American Journal of Biochemistry and Biotechnology

Research Article

Analysis of Combustion Curve for Biomass Co-combustion with Coal

[1,2]Rong Li, [1,2]Li Li, [1,2]Lei Zhang and [1,2]Xin Zhang

[1]Hebei Key Laboratory of Man-machine Environmental Thermal Control Technology and Equipment, Xingtai, 054000, China
[2]Hebei Vocational University of Technology and Engineering, Xingtai, 054000, China

Article history
Received: 24-10-2024
Revised: 04-12-2024
Accepted: 17-02-2025

Corresponding Author:
Rong Li
Hebei Key Laboratory of Man-machine Environmental Thermal Control Technology and Equipment, Xingtai, 054000, China;
Hebei Vocational University of Technology and Engineering, Xingtai, 054000, China
Email: yanglirong39@163.com

Abstract: Biofuel-coal co-combustion represents an innovative approach to combustion that optimally harnesses biomass energy alongside coal resources, resulting in a significant reduction in pollutant emissions. This study investigates the combustion characteristics of peanut shell biomass, coal, and their blends at varying heating rates (5, 10, 20, and 40°C/min) and different blending ratios. The effects of these parameters on the combustion process were systematically analyzed. The results indicate that increasing the heating rate causes a shift in the TG curve towards higher temperatures. Notably, peanut shells exhibit lower characteristic combustion temperatures and faster burning rates compared to coal. Furthermore, incorporating peanut shells into coal leads to earlier ignition times and enhanced combustion properties, thereby substantially improving biomass utilization efficiency.

Keywords: Biomass, Coal, Thermogravimetric Analysis, Combustion Curve

Inroduction

Energy shortages and environmental degradation are facing significant challenges. Energy plays a crucial role in shaping human life and development, profoundly influencing the economic and social progress. Biomass fuels are recognized as renewable and clean alternatives to fossil fuels. Globally, biomass energy consumption ranks the fourth, following by oil, coal, and natural gas (Huang *et al.*, 2023). Biomass energy has attracted widespread attention due to its unique attributes of storability and transportability, as well as its high conversion efficiency and environmental sustainability (Camelo *et al.*, 2018; Pérez *et al.*, 2018; Wang *et al.*, 2018).

There are a large variety of biomass resources worldwide, which can be classified into several categories such as wood and forestry waste, agricultural residues, animal manure, as well as urban waste, sewage, and various aquatic or oil-bearing plants (Radenahmad *et al.*, 2018; Chowdhury *et al.*, 2020). China has abundant biomass resources, estimated to be equivalent to approximately 5 billion tons of standard coal. It is estimated that the potential utilization biomass energy will reach around 700 million tons. According to Glushkov *et al.* (2024), there are significant differences between the characteristics of biomass and fossil fuels. These differences result in significant changes in combustion mechanisms, reaction rates, and composition of combustion products compared to fossil fuels.

The application and extraction methods of biomass mainly include solidification, gasification, and liquefaction (Svedovs *et al.*, 2023). In these approaches, gasification is considered the most advantageous, as it can generate efficient and environmentally sustainable energy fuels (Abioye *et al.*, 2024). In addition, direct combustion remains a viable option.

The utilization of biomass fuel can be seen as a reverse process of energy and material conversion during photosynthesis. The reversible relationship is as follows:

$$CO_2 + H_2 \Leftrightarrow \{[CH_2O] + H_2\} + O_2$$

This equation indicates that photosynthesis and biomass combustion are interconnected terrestrial processes. This cycle is carbon-neutral and will not result in net increase in atmospheric carbon. Unlike fossil fuels, biomass contains lower concentrations of sulfur (S) and nitrogen (N), and the ash generated from combustion can be used as a soil amendment. Therefore, replacing fossil fuels with biomass fuels for energy production can significantly reduce CO_2, SO_x, and NO_x emissions, thereby mitigating air pollution and greenhouse effect.

Biomass energy is being studied and promoted worldwide. Given China's unique national context and current level of biomass energy utilization and development capabilities, direct combustion emerges has become one of the most practical and feasible approach to effectively use biomass resources.

SCIENCE Publications

Problems with Direct Biomass Combustion

Since biomass direct combustion is a relatively mature method, it has the advantages of simple equipment and wide utilization of post-combustion ash, and there are still some challenges:

