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A model fitting approach for the investigation of thermo-kinetic parameters of rice straw: a viable renewable energy resources in Bangladesh

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Abstract

This study investigates the potential of renewable energy sources to address the growing energy demands of developing nations while ensuring environmental sustainability. Here, a model-based analysis to assess the feasibility of utilizing rice straw pyrolysis as a renewable energy source is investigated. The thermogravimetric analysis identified the optimal temperature range for pyrolysis (230–400 °C) and the Coats–Redfern model was employed for kinetic analysis. Diffusion models, particularly D3, exhibited the best fit with an activation energy of 16–18 kJ/mol. Thermodynamic analysis confirmed the endothermic nature of the process, with positive enthalpy and negative entropy changes indicating an increase in energy and a more ordered product. These findings suggest that rice straw pyrolysis holds promise as a viable renewable energy option. This study contributes to understanding the rice straw pyrolysis mechanism which could be helpful for its effective utilization at commercial scale.

Keywords Thermal analysis, Kinetics, Thermodynamics, Coats Redfern method

Introduction

There has been increasing global interest in biofuels in recent years due to their significant potential to address the growing disparity between energy demand and supply. In addition, biofuels offer a means to reduce carbon dioxide (CO_2) emissions stemming from the extensive use of petroleum-based fuels, thereby aiding in climate change mitigation efforts. Moreover, adopting biofuels contributes to enhancing both energy security and sustainability on a broader scale (Mohammadi et al., 2023). Liquid biofuels are especially beneficial for the transport sector, offering environmental and economic advantages and global stability by decreasing reliance on imported fossil fuels. The substitution of gasoline, diesel, and jet fuel with liquid biofuels has been prominently highlighted in international frameworks like the Kyoto Protocols and the Paris Agreement. As a result, diversifying the varieties and sources of biofuels has emerged as a

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crucial energy-matter in both developed and developing nations, driven by environmental and energy policies that support sustainable development (Khan et al., 2024a; Yerizam et al., 2023). The need to switch from conventional fossil fuels to more sustainable and ecologically friendly energy sources is currently the world's most serious concern (Asif et al., 2020; Khan et al., 2024b). Biofuels, which are made from organic materials like plants, algae, and even garbage, have drawn a lot of attention because of their potential to lower greenhouse gas emissions and lessen our reliance on limited fossil fuel supplies (Asif et al., 2022). Bioethanol stands as a prevalent liquid biofuel utilized for transportation purposes in various countries, including the USA and Brazil. However, most of the commercially available bioethanol originates from edible food crops like grains, sugarcane, and vegetable waste (Khan et al., 2024b; Kumar & Vyas, 2024; Raza et al., 2022a, 2022b). Biofuel production from biomass primarily encompasses four distinct conversion technologies: thermal methods, involving heat-based processes such as direct combustion, pyrolysis, and torrefaction; thermochemical approaches, which utilize both heat and chemical processes like gasification, liquefaction, and syngas production; chemical techniques, employing chemical agents for processes like trans esterification and catalytic conversion; and biochemical methods, utilizing enzymes, bacteria, or other microorganisms for processes like anaerobic digestion, methanogenesis, and anaerobic fermentation (Darmawan et al., 2018; Ezz et al., 2023; Ghosh et al., 2019; Kung & Zhang, 2015; Kung ChihChun & Zhang Ning, 2015) As a result, biomass-derived energy is gaining popularity, and pyrolysis stands out as a potential method in this area. In pyrolysis, which is a thermochemical process, organic materials like agricultural waste and lignocellulosic biomass are broken down into useful byproducts like biochar, bio-oil, and syngas in the absence of oxygen (Asif et al., 2021).

As a staple food for billions, rice production is critical for achieving Zero Hunger, the second Sustainable Development Goal. With a growing global population, rice demand is projected to rise by 28% by 2050. Asia, the dominant producer, contributes roughly 90.5% of the world's rice (Ahmed et al., 2023a, 2023b). Rice is a short-lived, water-loving crop that grows in a wide range of semi-aquatic (irrigated or rainfed) environments (i.e., lowland to upland). Rice straw (RS) is obtained as a post-harvesting residue during rice processing, which is recognized as one of the most abundant lignocellulosic biomass (LCB) resources in the world. The structural composition of RS mainly constitutes cellulose (35–40%), hemicellulose (17–25%), lignin (10–20%), silica (8–15%), and a significant amount of extractives (12%) (Krishania et al., 2018; Raj et al., 2015).

As Rice straw has little nutritional value for animals, following harvest, farmers frequently turn to burning the straw in the fields. This practice, known as paddy burning, is a major source of air pollution, linked to respiratory problems, heart disease, and even premature death. Paddy burning also harms soil fertility (Asif et al., 2023).

Bangladesh relies on a varied array of established commercial energy sources, including native natural gas and coal, as well as imports such as oil, LPG, LNG, electricity, and hydroelectric power (Murshed & Alam, 2021).The energy profile of the nation reflects a strategic equilibrium: biomass contributes roughly 25% of the primary energy supply, with the remaining 75% thoughtfully sourced through commercial avenues (Bank, 2009). Indigenous natural gas leads the pack, contributing approximately 51% to the nation's commercial energy, complemented by an additional 13% sourced from imported LNG (Al-tabatabaie et al., 2022; Bank, 2009).

The bulk of the remaining energy profile is accounted for by imported oil. Bangladesh recently imported ~ 9.56 million metric tons of crude oil and refined petroleum products during the 2021–2022 period (Al-tabatabaie et al., 2022; Bank, 2009).

Research has focused on the pyrolysis of rice straw to find sustainable solutions. Rice straw can be pyrolyzed to create a variety of useful products, such as biochar, which can enhance soil quality and carbon sequestration, and bio-oil, which can be used as a starting material for biofuels and targeted commercial chemicals. Therefore, using rice straw through pyrolysis is consistent with a circular economy and a sustainable bioenergy (Azam et al., 2020; Hassan et al., 2023).

