A Comparative Review of Technology Options and Contextual Considerations. Fuel 414, 138280. https://doi.org/10.1016/j.fuel.2026.138280

Puig-Arnavat, M., Bruno, J.C., Coronas, A., 2010. Review and analysis of biomass gasification models. Renew. Sustain. Energy Rev. 14, 2841-2851. https://doi.org/10.1016/j.rser.2010.07.030

Quan, C., Ravelomanantsoa, V.S., Olazar, L., Santamaria, L., Lopez, G., Liu, L., Gao, N., 2026. Thermochemical conversion of waste into energy: a review. Environ. Chem. Lett. 24, 295-320. https://doi.org/10.1007/s10311-025-01889-6

Rodjeen, S., Mekasut, L., Kuchontara, P., Piumsomboon, P., 2006. Parametric studies on catalytic pyrolysis of coal-biomass mixture in a circulating fluidized bed. Korean J. Chem. Eng. 23, 216-223. https://doi.org/10.1007/BF02705719

Rodrigues, R., Marcilio, N., Trierweiler, J., Godinho, M., 2011. Thermodynamic efficiency analysis of gasification of high ash coal and biomass, in: International Conference on Coal Science & Technology. Oviedo, Spain.

Sarwar, A., Nasiruddin Khan, M., Azhar, K.F., 2012. Kinetic studies of pyrolysis and combustion of Thar coal by thermogravimetry and chemometric data analysis. J. Therm. Anal. Calorim. 109, 97-103. https://doi.org/10.1007/s10973-011-1725-0

Senneca, O., Salatino, P., Chirone, R., 1999. A fast heating-rate thermogravimetric study of the pyrolysis of scrap tyres. Fuel 78, 1575-1581. https://doi.org/10.1016/S0016-2361(99)00087-3

Si, F., Zhang, H., Feng, X., Xu, Y., Zhang, L., Zhao, L., Li, L., 2024. Thermodynamics and synergistic effects on the co-combustion of coal and biomass blends. J. Therm. Anal. Calorim. 149, 7749-7761. https://doi.org/10.1007/s10973-024-13310-5

Tarani, E., Chrissafis, K., 2024. Isoconversional methods: A powerful tool for kinetic analysis and the identification of experimental data quality. Thermochim. Acta 733, 179690. https://doi.org/10.1016/j.tca.2024.179690

Tian, B., Wang, J., Qiao, Y., Huang, H., Xu, L., Tian, Y., 2023. Understanding the pyrolysis synergy of biomass and coal blends based on volatile release, kinetics and char structure. Biomass and Bioenergy 168, 106687. https://doi.org/10.1016/j.biombioe.2022.106687

TUMULURU, J.S., WRIGHT, C.T., 2010. A REVIEW ON BIOMASS DENSIFICATION TECHNOLOGIE FOR ENERGY APPLICATION. United States. https://doi.org/10.2172/1016196

Ungureanu, N., Vlăduț, N.-V., Biriș, S.-Ștefan, Ionescu, M., Gheorghiță, N.-E., 2025. Municipal Solid Waste Gasification: Technologies, Process Parameters, and Sustainable Valorization of By-Products in a Circular Economy. Sustainability. https://doi.org/10.3390/su17156704

Vamvuka, D., Kakaras, E., Kastanaki, E., Grammelis, P., 2003. Pyrolysis characteristics and kinetics of biomass residuals mixtures with lignite☆. Fuel 82, 1949-1960. https://doi.org/10.1016/S0016-2361(03)00153-4

Wang, Haiyan, Liu, S., Wang, Haoqi, Chao, J., Li, T., Ellis, N., Duo, W., Bi, X., Smith, K.J., 2025. Thermochemical conversion of biomass to fuels and chemicals: a review of catalysts, catalyst stability, and reaction mechanisms. Catal. Rev. 67, 57-129. https://doi.org/10.1080/01614940.2023.2275093

Wang, P., Hedges, S., Casleton, K., Guenther, C., 2012. Thermal Behavior of Coal and Biomass Blends in Inert and Oxidizing Gaseous Environments. Int. J. Clean Coal Energ. 1, 35-42. https://doi.org/10.4236/ijcce.2012.13004

Yadav, D., Saha, S., Sahu, G., Chavan, P.D., Datta, S., Chauhan, V., Kumari, N., 2023. A comparative review on thermal behavior of feedstocks during gasification via thermogravimetric analyzer. J. Therm. Anal. Calorim. 148, 329-354. https://doi.org/10.1007/s10973-022-11757-y

Yao, X., Liu, Q., Kang, Z., An, Z., Zhou, H., Xu, K., 2023. Quantitative study on thermal conversion behaviours and gas emission properties of biomass in nitrogen and in CO2/N2 mixtures by TGA/DTG and a fixed-bed tube furnace. Energy 270, 126904. https://doi.org/10.1016/j.energy.2023.126904

Youssef, M.A., Wahid, S.S., Mohamed, M.A., Askalany, A.A., 2009. Experimental study on Egyptian biomass combustion in circulating fluidized bed. Appl. Energy 86, 2644-2650. https://doi.org/10.1016/j.apenergy.2009.04.021

Zakaria, Z., Mohd Ishak, M.A., Abdullah, mohd fauzi, Ismail, K., 2010. Thermal Decomposition Study of Coals, Rice Husk, Rice Husk Char and Their Blends During Pyrolysis and Combustion via Thermogravimetric Analysis. Int. J. Chem. Technol. 2, 78-87. https://doi.org/10.3923/ijct.2010.78.87

Zein, S.H., 2026. Thermodynamic Analysis of Plastic Waste Conversion to Hydrogen: Heat Integration and System Performance-A Review. Thermo. https://doi.org/10.3390/thermo6010014

Zhang, Xuefei, Li, Y., Zhang, Xianwen, Ma, P., Xing, X., 2023. Co-combustion of municipal solid waste and hydrochars under non-isothermal conditions: Thermal behaviors, gaseous emissions and kinetic analyses by TGA-FTIR. Energy 265, 126373. https://doi.org/10.1016/j.energy.2022.126373