1. Biomass fluidized bed boiler have strict requirements for fuel particles, requiring pre-treatment processes such as screening, drying and crushing to ensure uniformity of sizes and effective fluidization of biomass fuels
2. To facilitate efficient combustion of lightweight, loosely structured biomass materials (such as rice husks and wood chips), it is necessary to continuously add bedding materials (such as quartz sand) to maintain the required thermal storage medium for normal combustion (Odzijewicz *et al.*, 2022). However, this method will generate hard residues such as fly ash, which increases the wear on the boiler's heat-receiving surfaces. Moreover, these ashes can lead to mixed waste, posing recycling challenges due to their composition (Cruz *et al.*, 2019)
3. Biomass typically contains high concentrations of alkali metal (*Na*, *K*) oxides and salts, which can significantly lower the ash melting point and pose various challenges during combustion (Wang *et al.*, 2024; Shamooni *et al.*, 2024). Bapat *et al.* demonstrated that in fluidized bed combustion of biomass characterized by high alkali metal content, these alkali metals can cause severe agglomeration of bed material particles. This occurs because alkali metal (*Na*, *K*) oxides and salts can react with SiO_2 (Gogolev (et al., 2021)

   $$2S_iO_2 + Na_2CO_3 \rightarrow Na_2O(2S_iO_2) + CO_2$$

   $$4S_iO_2 + K_2CO_3 \rightarrow K_2O(4S_iO_2) + CO_2$$

   The formation of low-temperature eutectic results in a decrease in melting temperature, showing significant sintering (Yao *et al.*, 2020)

4. High moisture in biomass fuels leads to an increase in exhaust volume and a decrease in overall efficiency. Combusting fuels rich in alkali metals (such as rice straw) increases the risk of corrosion on heat-receiving surfaces at high temperatures. Certain fuels may chemically react with bedding material in the fluidized bed system, leading to condensation. Moreover, some high-nitrogen fuels generate excessive NO_x emissions indirect combustion, which hinders the improvement of combustion efficiency and effective strategies of emission control
5. Regarding waste incineration technology, urban household waste brings additional complications due to variable moisture content

Emerging Trend of Co-Firing Biomass and Coal

China mainly relies on fossil fuels such as coal for electricity generation. These fuels emit large amounts of NO_x (nitrogen oxides), CO_2 (carbon dioxide), and particulate pollutants, which are key contributors of acid rain, ozone depletion and greenhouse effect (Glushkov *et al.*, 2021; Ye *et al.*, 2019; Oberschelp *et al.*, 2019). Considering that the carbon dioxide released during biomass combustion is equal to that absorbed during its growth phase, this process effectively reduces net atmospheric CO_2 emissions to zero. Moreover, biomass combustion helps to reduce the production of natural CH_4 (methane) during decomposition, further reducing gas emissions of greenhouse, as methane has a greenhouse effect 21 times that of CO_2 (Xiao *et al.*, 2003). As a result, co-firing biomass and coal can reduce SO_x (sulfur oxides), NO_x (nitrogen oxides), and particulate matter in coal combustion while significantly reducing the greenhouse effect (Kanwal *et al.*, 2021).

The utilization of biomass energy is continuously increasing. However, the disadvantages of scattered biomass distribution, low energy density, high costs of collection, transportation and pretreatment, low heat value, high moisture content, and the need for external heat sources for conversion and utilization make the individual utilization of biomass fuels challenging. This results in small equipment capacity, high investment costs, poor system independence, and low efficiency. To achieve large-scale effective utilization and commercial competiveness of biomass in a short period of time, the co-firing and co-conversion technology of biomass and coal is a feasible alternative solution for low-cost and large-scale utilization of biomass energy. Efficient and cost-effective conversion of biomass into electricity is the core of biomass utilization. Combining with modern coal-fired power generation units is one of the significant ways to achieve the joint utilization of biomass and coal. Fully exploiting the residual heat of the thermal system of the power plant, and continuously or intermittently using a small proportion of biomass fuel in coal-fired boilers can significantly improve the utilization efficiency of biomass fuel, reduce cost, increase boiler efficiency, converse coal resources, and mitigate pollution.

Combining biomass with coal for combustion is a method of improving the efficiency of non-renewable energy sources through renewable means while reducing environmental pollution and extending resource longevity. This is undoubtedly a worthy effort and an effective strategy to address China's energy challenges and environmental pollution. However, there are some issues when biomass is combined with coal for combustion. For instance, the relatively high heavy metal content in coal might bring new pollution problems to the combustion of biomass-coal mixtures. Despite having pollution control equipment, some power plants still exceed the emission standards set by the US Environmental Protection Agency (EPA).

To date, some fundamental experimental studies on the co-pyrolysis of biomass and coal by using the reactors such as a thermogravimetric analyzer have been carried out. Some countries in Europe and the United States have implemented new measures to mix a portion of biomass with coal for power generation or gasification, demonstrating the feasibility of co-combustion of biomass and coal. The research on the co-pyrolysis of biomass and coal in China is highly limited, and the types of biomass investigated are also few. Therefore, strengthening the research on co-pyrolysis of biomass and coal is of great significance.

This study uses thermogravimetric analysis to investigate the co-combustion characteristics of peanut shells, and biomass with coal, and examine their combustion characteristics.

Coal is a substance deficient in hydrogen, whereas biomass is a substance rich in hydrogen. Adding hydrogen to coal during pyrolysis can significantly improve the efficiency of coal pyrolysis and enhance the characteristics of pyrolysis products. Peanut shell is a common biomass that is more economical and easily obtained than coal. In this study, the co-combustion of peanut shell and coal is experimentally selected for investigation.