It is essential to comprehend the kinetics and thermodynamics of rice straw pyrolysis to improve product yields, process conditions, and ultimately the exploitation of this renewable resource. This study uses a Thermogravimetric Analyzer (TGA) as the main analytical tool to give a thorough analysis of the kinetic and thermodynamic aspects of rice straw pyrolysis. To build and scale up pyrolysis systems for the generation of bioenergy and waste management, the study intends to provide useful insights into the pyrolysis behavior of rice straw (Conesa et al., 1997).

The calculation of reaction kinetics parameters, including the activation energy (Ea) and pre-exponential factor (A), is a necessary step in the kinetic study of pyrolysis to comprehend the pace at which biomass decomposes at various temperatures. These metrics can offer crucial data for process design and optimization (Donald et al., 2022). In this study, a non-isothermal model fitting approach was carried out using TGA. The objective of this study is to clarify the mechanisms for the degradation of rice straw during pyrolysis by examining the weight loss profiles and applying a variety of kinetic models (Habib et al., 2021).

For evaluating the viability and effectiveness of pyrolysis operations, thermodynamic analysis is essential. The thermodynamic parameters such as Gibbs free energy (G), enthalpy change (H), and entropy change (S) can show whether rice straw pyrolysis is spontaneous under specific circumstances and can give information about the energy requirements for the process or not. Thermodynamic analysis of rice straw pyrolysis allows us to pinpoint the ideal temperature ranges and pressure settings that maximize product yields and energy recovery (Hafiza et al., 2023).

The results of this study are important for the setup of long-term bioenergy systems. Understanding the kinetics and thermodynamics of rice straw pyrolysis can facilitate the development of efficient pyrolysis reactors, improve the quality of the resulting biochar and bio-oil, and contribute to reducing greenhouse gas emissions through the utilization of renewable feedstock. The information gathered in this study helps to educate stakeholders and policymakers about the viability of using rice straw pyrolysis on a broad scale to manage agricultural waste and provide clean energy. This research endeavors to unravel the intricate processes involved in rice straw pyrolysis by kinetic and thermodynamic analyses (Naqvi et al., 2019). By shedding light on the crucial components of this thermochemical conversion, we hope to pave the path for the sustainable use of rice straw as a useful feedstock for bioenergy production and environmental Sustainability. We assist ongoing efforts worldwide to transition to a greener, more sustainable energy future while addressing the challenges posed by agricultural waste by undertaking this study.

Materials and methods

Study area and sample collection

This research utilized rice straw; an abundant agricultural residue found in local fields across Bangladesh. Ten different locations across the country were chosen for the study, focusing on regions significant for rice production. These areas included Ghatcheck (Rangunia), Bazalia (Sathkania), Hithkandi (Mirsarai), Borodargarhat (Sitakunda), Haildhar (Anwara), Suharna char (Noakhali), Sonagazi (Feni), Bakerganj (Barisal), Shatgara (Rangpur), and Birampur (Dinajpur). The exact geographical coordinates of each sampling site were recorded using GPS technology (see Table 1 for details).

A total of 5 kg of rice straw samples were collected from these locations and transported to the laboratory for further processing, characterization, and analysis. The sampling sites across the study areas are illustrated in Fig. 1.

Sample preparation

The rice straw underwent a series of preparation steps, starting with washing, sun-drying, and removal of any physical impurities. Subsequently, the dried straw was processed in a rotary cutting mill and sieved to obtain particles sized between 0.6 mm and 1.18 mm. This fraction was further refined into a fine powder with particles smaller than 250 µm for analysis of carbon, oxygen, hydrogen, nitrogen, and sulfur compositions. Proximate analysis, following ASTM standards as outlined in prior research, was conducted on the air-dried samples. (Al-Wabel et al., 2013; Hassan et al., 2023). To determine the moisture content, ~ 1 g of air-dried biomass was placed into a ceramic crucible (Minitial-BC) and heated for 1 h at 110 °C under a nitrogen purge. The samples were subjected to a nitrogen flow of 6 L min^{-1} for at least 25 min before heating and then at a rate of 3 L min^{-1} during

Table 1 Geographical locations of the selected study areas

Sample code	Study area	Geographical location	
		Latitude	Longitude
RS-1	Ghatcheck (Rangunia)	22.472757371072884	92.05426693041244
RS-2	Bazalia (Sathkania)	22.12188780990971	92.13653903154399
RS-3	Hithkandi (Mirsarai)	22.76568308576829	91.58619846038793
RS-4	Borodargarhat (Sitakunda)	22.679307021923574	91.6279660415714
RS-5	Haildhar (Anwara)	22.194399651009373	91.93682704317582
RS-6	Subarna char (Noakhali)	22.60184334855384	91.17061838043826
RS-7	*Sonagazi* (Feni)	22.81780720612325	91.36092278911947
RS-8	Bakerganj (Barisal)	22.540009452284817	90.34786726217534
RS-9	Shatgara (Rangpur)	25.73791347128492	89.21382557246537
RS-10	Birampur (Dinajpur)	25.3919790991708	88.9950590618239

Gross sample of Rice straw about 5 kg of each sample

Gross sample of Rice Straw after drying and grinding

Fig. 1 Fine sample of the rice straw

heating. After the heating period, the samples were transferred to a desiccator for cooling and then weighed after 1 h.

For volatile matter analysis, the oven-dry samples were heated under nitrogen purge at 950 °C for 7 min. The crucibles containing the biomass were covered with ceramic lids and placed in a stainless-steel box inside a muffle furnace (Thermo Scientific Lindberg/Blue M Box Furnace BF51894C-1). Nitrogen gas was purged into the box at a flow rate of 6 L min^{-1} for at least 15 min (~ 10 box volumes), which then decreased to 3 L min^{-1} during heating.

