International Journal of Heat and Technology
Vol. 42, No. 6, December, 2024, pp. 1859-1869
Journal homepage: http://iieta.org/journals/ijht

The Application of Thermodynamic Analysis in Assessing the Efficiency and Cost-Effectiveness of Biomass Energy Conversion

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https://doi.org/10.18280/ijht.420603

Received: 8 June 2024
Revised: 2 November 2024
Accepted: 13 November 2024
Available online: 31 December 2024

Keywords:
biomass energy, thermodynamic analysis, kinetic analysis, combustion process, conversion efficiency, cost-effectiveness

ABSTRACT

As global energy demand increases and environmental pollution becomes more severe, biomass energy, as a renewable and low-carbon green energy source, has gained widespread attention. The conversion process of biomass energy involves complex thermodynamic and kinetic reactions, making the accurate assessment of its conversion efficiency and cost-effectiveness crucial for large-scale application. Thermodynamic analysis and kinetic models provide powerful tools for evaluating the combustion process of biomass energy. Although existing studies have made preliminary explorations into the thermodynamic and kinetic characteristics of biomass combustion, current analytical methods still have certain limitations, such as insufficient systematic analysis of different types of biomasses, and incomplete consideration of combustion reaction mechanisms and multiphase reactions. The main objective of this study is to explore the key parameters in the biomass energy conversion process through a combined approach of thermodynamic and kinetic analysis. The research content includes two aspects: first, calculating thermodynamic parameters of the biomass combustion process based on thermodynamic principles, and second, quantitatively analyzing the kinetic parameters of biomass combustion reactions using kinetic models. Through these two research aspects, this paper aims to provide more accurate evaluation tools for the efficient utilization of biomass energy and offer theoretical support for its cost-effectiveness optimization.

1. INTRODUCTION

With the growing global energy crisis and the severity of environmental pollution, finding sustainable and clean alternative energy sources has become a global focus [1-4]. Biomass energy, as a renewable green energy source, has gradually become a research and application hotspot due to its abundant raw materials and low carbon emissions [5, 6]. The conversion process of biomass energy involves complex thermodynamic and kinetic reactions, and the efficiency and cost-effectiveness assessment of these reaction processes are key to realizing large-scale biomass energy applications [7-10]. However, due to the diversity of biomass materials and the complexity of the conversion process, accurately assessing its conversion efficiency and cost-effectiveness still faces many challenges.

In this context, thermodynamic analysis has become an important tool for evaluating biomass energy conversion efficiency. Thermodynamic models can reveal the energy flow, energy conversion efficiency, and the formation mechanisms of by-products during the combustion process, providing theoretical basis for optimizing biomass energy utilization efficiency [11-15]. At the same time, the study of combustion kinetics can help reveal the reaction rate, reaction mechanisms, and other factors in the process, offering guidance for improving and optimizing combustion technologies [16-21]. Combining thermodynamic and kinetic analysis allows for a comprehensive assessment of biomass energy conversion processes from multiple perspectives, providing crucial support for improving its cost-effectiveness and reducing environmental impacts.

Although significant progress has been made in the thermodynamic and kinetic analysis of biomass energy, most studies still have certain limitations [22-26]. On one hand, existing thermodynamic analysis methods tend to focus on single substances or standardized conditions, lacking systematic analysis of different types of biomasses under actual combustion conditions. On the other hand, current kinetic models often ignore complex reaction mechanisms and multiphase reaction processes, limiting their prediction accuracy and practical application value. Therefore, there is an urgent need to develop more accurate and comprehensive analysis methods to better guide the efficient conversion and utilization of biomass energy.

This study aims to explore the key parameters in the biomass energy conversion process through a combined approach of thermodynamic and kinetic analysis. The study mainly consists of three parts: first, the calculation of thermodynamic parameters in the biomass combustion process based on thermodynamic principles; second, the quantitative analysis of kinetic parameters of biomass combustion reactions using kinetic models; third, the development of an evaluation scheme for biomass energy conversion efficiency and cost-effectiveness based on thermodynamic analysis. Through these three research areas, we hope to provide more accurate evaluation tools for the efficient utilization of biomass energy and offer theoretical support for optimizing its cost-effectiveness, thereby promoting the widespread application of biomass energy in the future energy structure.

2. CALCULATION OF THERMODYNAMIC PARAMETERS IN BIOMASS ENERGY COMBUSTION

In the conversion process of biomass energy, the key to calculating thermodynamic parameters lies in revealing the energy flow and energy conversion efficiency in the combustion reactions. The combustion reactions of biomass energy not only involve the release of energy but also the generation of various by-products, which directly affect the conversion efficiency and environmental impact. Therefore, by accurately calculating thermodynamic parameters, the heat release, energy loss, and potential energy efficiency optimization space during biomass combustion can be quantified.

Thermogravimetric (TG) analysis is an important analytical method in the biomass combustion process. By measuring the relationship between sample mass and temperature under program-controlled heating, the obtained TG curve can directly reflect the mass loss characteristics of biomass in different temperature ranges during combustion. In the evaluation of biomass energy conversion efficiency and cost-effectiveness, the TG curve can reveal the pyrolysis process, the release of volatile matter, and the conversion process of fixed carbon during biomass combustion. By analyzing the mass changes at these key stages, the conversion characteristics of different components, energy release patterns, and potential thermal efficiency can be accurately determined during combustion. For example, in the early stages of biomass combustion, the evaporation of water and the release of volatile organic compounds affect the calorific value, while as the temperature increases, the conversion efficiency of the residue directly influences the final energy utilization rate. Furthermore, thermogravimetric analysis not only provides the conversion efficiency of biomass during combustion but also helps analyze energy losses in the combustion process, thus supporting cost-effectiveness evaluation. In the biomass combustion process, in addition to energy release, there are also heat losses and the generation of by-products such as carbon dioxide, volatile organic compounds, and particulate matter. These by-products not only affect the environment but also reduce the overall energy utilization efficiency. Through thermogravimetric analysis, the generation of these by-products and mass loss can be quantified, thus evaluating the economics and environmental impact of different types of biomasses under different combustion conditions.

Each biomass material has different composition and properties, and the energy release, mass changes, and reaction rates during combustion vary. Therefore, through experimental data such as TG analysis, derivative thermogravimetric (DTG) analysis, and differential thermal analysis (DTA), a series of key thermodynamic characteristic parameters can be calculated. These parameters can quantitatively describe the energy conversion efficiency, reaction kinetics, and heat release characteristics of biomass during combustion. For example, the mass percentage changes on the TG curve can reflect the proportion of volatile matter, fixed carbon, and ash in biomass, thereby revealing the energy release potential and conversion efficiency of different biomasses. The DTG curve can reflect the relationship between weight loss rate and temperature, thereby inferring the reaction rate and reaction stages, helping to assess the speed and completeness of the biomass combustion process. The DTA curve shows the change in heat flow during combustion, revealing the time characteristics of heat release, which further helps analyze its energy efficiency. By comprehensively calculating and analyzing these thermodynamic parameters, quantitative evidence can be provided for the combustion performance and energy efficiency evaluation of different biomasses, laying the foundation for subsequent cost-effectiveness analysis.

