

ENHANCED COMBUSTION AND GASIFICATION OF BIOMASS VIA LOW-TEMPERATURE PRESSURIZED AIR OXIDATION

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Abstract

This study investigated the combustion and gasification behaviors of biomass enhanced through a low - temperature pressurized air oxidation process - an approach developed by the authors. Rice straw (RS) and its upgraded form (Upgraded RS), treated at 250°C under pressures of 0.1 and 1.0 MPa, were assessed. The Upgraded RS exhibited significantly altered combustion and gasification behaviors compared to raw RS. Thermogravimetric analysis (TGA) showed a notably faster char combustion rate, although this rate slightly decreased with increasing treatment pressure. Under CO₂ gasification, the yield of fuel gas - particularly CO - was higher for the Upgraded RS and increased with pressure. Kinetic parameters calculated using the global kinetic model indicated lower activation energies for the Upgraded RS, suggesting enhanced thermal reactivity. An increase in surface area from 1.16 to 17.02 m²/g due to treatment pressure may partly explain the accelerated reaction rates. These findings underscore the potential of pressurized air oxidation as an effective biomass upgrading method for thermochemical applications.

Keywords: Pressurized air oxidation; Low temperature treatment; Biomass upgrading; Combustion; Gasification

Introduction

Biomass has been increasingly promoted as a sustainable alternative fuel for power generation. However, due to several negative properties such as high moisture content and low heating value, numerous studies have focused on upgrading biomass to enhance its energy density. Upgraded or

treated biomass can effectively replace or be co-fired with coal, thus addressing the limitations associated with raw biomass as fuel.

At present, several upgrading processes have been applied to industrial applications. The torrefaction process, for example, has garnered

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significant industrial interest, producing torrefied biomass with heating values comparable to lignite coal (16–21 MJ/kg) (Prins *et al.*, 2006; Pimchui *et al.*, 2010; Wannapeera *et al.*, 2011; Li *et al.*, 2012; Wannapeera and Worasuwanarak, 2015; Luo and Agraniotis, 2017). Laboratory studies have further explored torrefaction under pressure, achieving up to 95% biomass yield with higher heating values (21–26 MJ/kg) than conventional torrefaction (Wannapeera and Worasuwanarak, 2012a; Setkit *et al.*, 2020; Sun *et al.*, 2020; Setkit *et al.*, 2021). Another promising method is solvent treatment, which can increase biomass heating values to levels comparable to bituminous or sub-bituminous coal (32–34 MJ/kg) with high yields at 350°C. However, both torrefaction and solvent treatment processes have limitations. Conventional torrefaction at 300–320°C produces tar, leading to operational challenges such as dust accumulation and clogging. While pressurized torrefaction reduces tar formation and increases carbon content, it necessitates high pressures (>4 MPa) and an oxygen-free environment. Solvent treatment, while effective, is complex and energy-intensive due to the need for solvent separation (Wannapeera *et al.*, 2012b; Jadsadajerm *et al.*, 2018a; Jadsadajerm *et al.*, 2018b). To overcome these limitations, the authors have recently developed a new method called pressurized air oxidation at low temperatures to improve biomass properties. Preliminary studies have observed promising results, with significant removal of oxygen from the biomass structure and increased heating values at temperatures below 250°C (Liplap *et al.*, 2022).

In this study, the potential of biomass upgraded through pressurized air oxidation as a fuel for combustion and gasification, key thermal conversion methods for biomass energy production, will be evaluated. The combustion and gasification behavior of the upgraded biomass will be examined under laboratory-scale conditions. Kinetic parameters, which are crucial for reactor design, process control, and optimization, will be investigated. Comparisons of raw biomass and biomass upgraded under various conditions will also be conducted.

Materials and Methods

Materials

Rice straw (abbreviated as RS), a by-product from rice fields in Chachoengsao province, Thailand, was used as a sample in this study. It was cut and ground to less than 150 mm, then dried at 70°C using a vacuum oven before being used in the experiment.

Pressurized Air Oxidation Process

The schematic diagram of the pressurized air oxidation process used to produce upgraded biomass is shown in Figure 1. Rice straw (1.5 mm diameter) was treated in a 600 ml batch autoclave reactor (Parr Instrument Company, Series 4560 Mini Reactors). For each run, approximately 3 g of the sample was heated to 250°C and maintained for 30 minutes under varying gas pressures. Reaction pressures were controlled by setting initial gas pressures (22% O₂ balanced in He) at 0.5 and 1 MPa before initiating heating. The final pressures were approximately double the initial pressures, reaching about 1.0 and 2.0 MPa, respectively. Atmospheric pressure pretreatment (0.1 MPa) was also conducted by opening a valve, allowing gas to flow through the sample at 200 ml/min. All resulting products were quantified and analyzed. Liquid products were recovered by washing with acetone, which was then removed using a rotary evaporator. Gaseous products were collected in a gas bag. The remaining solid, designated as upgraded biomass, was dried and characterized. To ensure reproducibility and data reliability, each experiment was repeated at least three times, and the collected products were used for subsequent analyses. The reported values represent the average of multiple independent measurements, with standard deviations included as error estimates where applicable.