The biomass's ash content was assessed by subjecting the same samples to a temperature of 550 °C in an ambient air environment within the previously mentioned muffle furnace. To ensure thorough combustion, the crucible lids were removed, and a gentle airflow of 1.5 L min^{-1} was maintained throughout the heating process. The furnace was held at 550 °C for 4 h to guarantee complete combustion. After cooling the furnace for an hour, the samples were transferred to a desiccator. The crucibles, along with the samples, were then weighed to determine the ash mass by subtracting the weight of the empty crucible. All proximate analysis data reported in this study are the average of triplicate measurements.

Thermodynamic analysis

About 10 mg of the ground MSW sample was placed in a TGA pan. The TGA instrument (Model: TA SDT 650) was set to heat the sample from room temperature to 1000 °C at a rate of 5 °C/min under a nitrogen atmosphere. The weight loss of the sample was recorded as a function of temperature to determine the thermal stability and decomposition characteristics of the sample (Azam et al., 2020).

Kinetic study of rice straw

The conversion of biomass to biofuel involves numerous intricate steps, as depicted in Fig. 2. This study narrows its focus to the pyrolysis process and the comprehension of various kinetic and thermodynamic parameters through the Coats Redfern Method. (De Meyer, et al., 2012; Elgarahy et al., 2021).

Kinetic analysis of pyrolysis helps us understand the reaction rates involved in the process. This analysis is based on the Arrhenius equation, which relates reaction rate to factors like temperature and activation energy. The equation used for kinetic analysis of pyrolysis typically takes the following form:

$$\frac{\mathrm{d}\alpha}{\mathrm{d}t} = k(T)f(\alpha), \tag{1}$$

where $\alpha = \frac{m_0 - m_i}{m_0 - m_f}$. In which m_0 is the initial mass, m_i is the mass at a given time t and m_f is the final mass in mg:

$$k(T) = A\exp\left(\frac{E_\alpha}{RT}\right), \tag{2}$$

where A is the pre-exponential factor, E_a is activation energy (kJ/mol), R is the universal gas constant and T is reaction temperature (K).

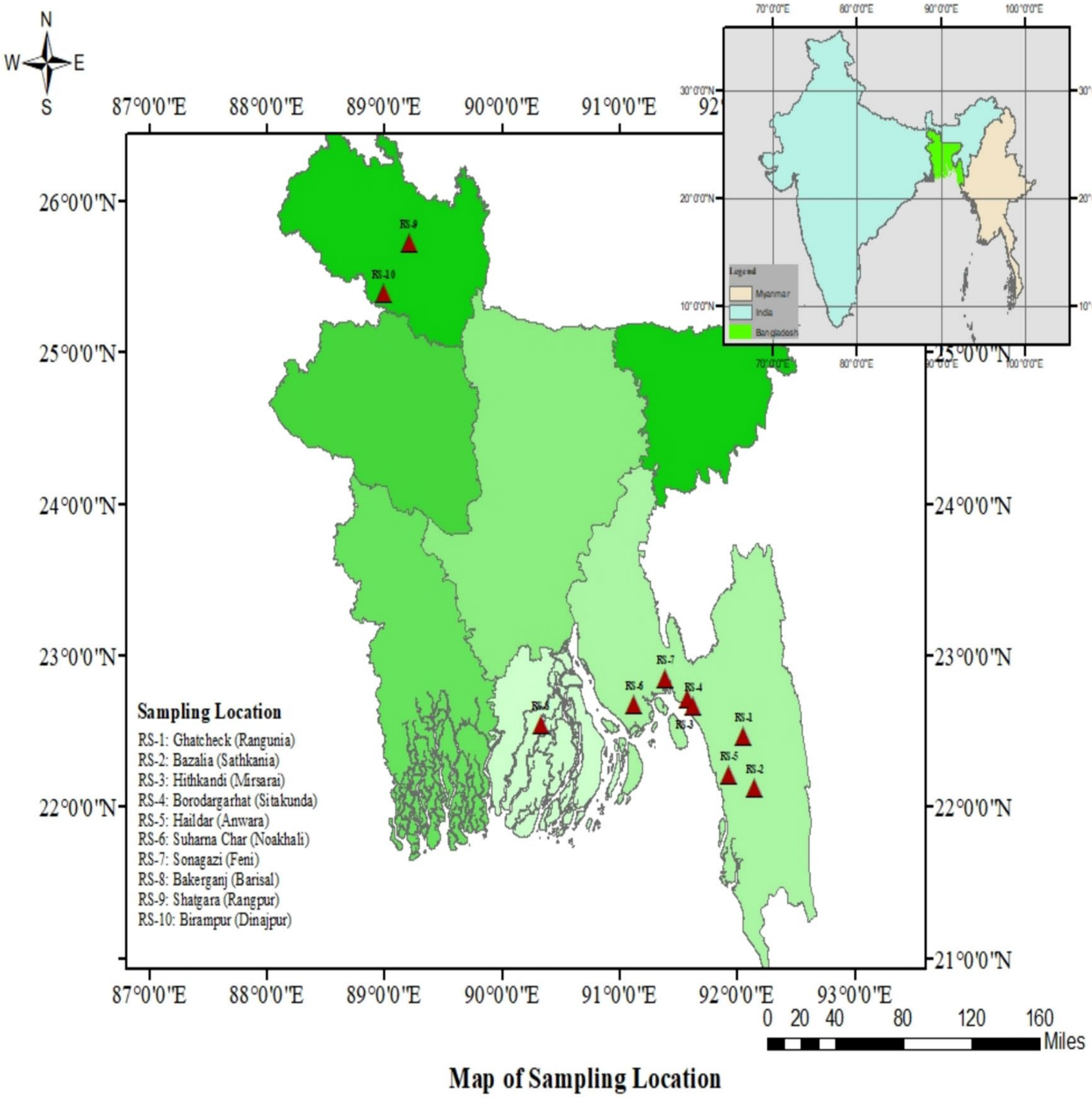

Fig. 2 Rice straw samples collection spots within the study areas

Coats–Redfern models a model fitting model

The Coats–Redfern method is a widely used kinetic analysis technique that involves fitting experimental data obtained from TGA experiments to theoretical models, typically based on various reaction mechanisms. By comparing experimental data with the predictions of the model, parameters such as the activation energy and pre-exponential factor can be estimated, providing insights into the thermal decomposition behavior of the sample.