The methods for solving thermodynamic characteristic parameters are as follows:

(1) Maximum mass loss rate

In the evaluation of biomass energy conversion efficiency and cost-effectiveness, the maximum mass loss rate FSH_{MAX} is an important thermodynamic characteristic parameter. It represents the most intense reaction rate of biomass during the combustion process, usually corresponding to the inflection point of the TG curve, i.e., the maximum value of the mass loss rate. The calculation of this parameter can help assess the intensity of the biomass combustion reaction and the rate of reaction. For different types of biomass, the release of volatile matter and the combustion of fixed carbon during the combustion process will affect the intensity of the reaction. By calculating FSH_{MAX}, especially in the case of multiple peaks, the two main stages of combustion—volatile combustion and fixed carbon combustion—can be revealed. The larger the value of FSH_{MAX}, the more intense the reaction, while a smaller value indicates a gentler combustion process. In the evaluation of biomass energy conversion efficiency, a higher maximum mass loss rate typically indicates a faster energy release process, which helps improve energy utilization efficiency. At the same time, FSH_{MAX} can reflect the combustibility characteristics of different biomasses, helping to select the best combustion material, optimize the combustion process, and improve the energy conversion efficiency and cost-effectiveness of biomass energy.

(2) Ignition temperature S_u

The ignition temperature S_u is another key thermodynamic parameter, representing the lowest temperature at which biomass begins to burn, reflecting the ease of ignition of the sample. The higher the ignition temperature, the more difficult it is to ignite the biomass, which may require a longer preheating time or higher energy input to initiate combustion. By calculating S_u using the tangent method, the temperature at which the biomass begins continuous combustion during heating can be obtained, which is an important indicator of the combustion characteristics of biomass. In the evaluation of biomass energy conversion efficiency and cost-effectiveness, the calculation of S_u can help predict the difficulty of starting combustion equipment and preheating requirements. If the biomass has a lower ignition temperature, the combustion equipment will start more quickly and save energy, reducing initial energy consumption and overall operational costs. In addition, S_u is closely related to the chemical composition and structure of biomass. Therefore, through the calculation and analysis of S_u, the combustion performance of different biomass types can be effectively compared, optimizing biomass selection and combustion conditions to improve energy economics and environmental benefits.

(3) Burnout temperature S_g

The burnout temperature S_g represents the endpoint of the biomass combustion process, typically occurring when the sample is almost completely burned and has reached a stable state. The calculation of S_g directly reflects the burnout performance of biomass, i.e., the completeness of energy release during combustion. The lower the burnout temperature, the more complete the combustion process, with less residue and higher combustion efficiency. In the evaluation of biomass energy conversion efficiency, S_g can help assess the integrity of the combustion process and the extent of energy loss. In general, a lower burnout temperature helps improve energy utilization efficiency because it means the combustion process is nearly complete, with fewer unburned materials left, which helps reduce subsequent treatment and cost expenses. By combining S_u and FSH_{MAX} parameters, the calculation of S_g can further improve the evaluation of the combustion process and provide theoretical support for the design and optimization of combustion systems, enhancing overall conversion efficiency and reducing costs.

(4) Average mass loss rate FSH_{ME}

In the evaluation of biomass energy conversion efficiency and cost-effectiveness, the average mass loss rate FSH_{ME} represents the average mass loss rate during the entire combustion process from the ignition temperature S_u to the burnout temperature S_g. The calculation of FSH_{ME} helps us understand the reaction intensity of biomass throughout the combustion process. If FSH_{ME} is high, it indicates that the biomass combustion reaction is intense and energy is released rapidly, which is beneficial for improving energy conversion efficiency. On the contrary, a lower average mass loss rate means slower reactions, which may lead to incomplete or inefficient energy release, reducing conversion efficiency. In cost-effectiveness evaluation, a higher FSH_{ME} can reduce combustion time and improve thermal energy utilization, thus reducing the energy consumption of equipment and operational costs. Specifically, assuming that the conversion efficiency of the biomass energy sample at burnout and ignition times is represented by β_{Sg} and β_{Su}, the calculation formula is:

$$FSH_{ME} = \frac{\beta_{Sg} - \beta_{Su}}{S_g - S_u} \tag{1}$$

Assuming the initial weight of the sample is represented by l_0, the mass of the sample at a certain time is represented by l, and the mass at the end of the reaction is represented by l, β, i.e., the biomass energy sample conversion efficiency, can be defined as:

$$\beta = \frac{l_0 - l}{l_0 - l_\infty} \tag{2}$$

(5) Ignition index F_u

The ignition index F_u is an important indicator for assessing the ignition performance of biomass. The larger the value, the better the ignition performance of the fuel. F_u is usually calculated based on the relationship between the ignition temperature S_u and the combustion rate, reflecting the energy input and startup time required during the ignition phase. In biomass energy conversion, a higher ignition index means that biomass ignites easily, thus shortening the preheating time of combustion equipment and reducing energy consumption during the startup process. This is crucial for improving overall energy utilization efficiency because reducing preheating time and energy loss directly impacts the operational costs of the combustion system. Biomass with good ignition performance not only improves conversion efficiency but also reduces environmental pollution and incomplete combustion by-products, further optimizing economic and environmental benefits. Therefore, the calculation and analysis of the ignition index help provide valuable decision-making basis for selecting biomass fuels and optimizing combustion systems. Specifically, assuming the heating rate is represented by α, the comprehensive combustion characteristic index is represented by T, the calculation formula is:

$$F_u = \frac{\left(\frac{dq}{d\pi}\right)_{MAX}}{S_u S_{MAX}} = \frac{FSH_{MAX}}{S_u S_{MAX}} \times \alpha \tag{3}$$

(6) Comprehensive combustion characteristic index T

The comprehensive combustion characteristic index T is a composite evaluation index for biomass fuel performance, combining multiple factors such as ignition characteristics, combustion intensity, and burnout characteristics. The larger the value of T, the better the ignition performance, combustion efficiency, and burnout efficiency of the fuel. In the evaluation of biomass energy conversion efficiency and cost-effectiveness, T can provide a comprehensive assessment standard to help select biomass materials with excellent combustion performance. A higher T value indicates that the combustion process can quickly start and effectively complete, reducing energy losses and incomplete combustion, thus improving energy conversion rates. The comprehensive combustion characteristic index not only helps assess the overall performance of the combustion process but also provides quantitative support for optimizing biomass fuel selection, combustion equipment design, and operational condition adjustments. In cost-effectiveness analysis, biomass with a higher T value usually means higher calorific value and lower operating costs, thus optimizing economic benefits.