Materials and Methods

Experimental Raw Materials

Preparation of Raw Materials

Peanut shells and coal were used as raw materials for experiment. In the experiment, the kernels of peanuts and coal were pulverized into powder through appropriate means. Coal was crushed using an electric coal grinder, while biomass was manually ground in an iron boat. Before the experiment, all materials were ground to a particle size of less than 0.5 mm, dried and evenly mixed, and then placed in a dryer for use.

Industrial and Elemental Analysis of Raw Materials

Industrial analysis of raw materials. Industrial analysis of raw materials includes determining the moisture content, ash content, volatile matter yield, and fixed carbon content.

Determination of moisture content: Initially, the empty glass container was weighted using a precision balance. Then the raw material was added to record the combined weight. The container was put in an oven at an 80°C for one hour to ensure complete drying. After removing from the oven, the sample was cooled to room temperature for about three minutes, and then transferred to a desiccator for stabilization before reweighing. This procedure requires a check experiment to be conducted every 0.5 h until two consecutive measurements indicate a weight loss of no more than 0.001 grams. The pre-drying weight was taken as a reference value. The moisture content is calculated as a percentage of mass reduction relative to the original sample weight.

Assessment of ash content: It involves weighing a specific quantity of raw material and placing it into a crucible. The crucible was then placed in a muffle furnace with a maximum temperature of not exceeding 300°C. The furnace door was securely locked, allowing the temperature to gradually increase to 500°C within one hour while maintaining a stable range of ±20°C during this process. The sample was combusted for 0.5 h to ensure that the crucible was in a high-temperature in this duration. After combustion, the crucible should be immediately removed from the furnace and cooled in ambient air for five minufftes, and then transferred to a dryer for further cooling until it reached room temperature (about 25 min). After that, it was reweighed. In addition, the experiment was repeated every 0.5 h until the weight changes measured were less than 0.001 g. The final recorded weight was used as the basis for calculation. The percentage of residual material in the crucible relative to the original sample mass represents the ash content of initial material.

Assessment of volatile matter: The first step was to weigh an accurate quantity of sample material and place it into a preheated specialized crucible that has been heated to a constant weight at 300 °C . The crucible containing the sample was covered with a lid and positioned on an appropriate stand. It was then quickly introduced into the stable temperature environment of a muffle furnace that has been heated to 300 °C. As the furnace door was locked, a stopwatch was immediately activated for continuous heating of the sample for 7 min. After this duration, the crucible stand was promptly removed and cooled in ambient air for 5 min. The cooled crucible was then transferred to a desiccator until it reached the room temperature before it was measured. The percentage of the sample mass lost after heating for 7 min represents the volatile matter content of the sample after adjusting the moisture content percentage.

Assessment of fixed carbon: After removing the initial three components, the remaining content corresponds to the fixed carbon.

Heating value: The automatic calorimeter can measure the heating value, which corresponds to the calorific content of the shell. Table (1) shows the data of industrial analysis and heating values

Elemental characterization of raw materials: The data in Table (2) shows the results of elemental analysis. This analysis uses a carbon-hydrogen-nitrogen analyzer, with an infrared spectroscopy used for measuring C and H, and the thermal conductivity methods for determining N.

The oxygen content was calculated by subtracting the contributions of C, H, N, moisture, and ash from the total mass. Unfortunately, due to technical constraints, we are unable to assess the sulfur content in biomass and coal samples.

The results of elemental analysis on various samples are shown in Table (2). It is analyzed by a carbon-hydrogen-nitrogen analyzer. The infrared spectroscopy was used to quantify carbon and hydrogen, while nitrogen content was assessed through thermal conductivity techniques. The oxygen content is calculated by subtracting the contributions of carbon, hydrogen, nitrogen, moisture, and ash from the total mass (100%). However, the sulfur content in biomass and coal samples was unmeasured.

Assessment of ash content in raw materials: The ash component analysis for biomass and coal are shown in Table (3). This analysis is according to the GB/T14506-93 standard, using a quantitative chemical analysis method and the testing equipment such as 180-70 atomic absorption spectrometer and UV-75433 ultraviolet-visible spectrophotometer.

Table 1: Industrial analysis and calorific value of biomass and coal

Samples	Industrial analysis%					Heat generation
	M_{ad}	V_{ad}	V_{daf}	A_{ad}	FC_{ad}	$Q_{ar,net,p}$ MJ/kg
Peanut shell	7.88	68.10	76.50	1.60	22.40	19.27
Coal	3.64	5.56	6.00	3.65	87.16	33.26

Table 2: Elemental composition analysis of biomass and coal

Samples	Elemental analysis of dry ash-free samples%, daf				Analysis of combustible elements%, maf			
	C	H	O	N	C	H	O	N
Peanut shell	45.31	6.68	35.96	1.07	50.90	7.50	40.40	1.20
coal	87.70	2.88	2.58	1.03	93.11	3.06	2.74	1.09

Table 3: Analysis of ash composition of biomass and coal (%)