The Coats–Redfern model allows us to determine key parameters like the pre-exponential factor and activation energy for a given sample. While various Coats–Redfern model forms exist, a common equation used for kinetic parameter calculation is presented in the following equation (Naqvi et al., 2019):

$$\ln\left[\frac{g(\alpha)}{\mathrm{T}^2}\right] = \ln\frac{AR}{\beta Ea}\left(1 - \frac{2RT}{Ea}\right) - \frac{Ea}{RT} \tag{3}$$

Kinetic parameters like activation energy and pre-exponential factor can be determined from the Coats–Redfern model equation (refer to Eq. (3) for this model's specific equation). This equation incorporates the heating rate (β), the universal gas constant ($R = 0.008314$ kJ/mol k), and a kinetic function ($g(a)$) that depends on the reaction mechanism. The function $g(a)$ itself is obtained through the integration of another function, $f(\alpha)$.

By plotting the left-hand side of the equation ($\ln[g(a)/T^2]$ vs. $1/T$) for various reaction mechanisms, we can obtain a straight line. The slope of this line yields the activation energy, and the intercept at $1/T=0$ provides the pre-exponential factor. This dependence of $g(a)$ on the reaction mechanism allows the Coats–Redfern model to be adaptable to different scenarios. The Coats–Redfern model has become a prevalent tool for estimating the kinetic parameters of solid fuel reactions.

Calculation of thermodynamic parameters

Thermogravimetric analysis (TGA) can be coupled with kinetic data to estimate thermodynamic parameters like Gibbs free energy and entropy for the pyrolysis process. Different reaction mechanisms are listed in Table 2, which have been calculated in this study. Most of the solid fuel pyrolysis mechanisms fall under the category of these five major reaction mechanisms. Based on the highest fit of linear regression coefficient the suitable pyrolysis reaction mechanism has been selected. These parameters are crucial for understanding the feasibility and spontaneity of the reaction. Equations (4–6) illustrate the relationships used to calculate these thermodynamic properties from kinetic data:

$$\Delta H = E_{\mathrm{a}} - \mathrm{RT}, \tag{4}$$

$$\Delta G = E_{\mathrm{a}} + RT_{\mathrm{m}} \ln\left(\frac{K_B T}{hA}\right), \tag{5}$$

$$\Delta S = \frac{\Delta H - \Delta G}{T_m}, \tag{6}$$

where K_{B} is the Boltzmann constant, which is equal to 1.381×10^{-23} $\mathrm{m^2 kg/s^{-2}\,K^{-1}}$. T_{m} is the maximum temperature at which maximum decomposition occurs. h is the planks constant which is equal to 6.626×10^{-34} $\mathrm{m^2\,kg/s}$, and R is the universal gas constant which is equal to 0.008314 kJ/mol k.

Results and discussion

Thermogravimetric analysis was conducted with a controlled heating rate of 5 °C/min, starting from room temperature and reaching 900 °C, all within an inert atmosphere maintained by a continuous flow of nitrogen gas. To ensure effective moisture evaporation, a 10-min temperature hold was implemented at 110 °C, followed by a 30-min pause at 900 °C for complete degradation. The degradation process was divided into three distinct stages: the initial stage involved moisture loss, followed by the second stage the release of volatile components, representing the primary biomass degradation phase with significant mass loss. The third stage marked the degradation and breakdown of heavy, complex hydrocarbons into smaller units, followed by their further degradation. The actual pyrolysis of the biomass commenced during the second degradation stage, providing valuable insights into the self-ignition temperature of the biomass, and critical information for its efficient storage and transport. The quantity of volatile matter within the biomass sample inversely affected the onset of degradation. Hence, understanding the thermal behavior of biomass in this temperature range is crucial for its storage, transportation, thermal conversion, and gasification processes. In the second degradation stage, a model-fitting approach was employed using the Coats Redfern method to identify the most suitable degradation model for rice straw (RS) degradation. It's noteworthy that solid fuel pyrolysis degradation reactions are typically categorized into five different models, as outlined in Table 1. The selection of the appropriate degradation reaction model was based on the highest regression coefficient. In addition, the pre-exponential factor, representing collision frequency

Table 2 Reaction mechanism, model names with their *f*(α) and *g*(α) (Naqvi et al., 2019)

Reaction mechanism	Model name	*f*(α)	*g*(α)
Chemical reaction order	Chemical reaction order 1 (F1)	$1 - \alpha$	$-\ln(1 - \alpha)$
	Chemical reaction order 1.5 (F1.5)	$(1 - \alpha)]^{3/2}$	$2[(1 - \alpha)^{-3/2} - 1]$
Diffusion	Parabolic law (D1)	$1/2\alpha$	α^2
	Valensi Equation (D2)	$-[\ln(1 - \alpha)]^{-1}$	$\alpha + (1 - \alpha)\ln(1 - \alpha)$
	Ginstling–Brousshtein equation (D3)	$3/2[(1 - \alpha)^{1/3} - 1]^{-1}$	$(1 - 2/3\alpha) - (1 - \alpha)^{2/3}$
Nucleation and growth	Avrami–Erofeev equation Nucleation and growth (N1.5)	$3(1 - \alpha)[-\ln(1 - \alpha)]^{2/3}$	$[-\ln(1 - \alpha)]^{2/3}$
	Avrami–Erofeev equation Nucleation and growth (N2)	$2(1 - \alpha)[-\ln(1 - \alpha)]^{1/2}$	$[-\ln(1 - \alpha)]^{1/2}$
Phase interfacial reaction	Shrinkage geometrical column (S1)	$2(1 - \alpha)^{1/2}$	$1 - (1 - \alpha)^{1/2}$
	Shrinkage geometrical spherical (S2)	$3(1 - \alpha)^{2/3}$	$1 - (1 - \alpha)^{1/3}$
Power law	Power law (P)	1	α