In this work, upgraded rice straw samples treated under various conditions are denoted using the treatment temperature and pressure. For example, RS 250-1.0 refers to rice straw treated at 250°C and 1.0 MPa.

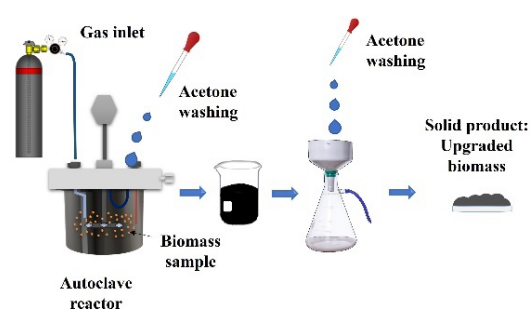


Figure 1. Schematic diagram of the experimental procedure for producing the upgraded biomass by a pressurized air oxidation treatment process

Combustion and Gasification Experiments

Combustion and gasification experiments were conducted using a TGA (TGA 50H, Shimadzu) and a fixed-bed reactor. The TGA was

utilized to examine the thermal behavior of the samples, specifically the weight changes occurring during the processes. Approximately 12 mg of the finely ground sample was continuously heated in an air atmosphere (Air zero) for combustion and in a CO₂ atmosphere (99.99%) for gasification. Both experiments involved heating the sample at a constant rate of 10°C/min from room temperature to approximately 700°C for combustion, and 950°C for gasification. In this work, the Upgraded RS was prepared at 250°C under initial pressures of 0.1 and 1.0 MPa (RS 250-1.0) and utilized as a sample. The combustion and CO₂ gasification of RS were also performed for comparative purposes.

The fixed-bed reactor was employed to quantify the products formed during gasification, with particular emphasis on the composition of the producer gas. Figure 2 illustrates the experimental setup, which comprises a horizontal cylindrical electric furnace, a quartz tube, an alumina sample holder, a thermocouple, a CO₂ gas supply, gas sampling bags, and a micro gas chromatograph (490 Micro GC, Agilent Technologies) for gas analysis.

The gas composition was determined using a Micro GC, with a combination of single-point and multi-point external standard calibrations, depending on the target analyte. Single-point calibration was applied to CO and H₂, based on a standard gas mixture containing CO₂ (1.2 vol%), CO (0.97 vol%), CH₄ (1.1 vol%), and H₂ (1.1 vol%), with helium as the balance gas. In contrast, CO₂ was calibrated using a three-point curve (1.2, 20.0, and 99.99 vol%) to ensure accuracy across the broad concentration range observed in the product gases. The instrument exhibits reliable performance over a concentration range of 1 ppm to 100 vol%, which is sufficiently broad to cover all analytes detected in this study.

In the experiment, approximately 1 g of the sample is placed in an alumina boat and positioned at the center of the electric furnace within the quartz tube reactor. Before gasification, the reactor is purged with nitrogen gas at a flow rate of 100 ml/min for 30 minutes to remove residual air. Subsequently, the gas is switched to CO₂ to initiate the gasification process. The sample is then heated at a constant rate of 10°C/min from room temperature to 900°C and maintained at this temperature for 1 hour. A thermocouple located above the sample monitors and controls the temperature. The produced gas was collected in a 10-liter gas bag and analyzed using micro gas chromatography immediately after cooling, to minimize any potential changes in gas composition during storage. Upon completion of the experiment, the sample is rapidly cooled and weighed at room temperature.

All combustion and gasification experiments were repeated at least three times to ensure reproducibility. Reported values are presented as mean values, while standard deviations were calculated and included in the tables where applicable. In the case of TGA, representative weight loss curves are shown. The results from repeated runs were found to be highly consistent.