$$T = \frac{\left(\frac{dq}{d\pi}\right)_{MAX} \times \left(\frac{dq}{d\pi}\right)_{ME}}{S_u^2 S_g} = \frac{FSH_{MAX} \times FSH_{ME}}{S_u^2 S_g} \times \alpha^2 \tag{4}$$

3. BIOMASS ENERGY COMBUSTION KINETIC PARAMETERS CALCULATION

The combustion process of biomass energy is not only a thermodynamic process but also a dynamic process involving complex reaction mechanisms. The calculation of combustion kinetic parameters can reveal the reaction rate, reaction pathway, and conversion mechanism of biomass combustion, which is crucial for optimizing the combustion process. Different types of biomasses have different chemical compositions and structural characteristics, resulting in significant differences in their combustion reaction rates and reaction pathways. Therefore, by calculating kinetic parameters such as reaction rate constants and activation energy using kinetic models, it is possible to better predict the rate-controlling steps and reaction efficiency during biomass combustion. This not only helps improve the integrity and stability of combustion but also supports the development of emission reduction technologies.

Assuming that the reaction model is represented by $h(\beta)$, biomass energy sample conversion efficiency is represented by β, the rate constant is represented by $j(S)$, the pre-exponential factor is represented by X, activation energy is represented by R, the universal gas constant is represented by E, absolute temperature is represented by S, time is represented by π, and heating rate is represented by α. The following equation represents the biomass energy combustion kinetics equation, which precisely captures the variation characteristics of the biomass combustion reaction at different temperatures by describing the exponential relationship between temperature and the reaction rate constant. By performing non-isothermal thermogravimetric analysis, the weight loss rate data of biomass at different temperatures can be obtained, and the reaction kinetics parameters in different temperature intervals can be calculated.

$$\frac{d\beta}{d\pi}=\alpha\frac{d\beta}{dS}=h(\beta)j(S)=X\exp\left(-\frac{R}{ES}\right)h(\beta) \quad (5)$$

To accurately evaluate biomass energy conversion efficiency and cost-effectiveness, it is crucial to select the appropriate kinetic parameter solving method. In biomass combustion reactions, multiple complex reaction mechanisms usually exist, with the bimodal mixed combustion phenomenon being particularly common. The advantage of the Coats-Redfern method lies in its good adaptability to bimodal reactions, effectively analyzing the kinetic characteristics of multiple combustion stages. Therefore, for biomass exhibiting more complex reaction curves during the experiment, especially multi-stage and heterogeneous combustion behavior, the Coats-Redfern method provides a more accurate and reliable analytical tool. Additionally, the Coats-Redfern method can solve kinetic parameters under multiple heating rate conditions, making it highly advantageous in the evaluation of biomass energy conversion efficiency and cost-effectiveness. Since the experiment uses a constant heating rate, the equation can be converted as:

$$\frac{d\beta}{d\pi}=\frac{X}{\alpha}\exp\left(-\frac{R}{ES}\right)h(\beta) \quad (6)$$

Assuming that the reaction order is represented by v, the Coats-Redfern method, and the reaction mechanism function $h(\beta)$ model can be represented by the following equation:

$$h(\beta)=(1-\beta)^{v} \quad (7)$$

By integrating Eq. (6), we have:

$$\begin{aligned}H(\beta)&=\int_0^{\beta}\frac{d\beta}{(1-\beta)^{v}}\\&=\frac{X}{\alpha}\int_0^{S}\exp\left(-\frac{R}{ES}\right)dS=\frac{XES^2}{\alpha R}\left(1-\frac{2ER}{S}\right)\exp\left(-\frac{R}{ES}\right)\end{aligned} \quad (8)$$

Further, by taking the logarithm of both sides of the equation, we get:

$$LN\left[\frac{-LN(1-\beta)}{S^2}\right]=LN\left[\frac{XE}{\alpha R}\left(1-\frac{2ES}{R}\right)\right]-\frac{R}{ES}(v=1) \quad (9)$$

$$LN\left[\frac{1-(1-\beta)^{1-v}}{S^2(1-v)}\right]=LN\left[\frac{XE}{\alpha R}\left(1-\frac{2ES}{R}\right)\right]-\frac{R}{ES}(v\neq 1) \quad (10)$$

Assuming $1\text{-}2ES/R\approx 1$, $-R/ES\gg 1$, the two equations above can be simplified as:

$$LN\left[\frac{-LN(1-\beta)}{S^2}\right]=LN\frac{XE}{\alpha R}-\frac{R}{ES}(v=1) \quad (11)$$

$$LN\left[\frac{1-(1-\beta)^{1-v}}{S^2(1-v)}\right]=LN\frac{XE}{\alpha R}-\frac{R}{ES}(v\neq 1) \quad (12)$$

Let $b=LN(XE/\alpha R)$, and further convert the above equations to obtain the relationship between $[1\text{-}(1\text{-}\beta)^{1-v}/S^2]$ and 1/S. By using the slope and intercept of this line, the activation energy R and the pre-exponential factor X of the biomass energy can be determined.

4. THERMODYNAMIC ANALYSIS-BASED BIOMASS ENERGY CONVERSION EFFICIENCY AND COST-EFFECTIVENESS EVALUATION PLAN

This paper proposes a comprehensive biomass energy conversion efficiency and cost-effectiveness evaluation plan based on the results of biomass energy combustion thermodynamic parameter calculations and biomass energy combustion kinetic parameter calculations. The evaluation plan combines the results of thermodynamic and kinetic parameter calculations, quantifying energy conversion efficiency, pollution emissions, and economic costs during the combustion process, providing a scientific basis for optimizing biomass energy applications. The evaluation plan consists of the following key steps:

(1) Energy conversion efficiency evaluation

The evaluation of biomass energy conversion efficiency is based on its combustion thermodynamic parameters, particularly weight loss rate, ignition index, and comprehensive combustion characteristic index. Based on thermodynamic analysis, the energy conversion efficiency during combustion can be evaluated by calculating the ratio of the thermal energy input per unit of biomass to the actual released thermal energy. Specifically, the weight loss rate can reveal the release of volatile substances from biomass under high-temperature conditions, which affects the timing and magnitude of heat release. By combining the ignition index and SCI, the biomass combustion process can be further optimized to maximize heat energy release.

(2) Pollution emissions evaluation

Pollution emissions, such as carbon dioxide (CO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOCs), during biomass combustion have a significant environmental impact. Pollution emissions evaluation requires combining combustion kinetic parameters, particularly the reaction rate and the distribution of products, for detailed analysis. By comparing the combustion reaction characteristics of different biomass materials, it is possible to determine which combustion conditions result in the least pollution generation and which biomass has a lower pollution emission potential. Under high-temperature combustion conditions, biomass with higher combustion efficiency typically converts elements such as carbon and hydrogen into gaseous products more completely, thereby reducing harmful substances in solid residues and gases. By introducing pollutant emission factors and considering the operating parameters of combustion equipment, the quantitative assessment of pollution emissions can provide data support for optimizing combustion facility design and reducing pollution emissions.