and playing a pivotal role in chemical reactions, was computed using the intercept obtained from the Coats Redfern method. Figures 3 and 4 depict the graphical representations for each model, along with their corresponding equations and linear regression coefficients (R^2). All the diffusion models showed the best linear regression coefficients fitting, based on that it can be suggested that the diffusion model could be a suitable model for the explanation of the rice straw pyrolysis reaction mechanism.

Kinetic analysis

The kinetic analysis encompasses several key parameters, including the activation energy, which is computed from the slope of the natural logarithm of the ratio $\ln(g(a)/T^2)$ against $1/T$ plot, the regression coefficient derived from the linear plot of the Coats Redfern method fitted with various models, and the pre-exponential factor, often referred to as collision frequency, estimated from the intercept of the linear plot, as illustrated in Fig. 5. We applied ten different models to investigate

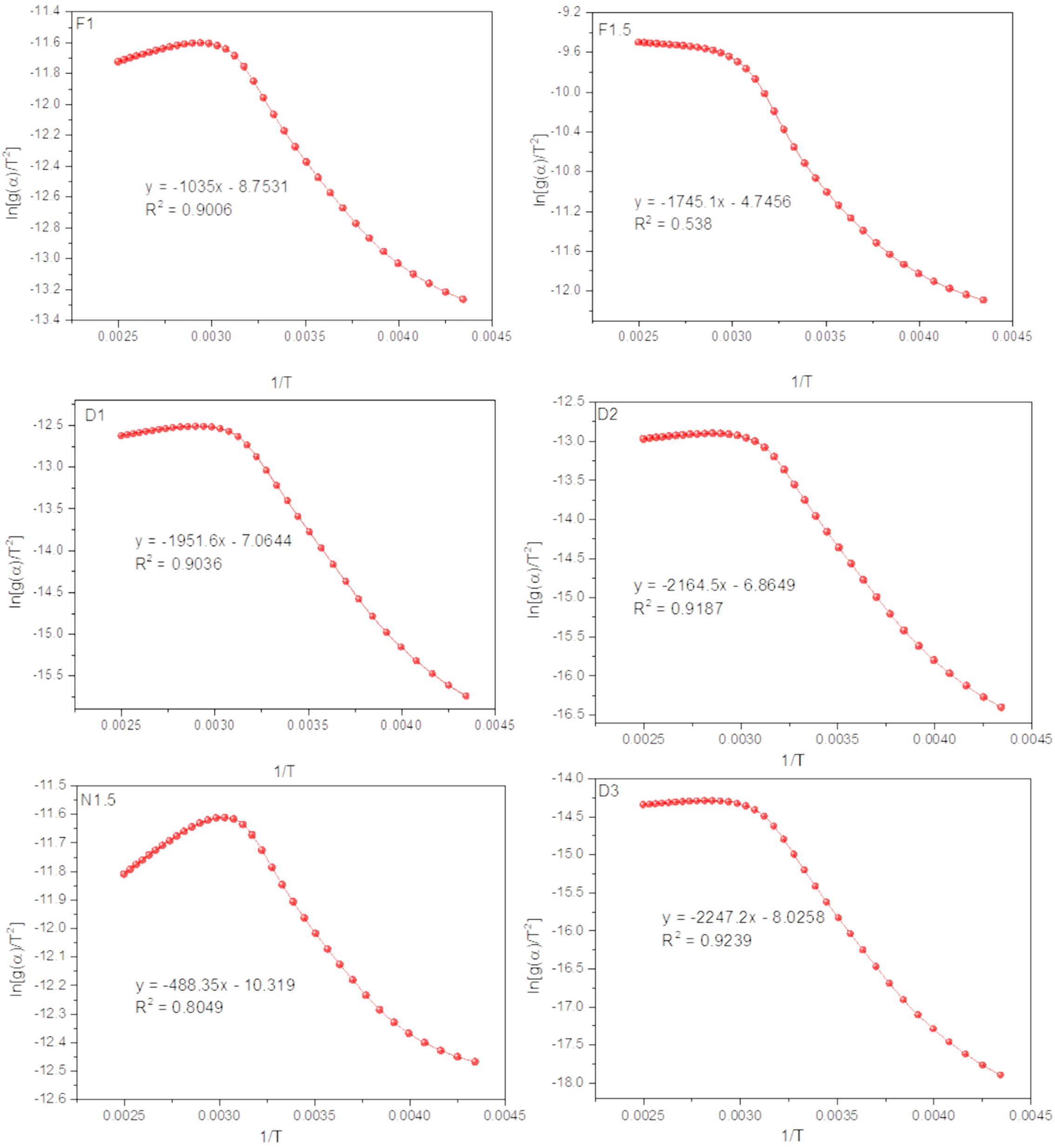

Fig. 3 Linear plots of different models fitted in Coats Redfern method Chemical Reaction Order 1 (F1), Chemical Reaction Order 1.5 (F1.5), Parabolic Law (D1), Valensi Equation (D2), Ginstling–Brousshtein equation (D3) and Avrami–Erofeev equation Nucleation and growth (N1.5)