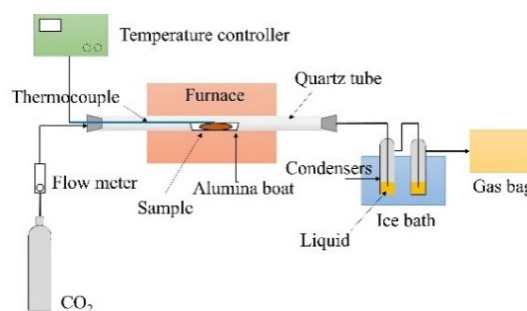


Figure 2. The experimental setup for investigating the gasification product

Proximate and Ultimate Analysis

The proximate analysis of the sample was conducted to evaluate the upgraded biomass. The amounts of ash, volatile matter, and fixed carbon on a dry basis were determined using the standard testing methods: ASTM D1102-84, ASTM E872-82, and ASTM D1762-84, respectively. Ultimate or element composition analysis was performed using a CHN analyzer (CHN JM10, J-Science Lab). For each measurement, approximately 2 mg of finely ground sample was used. The standard reference compound employed was 2,5-bis(5-tert-butyl-2-benzoxazol-2-yl) thiophene (BBOT), which contains 72.58 wt% carbon, 6.10 wt% hydrogen, 6.53 wt% nitrogen, and 7.44 wt% sulfur.

Heating Value Analysis

The higher heating value (HHV) of the samples, calculated on a dry basis from the elemental analysis results using the Dulong formula (Mott and Spooner, 1940), is expressed as follows:

$$\text{HHV (MJ/kg, db.)} = (338.1C + 1441.8H - 180.2O)/1,000 \quad (1)$$

In this equation, *C*, *H*, and *O* represent the weight percentages of carbon, hydrogen, and oxygen, respectively.

Kinetics Analysis of Combustion and Gasification

In this study, we carefully investigated the kinetic parameters of biomass and upgraded

biomass during combustion and CO₂ gasification to enable a detailed quantitative comparison of their reaction rates. Data obtained at constant heating rates will be used to determine the key kinetic parameters: activation energy (E) and pre-exponential factor (k_0). The global kinetic model was employed for this analysis because it effectively describes gas-solid reactions. The study was performed under a constant pressure of 1 atmosphere.

The model considers the separate-stage reaction that occurs throughout the decomposition process (Shen *et al.*, 2011; Shen, 2009a) as a first-order reaction, as shown in equation (2):

$$\frac{d\alpha}{dT} = kf(\infty) \quad (2)$$

where α is the mass loss fraction. The rate constant k is related to temperature according to the Arrhenius equation (3) while $f(\infty) = 1 - \infty$

$$k = k_0 \exp(-E/RT) \quad (3)$$

From equations (2) and (3), equation (4) can be derived as:

$$\frac{d\alpha}{f(\infty)} = \frac{k}{\beta} dT \quad (4)$$

where β is the heating rate. Integrating equation (4) with respect to temperature results in:

$$g(\infty) = \int \frac{d\alpha}{f(\infty)} = \frac{A}{\beta} \int \exp\left(-\frac{E}{RT}\right) dT \quad (5)$$

Substituting the values from equations (3) and (4) into equation (5) yields:

$$\ln\left(\frac{g(\alpha)}{T^2}\right) = \ln\left(\frac{AR}{\beta E} \left[1 - \frac{2RT}{E}\right]\right) - \frac{E}{RT} \quad (6)$$

Since $g(\infty) = \ln(1 - \infty)$ and the value of $\frac{2RT}{E}$ is very small and can be neglected, equation (6) then simplifies to:

$$\ln\left(\frac{g(\alpha)}{T^2}\right) = \ln\left(\frac{AR}{\beta E}\right) - \frac{E}{RT} \quad (7)$$

From equation (7), the value of E can be determined by plotting a linear equation between

$\ln\left(\frac{g(\alpha)}{T^2}\right)$ and $\frac{1}{T}$. This relationship can be rearranged as $\ln\left(\frac{-\ln(1-\alpha)}{T^2}\right)$ versus $\frac{1}{T}$.

Results and Discussion

Yields and Chemical Properties of Upgraded Rice Straw

Table 1 presents the yields and proximate analysis of upgraded rice straw (Upgraded RS) produced via the pressurized air oxidation process. On a dry weight basis, the yield of Upgraded RS was approximately 44.7% at 250°C under atmospheric pressure. However, the yield increased significantly with rising pressure, up to 18% higher at 1.0 MPa - likely due to pressure-induced changes in the carbon structure, as evidenced by an increase in fixed carbon and a decrease in volatile matter after pretreatment.