Ash constituents	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5
Peanut shell	21.14	5.30	2.21	8.23	19.74	0.99	36.22	0.35	0.34	5.49
Coal	49.19	41.79	1.23	0.36	1.32	3.68	0.51	1.87	0.02	0.03

Characterization of Original Biomass and Coal Samples

Comparative Analysis of the Industrial Properties of Biomass and Coal

The revised sentence is Table (1) shows a significant difference in water content between biomass and coal, with biomass having a higher moisture content and volatile matter. For example, the volatile matter of air-dried biomass was more than 60%, while that of dry ash-free biomass is significantly higher, reaching about 80%. In addition, there is a significant difference in ash between the two materials, and the fixed carbon (FC_{ad}) of air-dried biomass is much lower than that of coal. The quality of combustion can be gauged by the index proposed by Fu Weibiao. The higher the index value, the better the combustion. This is directly proportional to the internal moisture, volatile matter release, and carbon content of the coal. As shown in Table (1), due to the high volatile matter content of biomass, it can significantly improve the combustion of coal when co-combusted.

Comparative Analysis of Heat Output Between Biomass and Coal

The data in Table (2) indicates that the heat output of biomass is relatively lower than that of coal, which has a higher level of thermal energy release. The main reasons are as follows: From an elemental composition perspective, biomass contains more oxygen and less carbon than coal, resulting in decreased heat generation; on the contrary, the characteristics of coal are high carbon and low oxygen, leading to an increase in thermal energy release. Regarding the differences in material composition between the two fuels, biomass mainly consists of cellulose and lignin, which have lower calorific values and lower heat generation, while coal is mainly composed of condensed aromatic structures that produce higher calorific values.

The heating value of biomass is lower than that of coal. Therefore, when biomass is co-fired with coal, it will lead to a reduction in the output power and efficiency of the boiler, thereby limiting the blending ratio.

Comparative Analysis of Elemental Characteristics between Biomass and Coal

As shown in Table (3), the comparative results of the elemental composition of biomass and coal are based on dry ash-free and combustible basis. The main difference lies in the higher oxygen and lower carbon in biomass, while coal has the opposite characteristics with increased carbon and reduced oxygen. There is no significant difference in hydrogen (H) and nitrogen (N) contents between biomass and coal.

Comparative Analysis of Ash Components between Biomass and Coal

The ash of coal constitutes accounts for over 90% of the total, mainly consists of SiO_2, Al_2O_3, Fe_2O_3, MgO, and CaO. SiO_2 and Al_2O_3 account for more than 75%. The concentrations of other oxides such as Na_2O, K_2O, TiO_2, MnO, and P_2O_5 are negligible. Biomass contains higher alkali and alkaline earth metal oxides, as well as P_2O_5 than coal. The ash composition of the peanut shell biomass used here is mainly composed of SiO_2, CaO, and K_2O, accounting for 77% of the total ash.

Thermal Analysis Experimental Methods and Testing Conditions

The experiment used the WCT-2 high-temperature thermogravimetric analyzer produced by Beijing Optical Instrument Factory. This device is a fully automated sampling device that can continuously heat the test sample at a predetermined rate. The weight loss curve (TG curve) and differential weight loss curve (DTG curve) were recorded using the thermal analyzer.

The experimental system encompasses an electronic balance, a differential thermal analyzer, a data acquisition and processing system, as well as a gas cylinder. The electronic balance can achieve an accuracy of 0.001 grams. Two cylindrical Al_2O_3 crucibles are positioned within the heating furnace, each with a volume of 0.6 milliliters and can be filled with up to 1 gram of biomass powder for experimentation. In the experiment, the materials are only added to one crucible.

The specific experimental protocols are as follows:

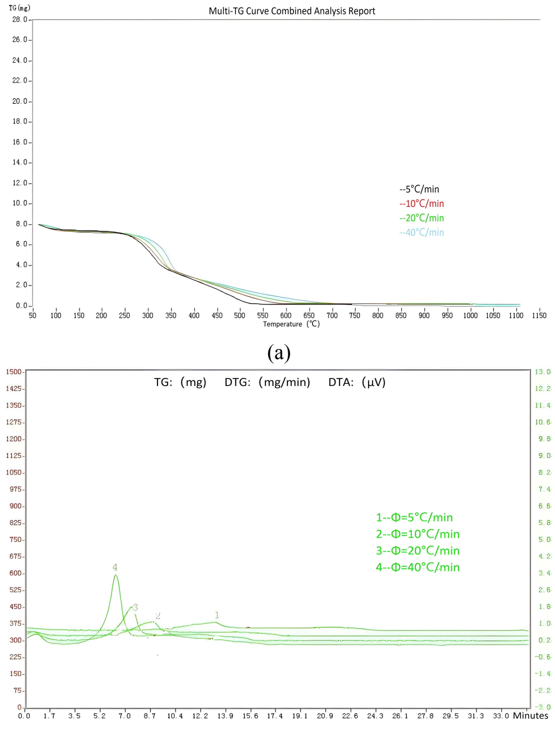
1. The heating rates were set to 5, 10, 20, and 40°C/min respectively for programmed heating of 4 mg of peanut shell and coal each for combustion experiments
2. 1.6 mg of peanut shell with 6.4 mg of coal is combined to ensure complete mixing. Programmed heating is conducted at the rates (5, 10, 20, and 40°C/min) for co-combustion experiment. The particle size of the samples was less than 0.5 mm, with a total weight of 8 mg. The testing atmosphere consists of an air flow rate of about 100 mL/min, and the sampling began at a temperature of 60 °C and ended at a temperature of 1100°C

Results and Analysis

Influence of Heating Rate

Thermogravimetric (TG) and differential thermogravimetric (DTG) curves are obtained using a thermal analyzer, as shown in Figs. (1-2).