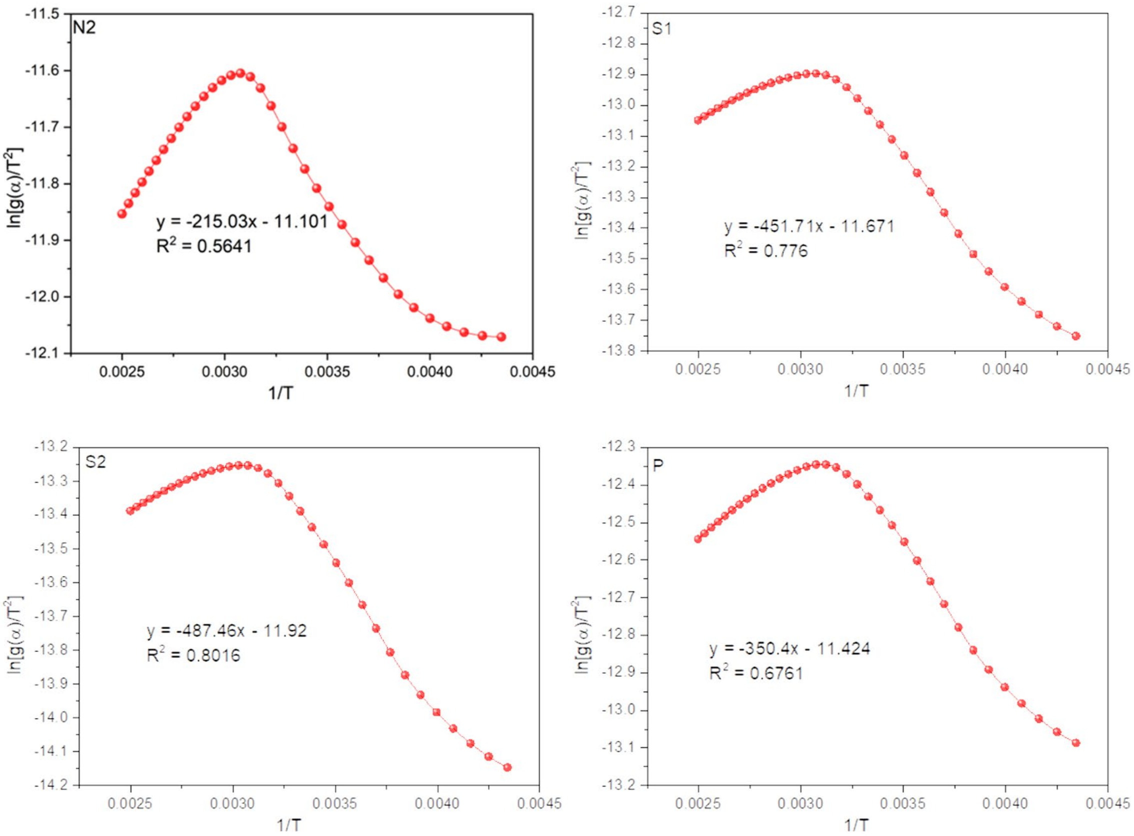

Fig. 4 Linear plots of different models fitted in Coats Redfern method Avrami–Erofeev equation Nucleation and growth (N2), Shrinkage gematrical column (S1), Shrinkage geometrical Spherical (S2) and Power law (P)

their suitability for describing the kinetics of RS pyrolysis. Notably, the chemical reaction order F1 and diffusion models (D1, D2, and D3) exhibited the highest regression coefficients, suggesting their appropriateness as reaction models for RS pyrolysis. Conversely, the nucleation model N2 displayed poor linear fitting, indicating their unsuitability for describing RS pyrolysis. A comparative examination of activation energy values and collision frequencies revealed a consistent trend: increasing collision frequencies corresponded to decreased activation energies. The diffusion models exhibited the highest activation energy values, ranging from 10 to 12 kJ/mole, along with the highest regression coefficients. In contrast, nucleation models and spherical models, including the power law, exhibited lower activation energy magnitudes, accompanied by higher collision frequencies, and improved regression coefficients for spherical models and the power law. However, the nucleation model N2 displayed an inadequate regression coefficient. Collision frequencies varied between 2000 and 8000 per minute, except for the chemical reaction order F1.5, which exhibited almost negligible frequency and a poor linear regression coefficient. In light of the insights gained from the kinetic analysis, it can be inferred that the chemical reaction order F1.5 and nucleation model N2 are not an appropriate model for explaining RS degradation. On the other hand, diffusion models, particularly D3, appear to be the most suitable models for elucidating the mechanism of RS pyrolysis, making them favorable for potential commercial-scale applications. Remarkably, the activation energy of RS pyrolysis is notably lower compared to other biomass sources, as reported in references (Ahmed et al., 2023b) and (Raj et al., 2015), indicating a substantial presence of volatile matter and underlining its significant potential for practical applications.

Thermodynamic analysis

The assessment of various crucial parameters, such as changes in enthalpy, Gibbs free energy, and entropy, is a part of thermodynamic analysis. Enthalpy can be used to measure the changes in heat that take place during a chemical reaction and can reveal whether the reaction is exothermic or endothermic. When robust linear regression models are used, enthalpy variations in the context of rice straw (RS) pyrolysis typically range between 8 and 12 kJ/mole. On the other hand, models with less