(3) Economic benefit evaluation

Economic benefit evaluation mainly measures the feasibility of the commercialization of biomass energy by calculating the costs of biomass energy conversion and the benefits of its output. Figure 1 shows the biomass energy integrated utilization economic benefit evaluation diagram. In the evaluation process, the raw material cost of biomass, the construction and maintenance costs of combustion equipment, and the market value of energy output need to be considered. On this basis, by comparing the total cost of biomass energy conversion with the economic benefits brought by the thermal energy released, the production cost per unit of energy is calculated. It is noteworthy that under high-temperature combustion conditions, improving combustion efficiency not only increases the energy output per unit of biomass but also may bring indirect economic benefits by reducing emissions and the treatment costs of combustion residues. Therefore, economic benefit evaluation should not only include direct energy production costs but also consider factors such as environmental governance and policy subsidies, ultimately calculating the overall cost-effectiveness ratio of biomass energy conversion.

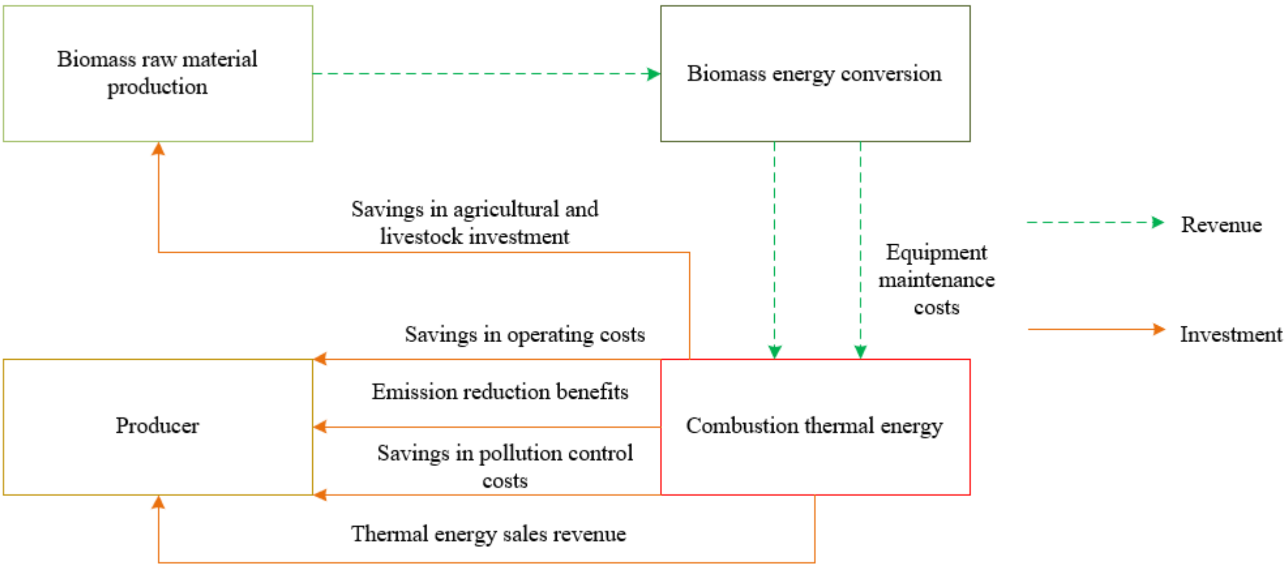


Figure 1. Biomass energy integrated utilization economic benefit evaluation diagram

(4) Integrated optimization plan formulation

Based on the results of the three evaluations above, an integrated optimization plan for biomass energy conversion can be proposed. The optimization plan should comprehensively consider energy conversion efficiency, pollution emissions, and economic benefits to achieve the sustainable and efficient use of biomass energy. Specifically, the optimization plan may include selecting appropriate biomass types and pretreatment methods, optimizing the operating parameters of combustion equipment, such as combustion temperature, oxygen supply, and reaction time. Through system optimization, efficient energy output can be ensured while reducing pollution emissions and improving economic benefits.

5. EXPERIMENTAL RESULTS AND ANALYSIS

Figure 2 shows the thermodynamic curves of different biomass energy raw materials, where raw material 1-4 correspond to straw, corn stover, sugarcane bagasse, and wood. Based on the TG, DTG, and DTA data in Figure 2, there are obvious differences in the thermodynamic and kinetic characteristics of the four biomass raw materials during the pyrolysis process. Straw shows slower and more stable mass loss, especially below 300°C, and its TG curve still maintains a high residual mass after 500°C, indicating that straw has more volatile matter at lower temperatures. The negative changes in the DTG curve suggest a relatively steady pyrolysis rate, and the main pyrolysis process occurs in the 400-500°C range. The peak in the DTA curve indicates a significant exothermic reaction during the pyrolysis of straw. Compared to straw, corn stover shows a more intense pyrolysis process, with a significant mass loss at 500°C, and the DTG curve shows a larger downward amplitude, especially near 500°C, displaying a strong exothermic characteristic. This indicates that the pyrolysis rate of corn stover is faster, particularly due to the decomposition of hemicellulose and cellulose. Sugarcane bagasse has a TG curve similar to wood, showing a more uniform mass loss, and at 500°C, the residual mass is about 47%, and the overall exothermic reaction is less pronounced compared to straw and corn stover. The DTG curve shows that the pyrolysis rate of sugarcane bagasse becomes more gradual after 450°C, and the DTA curve also indicates a relatively lower exothermic value. Wood shows a more stable mass decrease, with about 35% residual mass at 500°C, and its DTG curve changes gradually, indicating that the pyrolysis reaction of wood is slower at higher temperatures. The DTA curve indicates a relatively steady and widely distributed exothermic reaction of wood.

Based on the thermodynamic and kinetic data analysis, the following conclusions can be drawn: Straw has significant pyrolysis characteristics, making it suitable for low-temperature pyrolysis processes. Its higher residual mass suggests that it is suitable as a long-term energy source, but its lower pyrolysis rate may require process optimization. Corn stover, on the other hand, has a higher pyrolysis rate, especially at higher temperatures, showing stronger energy release characteristics, which makes corn stover perform better in high-temperature pyrolysis systems and is suitable for rapid energy conversion. Sugarcane bagasse and wood have relatively stable pyrolysis characteristics, with higher residual masses, but the exothermic reactions during pyrolysis are relatively low, indicating that their conversion efficiency may be more moderate, making them suitable for continuous and stable energy conversion. In the cost-benefit analysis, corn stover may have a higher conversion efficiency, making it suitable for high-temperature, rapid energy conversion, while wood and sugarcane bagasse are more suitable for long-term stable energy supply. Therefore, each has its advantages in different application scenarios. The final conversion efficiency and cost-benefit assessment will depend on the specific operational conditions of the pyrolysis process, the availability of raw material sources, and the processing methods of the biomass raw materials.