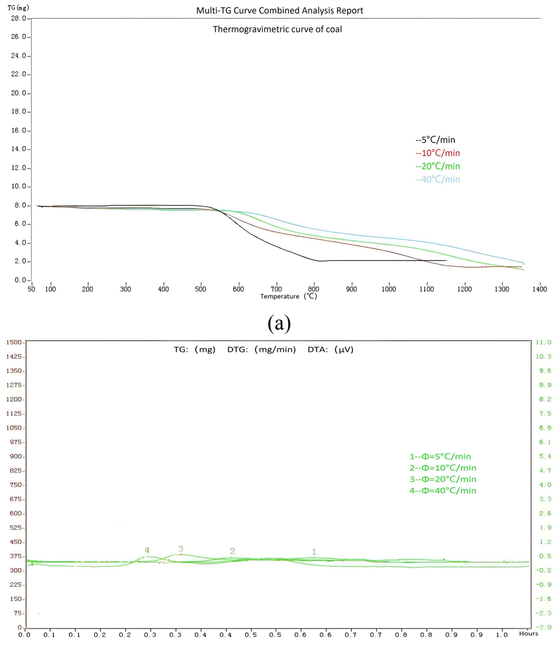
In Figure (1), it can be seen that the combustion of peanut shells consists of four different stages: drying, heating and holding, volatile combustion, and residual volatile and char combustion. It is worth noting that during volatile combustion, the mass loss accounts for 55%. There was a combined mass loss of 32% from residual volatiles and peanut shells during char combustion. This emphasizes the significance of the volatile combustion stage in the overall biomass combustion process.



(a)

(b)

Fig. 1: (a): Thermo Gravimetric (TG) curve of peanut shell combustion (b): DTG curve of peanut shell combustion



(a)

(b)

Fig. 2: (a): TG curve of coal combustion (b): DTG curve of coal combustion

Figure (1) shows that the increase rate of temperature significantly influences the combustion process: as the rate accelerates, there is a corresponding shift of the TG curve to higher temperatures. This indicates that for equivalent mass losses, as combustion is an endothermic reaction, an increase in temperature is required. Therefore, a faster heating rate can reduce the time required for a specific temperature. However, due to the poor thermal conductivity of biomass, the heating of internal samples lags behind external conditions, resulting in delayed internal combustion.

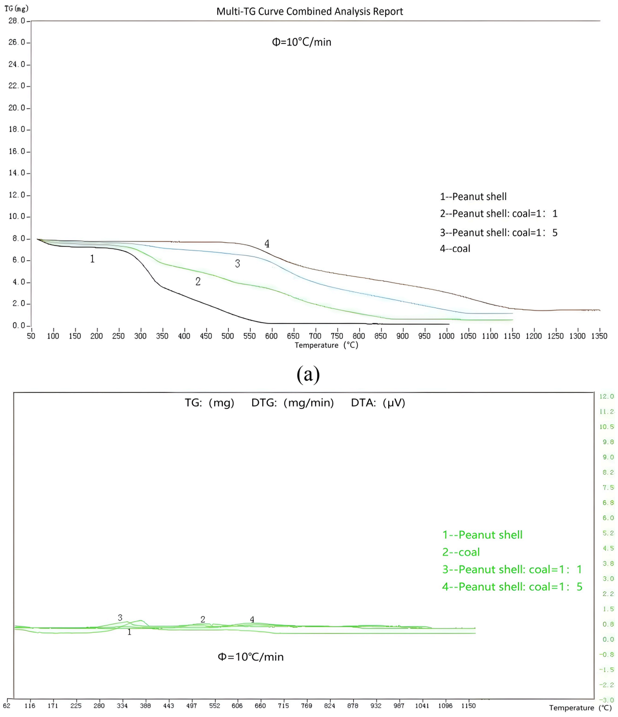
The combustion characteristics of coal are shown in Figure (2). It shows that the DTG curve of coal combustion has two peaks. The first peak indicates that the initial decomposition temperature of volatile matter in coal is significantly higher than that of biomass, and its ignition temperature also higher than that of biomass. This phase is accompanied by the combustion of volatiles. The second peak corresponds to the char combustion process. During the combustion process, the maximum combustion rate of coal in the middle stage characterized by increased temperature and prolonged duration. However, this maximum rate remains lower than that in biomass. This phenomenon can be attributed to a lower content of volatile matter in coal: once ignited, these volatiles will combust rapidly and increase fast in char temperature, releasing substantial heat. Therefore, the primary combustion process of coal is concentrated in the char combustion stage, and its residual combustion temperature is much higher than that of biomass.