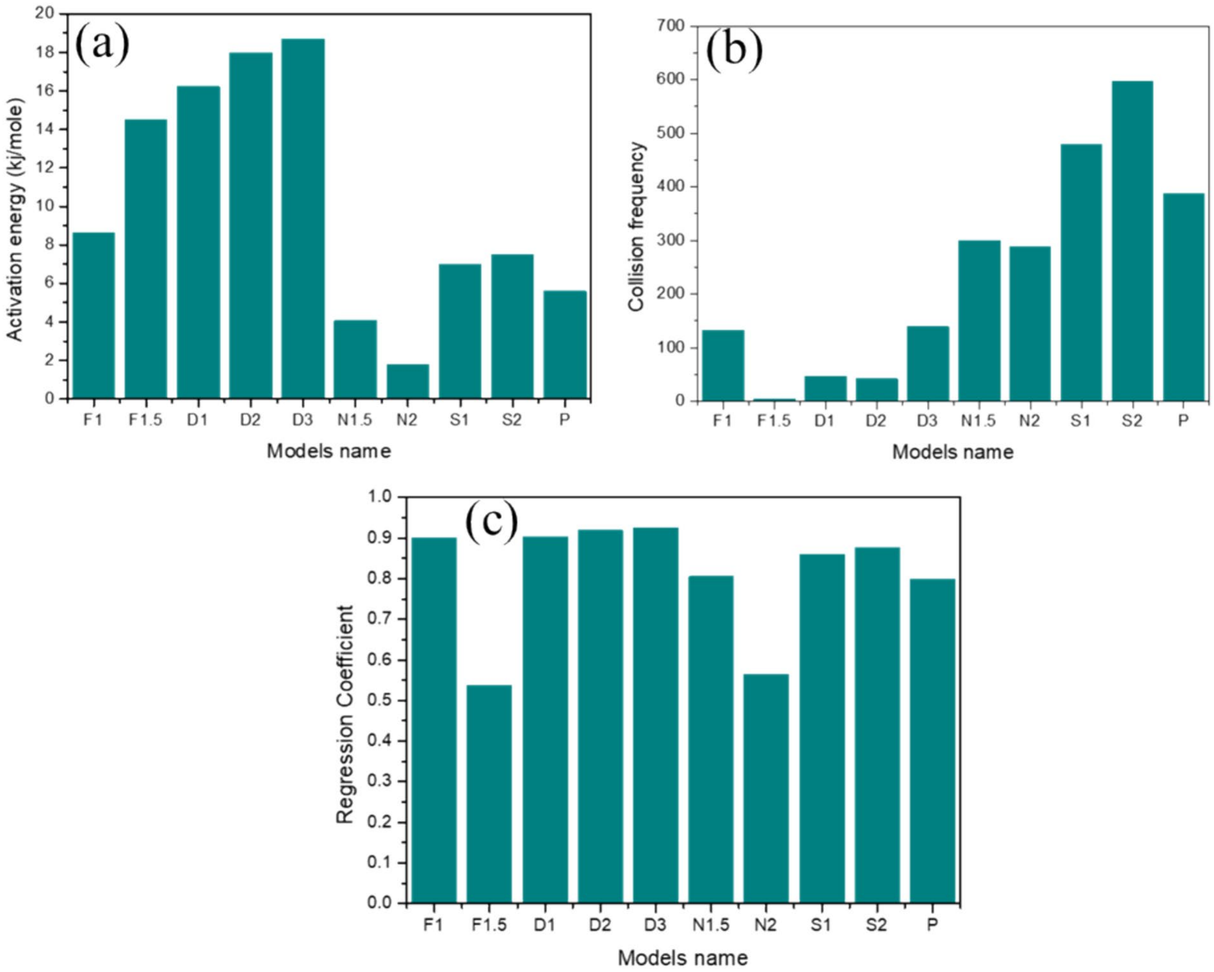

Fig. 5 Best fitted model for the thermal degradation of rice straw and their respective kinetics parameter (**a**) activation energy (kj/mole), (**b**) regression coefficient, and (**c**) collision frequency

desirable regression coefficients show enthalpy changes between − 4 and + 4 kJ/mole, as mentioned in Fig. 6. The product of an exothermic reaction has less energy than the reactant, and the enthalpy value is negative. However, with biomass pyrolysis, this is not the case. Since the primary goal of pyrolysis is to produce a high-energy–density alternative fuel, negative values are undesirable. When the enthalpy value is positive, the reaction is endothermic, meaning the product has more energy than the reactant. This fits with the results of our kinetic analysis. Since the product has more energy than the reactant, RS pyrolysis is endothermic. Gibbs free energy estimates the amount of energy that is available for chemical reactions at a given temperature and pressure, indicating whether the reaction will occur spontaneously or not. All reaction models have a different range for the Gibbs free energy, which suggests that the pyrolysis process is not spontaneous and requires an external heat source to drive the chemical reaction. Another crucial factor is entropy, which measures how disordered a chemical species is at a given temperature and pressure. Entropy constantly produces negative values in RS pyrolysis, regardless of the model that is used to analyze the reaction mechanism. Entropy values that are negative show that the result has more order than the reactant. The high-temperature pyrolysis process produces a large number of free radicals. These radicals tend to recombine with their counterparts to reduce energy and establish stability because of their quick kinetics (Raza et al., 2022b).

Comparison with existing literature

A review of the literature indicates that a great deal of attention has been paid to examining the thermogravimetric characteristics of different biomass and organic waste samples in order to evaluate their potential as alternative energy sources. Naqvi et al. (2019), for example, examined the thermal degradation properties of high ash sewage sludge and the thermodynamic and kinetic