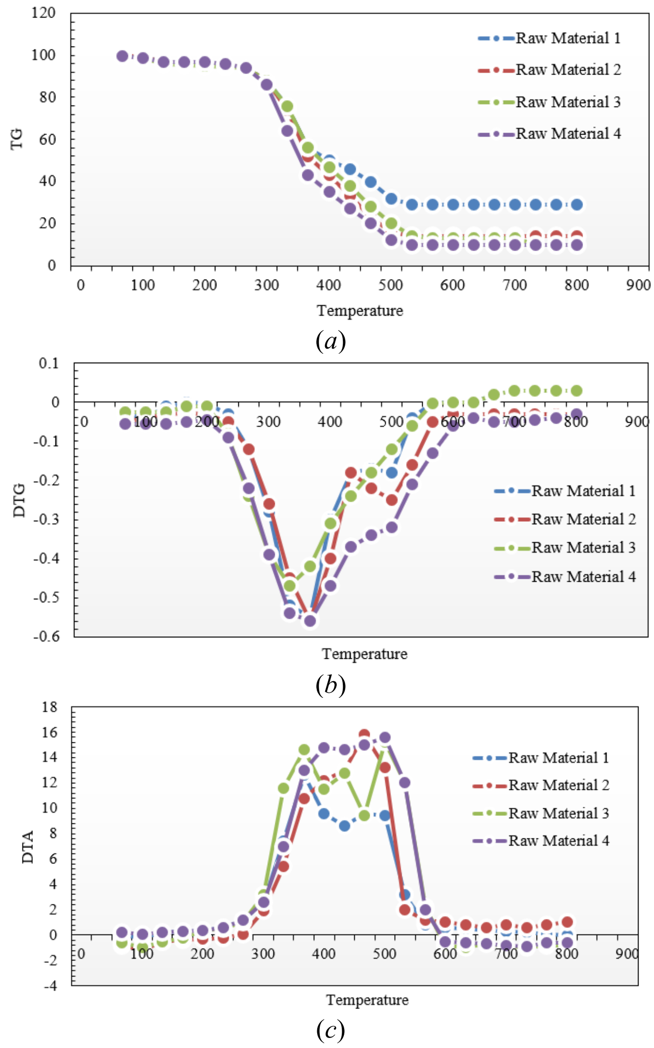


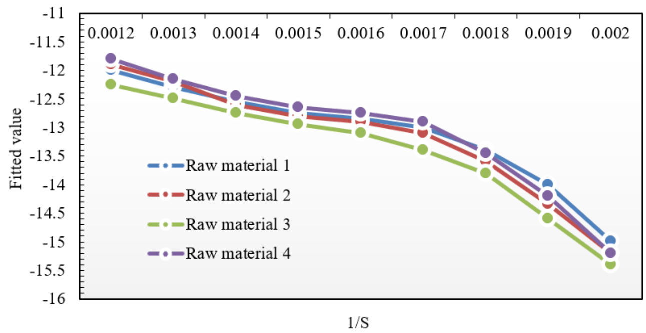
Figure 2. Thermodynamic curves of different biomass energy raw materials (a) TG curve (b) DTG curve (c) DTA curve

According to the data in Table 1, the combustion thermodynamic characteristics of different raw materials show significant differences. The ignition temperature of straw is 278°C, and the burnout temperature is 778°C, indicating a relatively high combustion stability. The weight loss peak of the volatile matter combustion stage occurs at 326°C, with a peak rate of 0.378%°C^{-1}, indicating that straw actively releases volatiles at lower temperatures. The weight loss peak of the fixed carbon combustion stage occurs at 674°C, with a peak rate of 0.022%°C^{-1}, indicating a moderate combustion of fixed carbon. The ignition index is relatively low, and the comprehensive combustion characteristics index is 0.123×10^{-9}. Compared to corn stover, the ignition temperature of corn stover is lower (265°C), and the burnout temperature decreases significantly to 554°C, indicating a faster combustion speed and more intense heat release. The weight loss peak of the volatile matter combustion stage occurs at 312°C, with a peak rate of 0.445%°C^{-1}, showing a stronger volatile combustion intensity. Since there is no obvious peak for fixed carbon, it suggests that the combustion of fixed carbon in corn stover is relatively weak. The ignition index is higher, and the comprehensive combustion characteristics index is 0.356×10^{-9}, indicating that the combustion speed is faster, making it suitable for efficient energy release. The ignition temperatures of sugarcane bagasse and wood are 269°C and 274°C, respectively, with burnout temperatures lower than straw: 654°C for sugarcane bagasse and 643°C for wood. Both sugarcane bagasse and wood show volatile matter combustion stage weight loss peaks at 312°C, with peak rates of 0.535%°C^{-1} and 0.652%°C^{-1}, respectively, indicating more intense volatile combustion. In the fixed carbon combustion stage, both sugarcane bagasse and wood show peaks at 432°C, with peak rates of 0.162%°C^{-1} and 0.256%°C^{-1}, indicating that both materials have more intense fixed carbon combustion, especially wood. The ignition indexes are 1.875×10^{-6} and 2.231×10^{-6}, and the comprehensive combustion characteristics indexes are 0.245×10^{-9} and 0.312×10^{-9}, indicating that both biomass types have higher combustion speeds and higher energy release efficiencies.