The images indicate that the ignition temperature of coal is much higher than that of biomass. However, the time reaching this temperature varies at different heating rates. More specifically, a higher heating rate leads to a shorter duration of ignition. There are differences in the maximum temperatures achievable at various heating rates, with each peak representing the highest combustion rate associated with its respective heating rate. Typically, from 550-700°C, this peak temperature increases as the heating rate increases. A comparison of the two figures reveals that a faster heating rate will lead to a higher combustion temperature and shorter combustion duration, which aggravates the thermal lag effects. As a result, the starting and ending temperatures on the TG curve are elevated. Regardless of the heating rate, due to the fact that ash content is the final product of coal combustion, the final content of residual components after coal combustion tends to be consistent, maintaining a constant composition.

Effects of Different Blending Ratios

The results at a fixed heating rate such as 10°C/min and the effects of different blending ratios are shown in Figure (3).

The TG and DTG curves shown in Figure (3) indicate that the combustion process of the mixture of peanut shells and coal can be categorized into four distinct stages: dehydration and drying, release and combustion of volatile compounds, a transition phase involving combustion of volatiles and surface combustion of char, as well as surface combustion of char.



(a)

(b)

Fig. 3: (a): TG curves of different blending ratios (b): DTG curves of different blending ratios

TG curve reveals that the weight loss onset of peanut shells occurs earlier than that of coal when combusted respectively. However, as the biomass content increases in coal blends, this onset point also advances coal combustion. Adding biomass can improve fuel flammability. Furthermore, the examination demonstrates a clear division in the combustion process into two stages: volatile combustion and char combustion. The peak shapes vary with different blending ratios. The DTG peak associated with volatile combustion from peanut shells is significantly higher than that char combustion. This indicates that due to the high volatile content in biomass, most reactions occur at lower temperatures, which facilitates early ignition. As coal is added to this mixture, an increasing proportion shifts the focus to the combustion of concentrated char combustion throughout the process.

As the proportion of peanut shell increases, the completion temperature of combustion gradually decreases, which is shorter than that of coal. The combustion completion characteristics are significantly better than pure coal. This is because adding peanut shell to coal can cause the ignition point to advance, and the maximum combustion rate tends to move forward. The combustion temperature range is extended, and the combustion time is shorter than that of coal. As the temperature decreases, the combustion characteristics of coal are enhanced. This indicates that the addition of biomass is beneficial for complete combustion and utilization rate of coal.

Discussion

Environmental Benefits of Biomass-Coal Mixed Combustion

Biomass, as a renewable resource, releases approximately the same amount of CO2 during combustion as it absorbs during growth, thus having a relatively low net carbon emission. Moreover, due to the much lower sulfur and nitrogen contents in biomass compared to coal, mixed combustion can significantly reduce the emissions of pollutants such as SOx and NOx, thereby alleviating the negative impact on the environment. This study demonstrates that adding an appropriate amount of biomass to coal not only optimizes the combustion process but also effectively reduces the emissions of harmful gases, providing a new idea for achieving cleaner energy utilization.

Improvement of Combustion Efficiency and Economic Performance

By adjusting the blending ratio of biomass and coal and controlling the combustion conditions, the complete combustion characteristics of the fuel can be improved, thereby enhancing the combustion efficiency. This study found that as the content of biomass increases, the maximum combustion rate of the fuel is advanced and the burnout temperature decreases. This indicates that the addition of biomass helps promote the complete combustion of coal, thereby improving the energy conversion efficiency. This is particularly important for industrial boilers and power plants, as higher combustion efficiency means lower operating costs and better economic benefits.

Challenges and Solutions in Practical Applications

Although the co-burning of biomass and coal has demonstrated many advantages, it still faces some challenges in practical promotion. For instance, the collection, transportation, and storage of biomass require significant infrastructure investment; meanwhile, there are considerable differences in physical and chemical properties among different sources of biomass, which impose higher requirements on the adaptability of combustion equipment. To address these issues, advanced biomass pretreatment technologies (such as pyrolysis and gasification) can be developed to enhance the energy density and stability of biomass, or existing coal-fired facilities can be improved to accommodate different types of biomass fuels.

Future Research Directions

Future research should focus on the following aspects: Firstly, conduct in-depth exploration of the interaction mechanism between biomass and coal under different combustion conditions, so as to better predict and control the combustion process. Secondly, develop more environmentally friendly and efficient biomass conversion technologies to overcome the problem of unstable supply of biomass raw materials. Finally, more long-term operation experiments should be carried out to evaluate the reliability and economic feasibility of the mixed combustion of biomass and coal in actual industrial applications.

To sum up, the co-combustion of biomass and coal is a technology with great potential. It not only helps solve the problem of energy shortage but also contributes to environmental protection. However, in order to fully realize its potential, extensive and in-depth research is still needed, and corresponding strategies and technical routes should be formulated based on actual conditions.