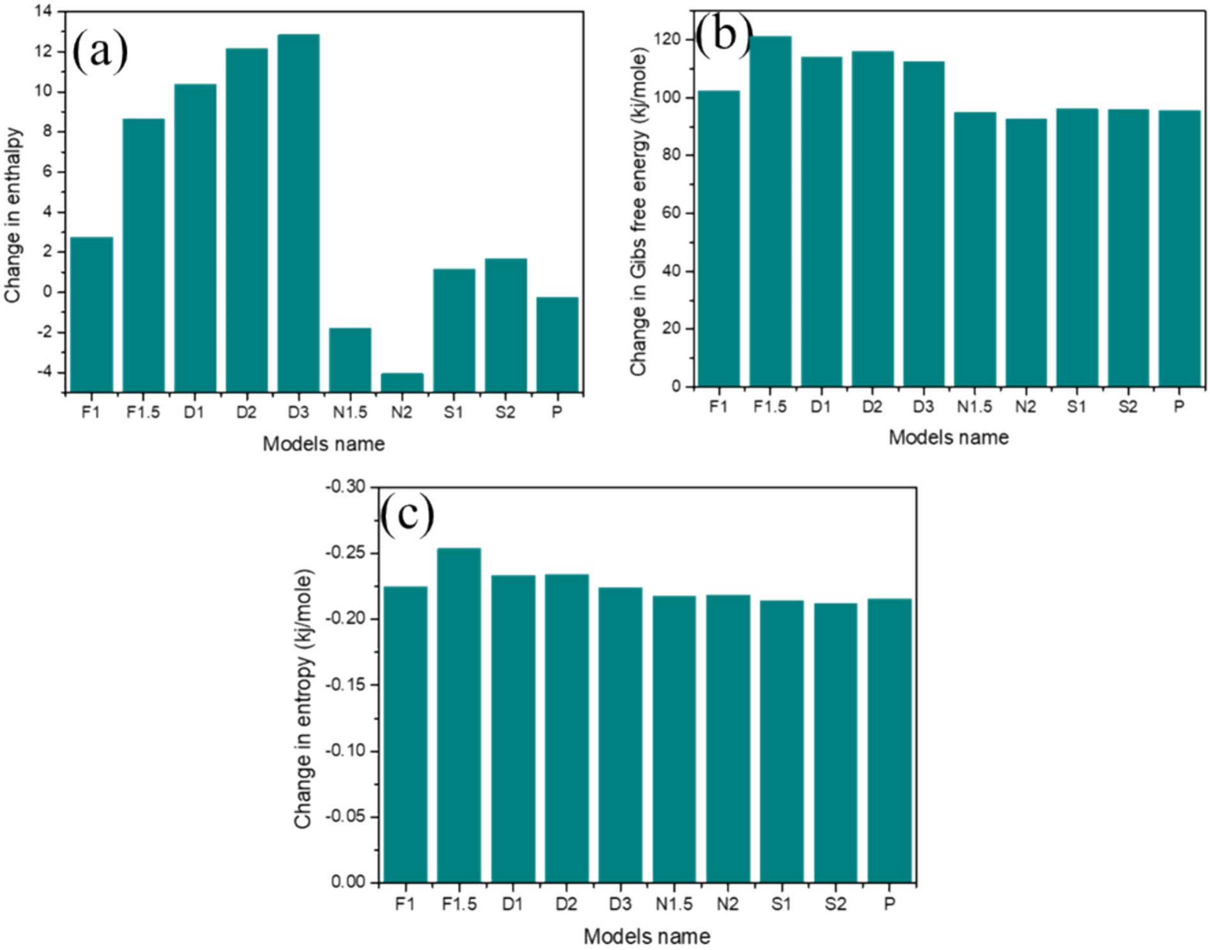

Fig. 6 Best fitted model for the thermal degradation of rice straw and their respective thermodynamic parameters (**a**) change in enthalpy (kj/mole), (**b**) change in Gibbs free energy, and (**c**) change in entropy

parameters necessary for its effective conversion into alternative fuel sources. (Naqvi et al., 2019). But when we compare our current work to the organic waste samples Naqvi et al. (2019) looked at, we find a significant difference in ash composition. In addition, the percentage of organic matter in the rice straw in our investigation is higher than that of studies conducted by Zeb et al. (2017) that looked at the process of turning microalgae into substitute fuels (Zeb et al., 2017). Notably, our results show that the low ash and moisture content of rice straw, along with its high amounts of fixed carbon and volatile matter, make it a good candidate for clean energy production. This is aligned with the composition shown in several previous investigations that have been published in the literature (De Meyer, 2012; Elgarahy et al., 2021; Zeb et al., 2017). As a result, rice straw becomes an attractive option for expanding the generation of clean energy, with the potential to support energy security as well as environmental sustainability. As a result, using rice straw offers a dual advantage by solving environmental issues and speeding up the switch to cleaner energy sources (Hassan et al., 2023).

Conclusion

The primary aim of this investigation was to conduct a comprehensive analysis of the kinetics and thermodynamics involved in the pyrolysis of Rice straw (RS) using the Coats Redfern method. The most significant degradation of RS was observed within the temperature range of 230–400 °C. Within this temperature range, a model-fitting approach was employed through the Coats Redfern method to select an appropriate model that could effectively elucidate the underlying mechanism of RS pyrolysis. Among all the models considered, diffusion models, and notably D3, exhibited the highest regression coefficients, suggesting their suitability for describing the process. The estimated activation energy falls within the range of 8–12 kJ/mole, and the thermodynamic parameters indicated that the product possessed a higher energy state compared to the reactant, reflecting a well-ordered structure as indicated by the negative entropy value. Moreover, the Gibbs free energy values confirmed the non-spontaneous nature of the pyrolysis process. The thermos-kinetic analysis of RS pyrolysis underscored its significant potential for low-temperature pyrolysis or gasification processes, positioning it as a promising renewable energy source alternative. This study contributes to understanding the rice straw pyrolysis mechanism which could be helpful for its effective utilization at commercial scale. However, there are some limitations of the study we could not focus on the product measurements which would be the subject of future research.

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Author contributions

Abu Md. Mehdi Hassan designed the study, data collection, analysis, and writing the original draft. Bushra Sharf—critical investigation, data analysis, and software validation. Md. Ripaj Uddin—laboratory analysis. Hassan Zeb data analysis and software validation. Mohammad Nazim Zaman review and editing, Md. Nuruzzaman reviewed and edited, and Mayeen Uddin Khandaker designed the study, review, and editing. Farzana Yasmin—supervision designed the study, review, and editing.

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Data availability

All data are available in the manuscript.

Declarations

Competing interests

The authors declare no competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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