Table 2 shows the elemental compositions, higher heating values (HHV), and atomic O/C and H/C ratios of RS and Upgraded RS. A clear trend was observed: carbon content increased proportionally with pressure, while oxygen content decreased, substantially improving HHV. Notably, Upgraded RS treated at 1.0 MPa reached an HHV of 18.63 MJ/kg - an increase of 13.67% over raw RS. Interestingly, under atmospheric pressure treatment (0.1 MPa), the HHV was lower than that of the raw RS. This reduction is primarily attributed to substantial carbon loss during the oxidation process, as a significant portion of carbon was released in the form of volatile products and liquid-phase compounds. In contrast, at higher pressures, a larger fraction of carbon was retained in the solid phase, resulting in improved HHV (Liplap *et al.*, 2022).

Compared to conventional torrefaction, which typically operates at 250-300°C in inert atmospheres, the pressurized air oxidation process used in this study achieved comparable or even superior improvements in fuel properties, despite being carried out at a lower temperature but under oxidative and pressurized conditions (Prins *et al.*, 2006; Wannapeera *et al.*, 2012b).

Table 1. Yield and proximate analysis of RS and the Upgraded RS

Samples (°C-MPa)	Yield (wt.%, d.b.)	Moisture (wt.%, w.b.)	Proximate Analysis (wt.%, d.b.)		
			Volatile matter	Fixed carbon	Ash
RS	-	4.5	74.1	13.2	12.7
RS 250-0.1	44.7 ± 0.8	3.8	28.5	36.3	35.2
RS 250-0.5	50.6 ± 1.2	2.4	31.6	38.9	29.5
RS 250-1.0	52.8 ± 1.1	1.3	28.3	46.7	25.0

Table 2. Elemental compositions, atomic ratios, and higher heating values of RS and the Upgraded RS

Samples (°C-MPa)	Elemental Compositions (% , d.b.)				O/C (-)	H/C (-)	HHV (MJ/kg, d.b.)
	C	H	N	O*			
RS	41.6	6.4	1.1	38.2	0.69	1.84	16.39
RS 250-0.1	39.3	2.6	1.5	21.4	0.41	0.80	13.18
RS 250-0.5	46.3	3.5	1.5	19.2	0.31	0.90	17.24
RS 250-1.0	49.6	3.8	1.5	20.1	0.31	0.91	18.63

Note: O/C and H/C atomic ratios were derived from dry ash-free data

Combustion Behaviors of Upgraded Rice Straw

The combustion behaviors of Upgraded RS: RS 250-0.1, RS 250-0.5, and RS 250-1.0 were thoroughly investigated using TGA, with RS serving as a basis for comparison. Figure 3 and Figure 4 illustrate the distinct combustion behavior of RS and Upgraded RS on a dry-ash-free basis under air at a heating rate of 10°C/min from 100 to 600°C, presented as weight loss profiles and Differential Thermal Analysis (DTA) curves, respectively. From the DTA curves, RS exhibits two distinct decomposition peaks: a low-temperature peak (210–340°C) attributed to devolatilization in RS, and a high-temperature peak (340–450°C) attributed to char combustion in RS. In contrast, Upgraded RS displays a single thermal decomposition stage, starting at 210°C, reaching its maximum rate around 420°C, and completing at approximately 510°C. This indicates a significant structural change in rice straw before and after upgrading. Comparing the pressure effect during the upgrading process, RS 250-1.0 begins combustion at a lower temperature (around 215°C) than RS 250-0.1 and RS 250-0.5. It reaches its maximum combustion rate at roughly 400°C and completes the process by 500°C. In contrast, RS 250-0.1 and RS 250-0.5 begin combustion at a similar temperature of 210°C but at a markedly slower rate. They achieve their maximum rate around 410°C and complete combustion by approximately 500°C. These findings demonstrate that upgrading rice straw under pressure

significantly alters its structure, improving combustion behavior.

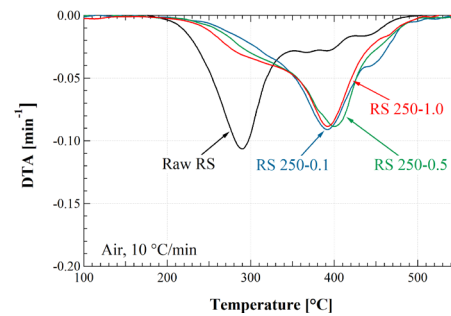


Figure 4. DTA curves of the combustion of RS and Upgraded RS prepared at different pressures