Conclusion

Based on the utilization of biomass energy, experiments on the combustion characteristics of the mixture of biomass and coal were conducted. The combustion characteristics of peanut shell, coal, and their mixture under different heating rates and blending ratios were analyzed by thermos gravimetric analysis. The combustion characteristics of the mixture of biomass and coal were studied from the characteristics of raw materials, heating rates, and different ratios. The main conclusions are drawn as follows:

1. Based on the experimental results, it can be seen that the volatile release temperature ranks as: peanut shell < peanut shell and coal in a 1:1 ratio < peanut shell and coal in a 1:5 ratios< coal. This indicates that as the biomass increases, the volatile in coal also increases, thereby resulting in a decrease in the initial volatile release temperature and the maximum combustion rate temperature. This demonstrates that the addition of biomass can facilitate the combustion of fuel
2. For pure biomass, as the heating rate increases, the TG curve migrates to high-temperature side. This means that to achieve the same weight loss, higher temperatures are required, and the temperature corresponding to reaching the highest combustion rate will shift to a higher value. This is mainly because biomass combustion is an endothermic reaction, and an increase in heating rate shortens the time required for the combustion environment to reach the same temperature. However, due to poor thermal conductivity of biomass, the interior of the sample cannot be heated promptly, thereby influencing the lag in internal combustion. For pure coal, the higher the heating rate, the higher the

combustion temperature, the shorter the combustion time, and the more severe the thermal lag. When biomass and coal are mixed and combusted, as the heating rate increases, the combustion temperature of the mixed coal increases and essentially presents a linear relationship

3. When biomass is added to coal, there is a tendency for the maximum rate of combustion to advance. It required a shorter time than that of coal, and the temperature at which combustion occurs is lower than that of coal. This means that adding biomass to coal can improve the maximum combustion intensity. As the proportion of biomass increases, the combustion temperature gradually decreases, and the time required for combustion is shorter than that of coal. The combustion characteristics are significantly better than only using coal. This indicates that the addition of biomass is beneficial for the combustion of coal and improvement of its utilization rate

Acknowledgment

This study was supported by the S&T Program of Hebei (22554302D) and the applied innovation project of Hebei Vocational University of technology and Engineering (No. 202004 and 202307).

Funding Information

This study was supported by the applied innovation project of Hebei Vocational University of Technology and Engineering (No.202307 and 20240203).

Author's Contributions

Rong Li and Li Li: Performed the experiments, analyzed the data, and prepared the paper.

Lei Zhang and Xin Zhang: Designed and performed the experiments, and revised the manuscript.

Ethics

The authors declare their responsibility for any ethical issues that may arise after the publication of this manuscript.

Conflict of Interest

The authors declare that they have no competing interests. The corresponding author affirms that all of the authors have read and approved the manuscript.

References

Abioye, K. J., Harun, N. Y., Sufian, S., Yusuf, M., Jagaba, A. H., Ekeoma, B. C., Kamyab, H., Sikiru, S., Waqas, S., & Ibrahim, H. (2024). A Review of Biomass Ash Related Problems: Mechanism, Solution, and Outlook. *Journal of the Energy Institute*, *112*, 101490. https://doi.org/10.1016/j.joei.2023.101490

Camelo, A., Genuino, D. A., Maglinao Jr, A. L., Capareda, S. C., Paes, J. L., & Owkusumsirisakul, J. (2018). Pyrolysis of Pearl Millet and Napier Grass Hybrid (PMN10TX15): Feasibility, Byproducts, and Comprehensive Characterization. *International Journal of Renewable Energy Research*, *8*(2), 682-691. https://doi.org/10.20508/ijrer.v8i2.7033.g7419

Chowdhury, T., Chowdhury, H., Hossain, N., Ahmed, A., Hossen, M. S., Chowdhury, P., Thirugnanasambandam, M., & Saidur, R. (2020). Latest Advancements on Livestock Waste Management and Biogas Production: Bangladesh's Perspective. *Journal of Cleaner Production*, *272*, 122818. https://doi.org/10.1016/j.jclepro.2020.122818

Cruz, N. C., Silva, F. C., Tarelho, L. A. C., & Rodrigues, S. M. (2019). Critical Review of Key Variables Affecting Potential Recycling Applications of Ash Produced at Large-Scale Biomass Combustion Plants. *Resources, Conservation and Recycling*, *150*, 104427. https://doi.org/10.1016/j.resconrec.2019.104427

Glushkov, D. O., Nyashina, G. S., Anand, R., & Strizhak, P. A. (2021). Composition of Gas Produced From The Direct Combustion and Pyrolysis of Biomass. *Process Safety and Environmental Protection*, *156*, 43-56. https://doi.org/10.1016/j.psep.2021.09.039

Glushkov, D. O., Zhuikov, A. V., Nurpeiis, A. E., Paushkina, K. K., & Kuznechenkova, D. A. (2024). Ignition Behavior of a Mixture of Brown Coal And Biomass During the Movement Of Fine Particles In a Hot Air Flow. *Fuel*, *363*, 131010. https://doi.org/10.1016/j.fuel.2024.131010