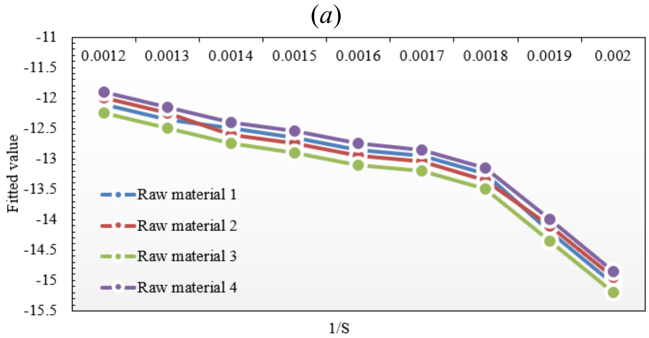
Combining the thermodynamic characteristics data, the advantage of corn stover in the combustion process lies in its lower ignition temperature and higher volatile matter combustion rate, allowing for rapid energy release during combustion, making it suitable for applications requiring rapid heat release. The faster combustion speed is also reflected in its higher ignition index and comprehensive combustion characteristics index (1.652×10^{-6} and 0.356×10^{-6}), showing higher pyrolysis efficiency. Therefore, corn stover has higher energy conversion efficiency and is suitable for high-efficiency energy conversion systems. In contrast, straw's higher ignition and burnout temperatures make its combustion process more gentle, suitable for long-term stable energy supply, although its conversion efficiency is slightly lower than corn stover. Sugarcane bagasse and wood have combustion characteristics that are relatively similar. Although their combustion speeds are relatively high, their lower burnout temperatures mean their energy release efficiency is not as good as that of corn stover in high-temperature pyrolysis systems. Particularly wood, with its higher ignition index and comprehensive combustion characteristics index, indicates that it can release large amounts of energy in a short time, making it suitable for applications requiring high heat. In terms of energy conversion efficiency and cost-benefit evaluation, corn stover, with its higher combustion speed and lower ignition temperature, is suitable for high-efficiency energy conversion systems, with good cost-effectiveness, especially in large-scale energy supply chains. Straw, due to its higher residual carbon content and lower energy release rate, may be more suitable for long-term energy supply systems, such as biomass boilers. Sugarcane bagasse and wood, due to their more stable combustion characteristics, are suitable for medium-load combined heat and power (CHP) systems. When determining the operating parameters of the combustion process, the combustion characteristics of different raw materials can be used to optimize combustion efficiency and reduce energy losses, thereby improving the overall system's economic and environmental benefits.

Table 1. Thermodynamic characteristics of combustion of different biomass energy raw materials

Characteristic Parameter	Raw Material 1	Raw Material 2	Raw Material 3	Raw Material 4
Ignition Temperature (°C)	278	265	269	274
Burnout Temperature (°C)	778	554	654	643
Volatile Matter Combustion Stage Weight Loss Peak Temperature (°C)	326	312	312	312
Volatile Matter Combustion Stage Weight Loss Peak Rate (%°C^{-1})	0.378	0.445	0.535	0.652
Fixed Carbon Combustion Stage Weight Loss Peak Temperature (°C)	674	-	432	432
Fixed Carbon Combustion Stage Weight Loss Peak Rate (%°C^{-1})	0.022	-	0.162	0.256
Average Weight Loss Rate (%°C^{-1})	0.165	0.278	0.312	0.312
Ignition Index ×10^{-6} (%·s^{-1}·°C^{-2})	1.235	1.652	1.875	2.231
Comprehensive Combustion Characteristics Index ×10^{-9} (%·s^{-2}·°C^{-3})	0.123	0.356	0.245	0.312



(*a*)



(*b*)

Figure 3. Different biomass energy combustion kinetic curves (a) Combustion interval curves (b) Segmented fitting of curves

From the combustion interval curves and segmented fitting results presented in Figure 3, significant differences in combustion characteristics among different raw materials are observed. For straw, during the combustion process, as the 1/S value increases, the reaction rate gradually slows down, and the curve becomes smoother. The reaction rate of this raw material remains relatively stable in the 1/S interval of 0.0012 to 0.0015, but after 0.0016, the curve flattens significantly, indicating a slower combustion characteristic. The combustion rate of corn stover is relatively high in all 1/S intervals, with a steep curve, especially in the higher 1/S value regions. The change shows a continuous decline, indicating a more intense combustion process and faster reaction speed. The combustion curve of sugarcane bagasse is similar to corn stover but somewhat smoother, with an overall reaction rate slightly lower than corn stover. Especially after 0.0018, the curve gradually declines to approximately -15.4, indicating a more uniform energy release characteristic. The combustion rate of wood is generally lower than the other three materials, with the curve gradually decreasing, and the change is relatively smooth. Particularly in the 1/S interval of 0.0017 to 0.0019, the curve changes very slowly, indicating a milder combustion process, suitable for long-term stable energy supply. From the segmented fitting results, the reaction rate of each raw material shows small differences in the lower 1/S interval (i.e., low-temperature interval), but as the temperature increases, the differences in reaction rates among the raw materials gradually become apparent. The combustion reaction speed of corn stover is significantly higher in the fitting curve, especially in the high-temperature stage, where it exhibits a rapid weight loss rate (0.445%°C^{-1}). Straw, sugarcane bagasse, and wood show relatively smooth curves in the higher 1/S value intervals, especially wood, where the curve gradually stabilizes as the temperature increases, with a low reaction rate and higher residue content.

Based on the combustion interval curves and segmented fitting analysis results, the following conclusions can be drawn: Corn stover has a higher combustion rate and faster reaction characteristics, especially in high-temperature conditions, where it demonstrates strong energy release capabilities. It is suitable for applications that require high-efficiency energy release, such as rapid pyrolysis reactions or biomass power plants. Straw exhibits slower and more stable combustion characteristics. Although its combustion rate is lower, it has a higher residue content, making it suitable for low-temperature, long-duration energy supply systems, such as biomass boiler systems. In terms of cost-effectiveness analysis, corn stover has a higher combustion efficiency, suitable for rapid energy conversion, but may require more precise control and higher equipment investment. Straw, due to its higher residual mass, provides long-term stable energy, making it more economical in long-term operational systems. For sugarcane bagasse and wood, their combustion characteristics demonstrate more uniform energy release, but the reaction rate is relatively low, especially wood, whose combustion process is milder and suitable for stable load energy supply. In long-term stable energy systems, sugarcane bagasse and wood can be used as raw materials for slow pyrolysis processes to meet continuous, steady thermal energy demand. Overall, corn stover performs well in energy conversion efficiency and cost-effectiveness, suitable for fast, efficient energy conversion, while straw, sugarcane bagasse, and wood are more suited for long-term stable thermal energy supply.

Table 2. Segmented fitting slopes, intercepts, and fitting errors of combustion kinetics curves of different biomass raw materials

		Intercept		Intercept		Linear Correlation Coefficient
		Value	Standard Error	Value	Standard Error	
First Segment	Material 1	-0.81245	0.02789	-7452.31252	15.26515	0.98524
	Material 2	-1.12325	0.02745	-7326.12548	15.25421	0.98562
	Material 3	-1.12424	0.03215	-7485.12582	17.52635	0.98412
	Material 4	3.12526	0.06625	-9632.15248	36.23521	0.98625
Second Segment	Material 1	-9.62352	0.01325	-2132.12526	9.45124	0.98756
	Material 2	-9.51247	0.01785	-2235.48620	12.32562	0.98752
	Material 3	-11.20352	0.01125	-2147.23525	6.87952	0.98326
	Material 4	-9.36258	0.01452	-2231.20152	11.25452	0.98741
Third Segment	Material 1	-4.51266	0.03125	-5625.25835	23.25625	0.98625
	Material 2	-4.12586	0.04562	-6234.58945	33.25456	0.98746
	Material 3	-7.32652	0.012325	-3874.12052	8.56254	0.98652
	Material 4	-2.32105	0.05326	-7123.23582	41.23582	0.98751