Gogolev, I., Pikkarainen, T., Kauppinen, J., Linderholm, C., Steenari, B.-M., & Lyngfelt, A. (2021). Investigation of Biomass Alkali Release In a Dual Circulating Fluidized Bed Chemical Looping Combustion System. *Fuel*, *297*, 120743. https://doi.org/10.1016/j.fuel.2021.120743

Huang, H., Gao, Y., Chen, H., Wu, Y., Wang, J., Yu, C., Li, J., & Zou, C. (2023). Biomass Briquette Fuel, Boiler Types And Pollutant Emissions of Industrial Biomass Boiler: A Review. *Particuology*, *77*, 79-90. https://doi.org/10.1016/j.partic.2022.08.016

Kanwal, F., Ahmed, A., Jamil, F., Rafiq, S., Ayub, H. M. U., Ghauri, M., Khurram, M. S., Munir, S., Inayat, A., Abu Bakar, M. S., Moogi, S., Lam, S. S., & Park, Y.-K. (2021). Co-Combustion of Blends of Coal and Underutilised Biomass Residues for Environmental Friendly Electrical Energy Production. *Sustainability*, *13*(9), 4881. https://doi.org/10.3390/su13094881

Oberschelp, C., Pfister, S., Raptis, C. E., & Hellweg, S. (2019). Global Emission Hotspots of Coal Power Generation. *Nature Sustainability*, *2*(2), 113-121. https://doi.org/10.1038/s41893-019-0221-6

Odzijewicz, J. I., Wołejko, E., Wydro, U., Wasil, M., & Jabłońska-Trypuć, A. (2022). Utilization of Ashes from Biomass Combustion. *Energies*, *15*(24), 9653. https://doi.org/10.3390/en15249653

Pérez, J. F., Osorio, L. F., & Agudelo, A. F. (2018). A Technical-Economic Analysis of Wood Gasification for Decentralized Power Generation in Colombian Forest Cores. *International Journal of Renewable Energy Research*, *8*(2), 1071-1083. https://doi.org/10.20508/ijrer.v8i2.6936.g7418

Radenahmad, N., Morni, N. A. H., Ahmed, A., Abu Bakar, M. S., Zaini, J., & Azad, A. K. (2018). Characterization of Rice Husk As a Potential Renewable Energy Source. *7th Brunei International Conference on Engineering and Technology 2018 (BICET 2018)*, 30. https://doi.org/10.1049/cp.2018.1527

Shamooni, A., Wen, X., Debiagi, P., Stagni, A., Gärtner, J. W., Zirwes, T., Stein, O. T., Hasse, C., & Kronenburg, A. (2024). Carrier-Phase Direct Numerical Simulation and Flamelet Modeling of Alkali Metal Emissions From Pulverized Biomass Flames. *Proceedings of the Combustion Institute*, *40*(1-4), 105309. https://doi.org/10.1016/j.proci.2024.105309

Svedovs, O., Dzikevics, M., & Kirsanovs, V. (2023). Bibliometric Analysis of the Alternative Biomass Types and Biomass Combustion Technologies. *Environmental and Climate Technologies*, *27*(1), 559-569. https://doi.org/10.2478/rtuect-2023-0041

Wang, J., Wen, L., Chen, Y., & Han, H. (2018). Study on The Combustion Characteristics and Kinetics of Biomass and Coal Char Blended Fuels. *2018 7th International Conference on Renewable Energy Research and Applications (ICRERA)*, 576-581. https://doi.org/10.1109/icrera.2018.8567016

Wang, Z., Liu, S., Weng, W., He, Y., Aldén, M., & Li, Z. (2024). Alkali Metal Release in Thermochemical Conversion of Biomass and Coal: Optical Measurements and Modeling. *Progress in Energy and Combustion Science*, *100*, 101131. https://doi.org/10.1016/j.pecs.2023.101131

Muthuraman, M., Namioka, T., & Yoshikawa, K. (2009). Conversion of Municipal Solid Waste into Fuel for Co-firing Application with coal by Hydrothermal Treatment (Part II: Co-firing Performance with Coal). *The Proceedings of the Symposium on Environmental Engineering*, 170-173. https://doi.org/10.1299/jsmeenv.2009.19.170

Yao, X., Zhao, Z., Chen, S., Zhou, H., & Xu, K. (2020). Migration and Transformation Behaviours of Ash Residues From a Typical Fixed-Bed Gasification Station for Biomass Syngas Production in China. *Energy*, *201*, 117646. https://doi.org/10.1016/j.energy.2020.117646

Ye, B., Jiang, J., Zhou, Y., Liu, J., & Wang, K. (2019). Technical and Economic Analysis of Amine-Based Carbon Capture And Sequestration at Coal-Fired Power Plants. *Journal of Cleaner Production*, *222*, 476-487. https://doi.org/10.1016/j.jclepro.2019.03.050