Table 3. Kinetic parameters of biomass energy combustion for different raw materials

Sample	Temperature Range (℃)	Fitting Formula	Activation Energy (kJ/mol)	Pre-exponential Factor (s^{-1})	Linear Correlation Coefficient
Material 1	245-315	y=-4.56215-5624.15x	46.25	16.25	0.985
	335-448	y=-9.62152-2125.26x	16.23	0.04	0.987
	465-526	y=-0.82515-7456.3x	61.25	1125.26	0.985
Material 2	235-345	y=-4.1256-6256.32x	52.36	34.25	0.986
	348-432	y=-9.56215-2236.51x	16.58	0.04	0.984
	432-512	y=-1.21256-7352.69x	61.24	823.23	0.982
Material 3	265-362	y=-7.32569-3895.21x	31.25	0.77	0.981
	362-447	y=-11.23152-2135.23x	15.23	0.03	0.983
	462-534	y=-1.23125-7456.23x	62.35	778.26	0.987
Material 4	258-342	y=-2.32152-7152.32x	61.28	223.26	0.989
	315-436	y=-9.32561-2235.62x	17.56	0.06	0.985
	456-489	y=3.12452-9654.26x	81.29	66524.23	0.984

Based on the segmented fitting data of combustion kinetics curves for different raw materials in Table 2, we observe significant differences in the combustion kinetic characteristics at different stages for each raw material. Straw, in the first segment, has an intercept of -0.81245, with a standard error of 0.02789, and a relatively small fitting error, indicating stable combustion behavior. In the second segment, the fitting result is further optimized, with an intercept of -9.62352, and a linear correlation coefficient of 0.98756, indicating that the combustion rate increases in this stage, but still maintains a good linear relationship. In the third segment, the fitting curve of straw slows slightly, with an intercept of -4.51266, and the linear correlation coefficient stays at 0.98625, indicating that the combustion process in this stage remains relatively stable. Corn stover has an intercept of -1.12325 in the first segment, with a standard error of 0.02745, and the fitting goodness is also good. In the second segment, the combustion rate increases, with an intercept of -9.51247, a small standard error, and a linear correlation coefficient close to 0.988, indicating that the combustion characteristics of this raw material are superior. Sugarcane bagasse has a relatively uniform combustion performance in each stage, especially in the second segment where the fitting error is the smallest, with a standard error of 6.87952 and a linear correlation coefficient of 0.98326, slightly lower than straw and corn stover, but still demonstrates good dynamic characteristics. Finally, wood shows a larger intercept in the first segment, but its linear correlation coefficient is 0.98625, indicating that its combustion characteristics in the first segment are more complex. However, the fitting effect in the latter two segments is still relatively good, especially in the third segment where the R^2 value is 0.98751, indicating strong combustion stability.

Through the analysis of the kinetic fitting results, the following conclusions can be drawn: Corn stover exhibits excellent dynamic characteristics during combustion, especially in the high-temperature stage (second segment), where its combustion rate is high and maintains a good linear relationship, indicating high reaction efficiency in energy conversion, suitable for applications that require high-energy release. Straw, although exhibiting milder combustion characteristics in the initial stage (first segment), increases its combustion rate and maintains stability in the subsequent stages, making it suitable for systems requiring stable and sustainable energy supply. Sugarcane bagasse demonstrates a relatively uniform combustion process, but slightly lags behind corn stover and straw, especially with a higher fitting error in the second segment, indicating slower reaction speed, making it suitable for long-term stable combustion systems. Wood's combustion characteristics are more complex, especially in the initial stage, where there is a larger fitting error. However, overall, its combustion curve shows high stability, particularly in the later stages, making it suitable for long-term stable load energy supply. From the perspective of energy conversion efficiency and cost-effectiveness evaluation, corn stover, due to its higher combustion rate and smaller fitting error, is suitable for systems requiring high conversion efficiency and short-term high energy output, while straw and sugarcane bagasse are more suited for applications requiring low load and long-term stable thermal energy supply. Although wood exhibits complexity in the early stages, its more stable combustion characteristics make it a good choice for long-term stable load energy supply in terms of economic feasibility and efficiency. Therefore, choosing different biomass raw materials should be based on optimizing the balance between cost-effectiveness and energy conversion efficiency according to the system's energy output characteristics and stability.

Based on the kinetic parameters of biomass energy combustion provided in Table 3 for different raw materials, it can be observed that each material has distinct combustion reaction characteristics in different temperature ranges. Straw has a relatively high activation energy in the low-temperature range of 245-315°C, with a small pre-exponential factor. However, in the 335-448°C range, the activation energy decreases significantly to 16.23 kJ/mol, and the pre-exponential factor drops sharply, indicating a reduction in reaction rate and a more gradual combustion process. In the 465-526°C range, although the activation energy rises to 61.25 kJ/mol, the pre-exponential factor is large, and the combustion process still shows strong reaction activity. Corn stover exhibits similar combustion characteristics in different temperature ranges. Especially in the 348-432°C range, the activation energy is 16.58 kJ/mol, and the pre-exponential factor is 0.04 s^{-1}, indicating a relatively low reaction rate. In the 432-512°C range, although the activation energy rises to 61.24 kJ/mol and the pre-exponential factor is 823.23 s^{-1}, the linear correlation coefficient decreases to 0.982, indicating that the fitting is not as good as in other ranges. Sugarcane bagasse shows relatively stable combustion characteristics across all temperature ranges. Particularly in the 462-534°C range, the activation energy is 62.35 kJ/mol, the pre-exponential factor is 778.26 s^{-1}, and the fitting error is small, showing relatively uniform energy release characteristics. Wood shows a high activation energy of 61.28 kJ/mol and a large pre-exponential factor in the low-temperature range, with a very high linear correlation coefficient, indicating that the combustion reaction is relatively intense at this stage. In the high-temperature ranges of 315-436°C and 456-489°C, although the pre-exponential factor and activation energy fluctuate, the combustion process remains relatively stable, with R^2 values maintained between 0.984 and 0.985.

Through the analysis of the biomass combustion kinetic parameters, the following conclusions can be drawn: Corn stover and straw show significant changes in combustion reactivity across different temperature ranges. Particularly in the high-temperature stage, they exhibit relatively rapid combustion reactions (higher pre-exponential factors and activation energies), but their reaction rates are slower in the low-temperature range, making them suitable for long-term heat supply in mid-low temperature stages. Sugarcane bagasse shows relatively uniform combustion characteristics across all temperature ranges. The higher activation energy and pre-exponential factor suggest a stronger reaction rate in the high-temperature stage, but its linear correlation coefficient is more stable compared to other materials, making it suitable for applications that require stable heat supply. Wood's combustion process shows high activation energy and pre-exponential factors in the low-temperature range, with intense combustion reactions, and maintains good stability in the high-temperature range, indicating that wood is an ideal long-term stable energy source, especially for applications with steady heat demand. From the perspective of biomass energy conversion efficiency and cost-effectiveness, corn stover, due to its higher combustion reactivity and lower activation energy, shows higher energy conversion efficiency, making it suitable for rapid pyrolysis or energy-intensive applications. However, its lower pre-exponential factor may result in reduced efficiency in the low-temperature range. Straw, although having a slower combustion rate in the low-temperature range, shows stable combustion characteristics and thus has good economic benefits for long-term operation systems, making it suitable for systems with relatively stable heat output and less need for frequent adjustments. Sugarcane bagasse, due to its higher activation energy and pre-exponential factor, is suitable for higher heat load scenarios, especially for rapid pyrolysis and efficient energy conversion. Wood, on the other hand, has long-term stability and is suitable for low-load systems with continuous operation, providing stable heat output while reducing system maintenance and operating costs.

Table 4. Comparison of economic characteristics of different energy sources

Item	Biomass Solid Fuel	Household Biomass Gasifier	Natural Gas	Liquefied Petroleum Gas	Honeycomb Coal	Traditional Coal Stove	Traditional Wood Stove	Biomass Biogas
Monthly Consumption	148*kg*	112*kg*	24m^3	14*kg*	149*kg*	179*kg*	512*kg*	44m^3
Unit Price (yuan)	0.3	0.3	2.15	4.1	0.42	0.3	0.08	0.77
Monthly Cost (yuan)	44	35	54	61	61	53	41	34

Table 5. Environmental benefits of biomass energy

	Emission Coefficient (t/tce)	Emission Reduction (10,000 tons)	Emission Reduction Benefit (yuan/t)	Total Emission Reduction Benefit (billion yuan)
CO_2	0.715	3562	56	74.23
SO_2	0.023	124	1325	12.32
NO_x	0.011	51	2124	11.25
TSP	0.016	84	546	4.56
Total	0.789	3789	3782	114.23

t tons, tce = tons of standard coal, TSP = total suspended particles.

Based on the data in Tables 4 and 5 and the thermodynamic and kinetic analysis methods used in this study, a comprehensive evaluation of the conversion efficiency and cost-effectiveness of biomass energy can be conducted. First, from an economic perspective, biomass solid fuel and household biomass gasifiers show significant advantages in both monthly consumption and costs. Biomass solid fuel uses 148 kg per month with a cost of 44 yuan, while the household biomass gasifier costs 35 yuan. In comparison, the costs for natural gas and liquefied petroleum gas are 54 yuan and 61 yuan, respectively, indicating that biomass energy is significantly cheaper than fossil fuels. Additionally, honeycomb coal and traditional wood stoves also have higher costs than biomass energy, especially honeycomb coal, which is economically less advantageous due to its high cost. Although the monthly consumption of biomass biogas is smaller, its cost is only 34 yuan, showing that biomass biogas also has certain economic advantages. Therefore, biomass energy has strong market competitiveness and cost advantages, especially in areas with significant economic pressure.

From an environmental benefit perspective, the use of biomass energy has significant emission reduction benefits, particularly in reducing greenhouse gas CO_2, acid gases SO_2 and NO_x, and suspended particulate matter TSP. The data in Table 5 shows that the emission reduction benefit for each ton of CO_2 is 56 yuan, and the total emission reduction benefit reaches 74.23 billion yuan, indicating that biomass energy has great potential in mitigating climate change. Moreover, the reduction in SO_2 is 1.24 million tons, with an emission reduction benefit of 1.232 billion yuan, and the reduction in NO_x is 510,000 tons, with an emission reduction benefit of 1.125 billion yuan. This shows that biomass energy plays an important role in reducing air pollution and improving air quality. Although the emission reduction benefit for TSP is relatively smaller, it still has a positive impact on improving local air quality. Overall, biomass energy's economic and social benefits in environmental protection are significant, providing strong support for sustainable development and emission reduction goals.

Through the combined analysis of thermodynamic and kinetic models, we can further improve our understanding of the conversion efficiency of biomass energy. Thermodynamic analysis helps us assess the efficiency of energy conversion in the combustion process of different raw materials, while kinetic analysis provides a quantitative evaluation of the changes in combustion reaction rates and reactivity. Taking straw and corn stalks as examples, their combustion reactions are relatively slow at low temperatures, but as the temperature increases, the combustion reaction rate increases significantly. This indicates that, in designing biomass energy conversion systems, combustion efficiency can be improved by optimizing temperature control to reduce energy waste. Furthermore, through the kinetic analysis of the combustion reactions of different raw materials, we can provide guidance for practical applications, selecting the most appropriate raw materials and combustion conditions to further improve the utilization efficiency of biomass energy.

6. CONCLUSION

This study, through the combination of thermodynamic and kinetic analysis, comprehensively explored the conversion process of biomass energy and its economic and environmental benefits. The results show that biomass energy has significant advantages in terms of heating value, conversion efficiency, economic feasibility, and environmental benefits, making it particularly suitable for a low-carbon economy and sustainable development. The application of biomass energy can not only effectively reduce dependence on fossil fuels but also significantly reduce pollution emissions, with broad application prospects and socio-economic value. However, although this study reveals the great potential of biomass energy at the theoretical level, there are still certain limitations. First, the research mainly focuses on the construction and quantitative analysis of thermodynamic and kinetic models, lacking a systematic study of technical issues, equipment wear, fuel quality fluctuations, and other factors that may arise in practical applications. Second, some of the data used in the study come from laboratory or small-scale simulations, lacking data validation from large-scale, long-term applications. Therefore, there may be certain uncertainties when applying the findings in real-world promotion. Future research could expand in the following directions: First, strengthen the research on the practical applications of biomass energy conversion processes, especially the biomass energy application models for different regions and scales, to verify their performance and adaptability in real-world environments. Second, further improve the kinetic models of biomass combustion, considering more external factors (such as air humidity, fuel storage conditions, etc.) that affect combustion efficiency and pollutant emissions. Third, explore more efficient biomass energy conversion technologies, such as efficient gasification and biomass pyrolysis, to provide technical support for achieving higher energy conversion efficiency and lower pollutant emissions. Finally, with the promotion of policies and markets, the commercialization of biomass energy will become an important research direction. Future work can focus on the technical challenges of biomass energy industrialization, exploring how to drive the widespread application and industrial development of biomass energy through technological innovation and policy support.

ACKNOWLEDGEMENTS

This paper was supported by Think Tank Platform for High-Quality Development of Civil Aviation Industry at Anyang Institute of Technology (Grant No.: ZKPT202401); Innovation Team for Collaborative and Sustainable Development of Aviation Industry (Grant No.: CXTD202206).

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