Gasification Behaviors of Upgraded Biomass

For the gasification process, gasification tests of biomass and upgraded biomass indicated a distinct change in gasification behavior compared to the original biomass. Figure 5 displays the CO₂ gasification behaviors of raw RS and Upgraded RS prepared under different conditions (RS 250-0.1, RS 250-0.5, and RS 250-1.0) in weight change curves (TG curves). On a dry-ash-free basis, RS starts to decompose rapidly at approximately 210°C, continuing until 360°C, after which the rate slows significantly. The DTA curves (Figure 6) show that the maximum decomposition rate occurs at about 350°C. Subsequently, the gasification rate noticeably slows until it reaches 980°C. The decomposition in the first temperature range can be attributed to the volatile matter decomposition stage, while temperatures above 600°C represent the char gasification stage. The gasification behavior of Upgraded RS displayed decomposition starting at a temperature similar to that of raw RS, but at a considerably slower rate. The gasification rate notably increased at approximately 925°C. Raising the treatment pressure at 250°C to 0.5 and 1.0 MPa resulted in a greater weight decrease than treatment at 0.1 MPa. However, the weight changes of the Upgraded RS prepared under 0.5 MPa and 1.0 MPa did not exhibit a clear distinction. These results indicate that the structural changes in RS

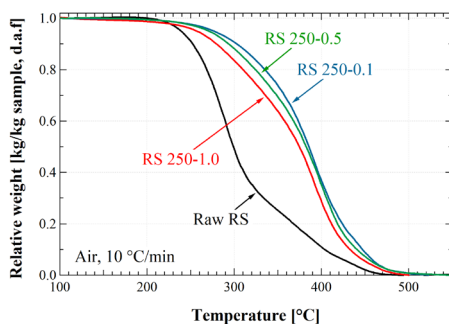


Figure 3. Weight change curves of the combustion of RS and Upgraded RS at a heating rate of 10°C/min

induced by the treatment enhance gasification behavior.

carbon content resulting from the upgrading process.

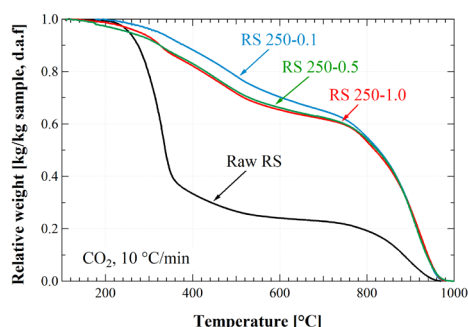


Figure 5. Weight change curves of RS and Upgraded RS during gasification in a CO₂ atmosphere

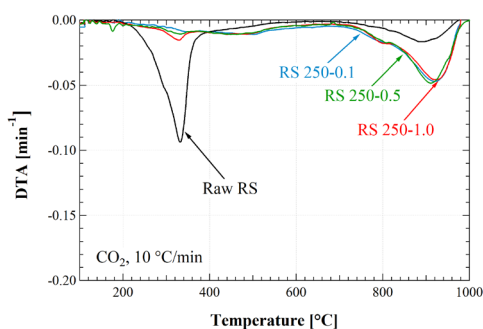


Figure 6. DTA curves of Upgraded RS prepared under various conditions during gasification in a carbon dioxide atmosphere

To investigate the gasification behavior of rice straw (RS) under a CO₂ atmosphere, experiments were conducted in a fixed-bed reactor with continuous heating up to 900°C. The results showed that raw RS exhibited a higher gas yield compared to Upgraded RS under mild upgrading conditions, likely due to its lower ash content and minimal structural changes.

The main gaseous products included CO₂, CO, and H₂, with CO₂ being the predominant component (>70 vol.%), followed by CO (13.9–25.9 vol.%) and a minor fraction of H₂ (<0.7 vol.%) as shown in Table 3. Notably, the Upgraded RS samples produced significantly higher concentrations of CO and H₂—approximately double that of raw RS—while CO₂ content decreased. This shift in gas composition can be attributed to the enhanced Boudouard reaction ($C + CO_2 \rightarrow 2CO$), which the increased availability of active carbon sites in Upgraded RS could promote. This explanation aligns with the observed increase in

Table 3. Composition of product gases from the gasification of CO₂ of RS before and after upgrading under various conditions

Sample	Gas Yield (wt.%)	Gas Compositions (%vol.)		
		H ₂	CO	CO ₂
Raw RS	81.7 ± 1.3	0.3	13.9	85.8
RS 250-0.1	64.3 ± 1.4	0.7	25.1	74.2
RS 250-1.0	69.5 ± 1.2	0.5	25.9	73.6

Kinetic Analysis of Combustion and Gasification of Biomass and Upgraded Biomass

Kinetic analysis in this study focused on comparing the combustion and gasification behaviors of raw and Upgraded RS samples at a heating rate of 10°C/min. Figure 7 shows the mass loss fraction (α) of RS and Upgraded RS under combustion and gasification, respectively. For gasification, kinetic parameters were calculated specifically for the char gasification step (600–1000°C), as temperatures below 600°C correspond to volatile gasification.

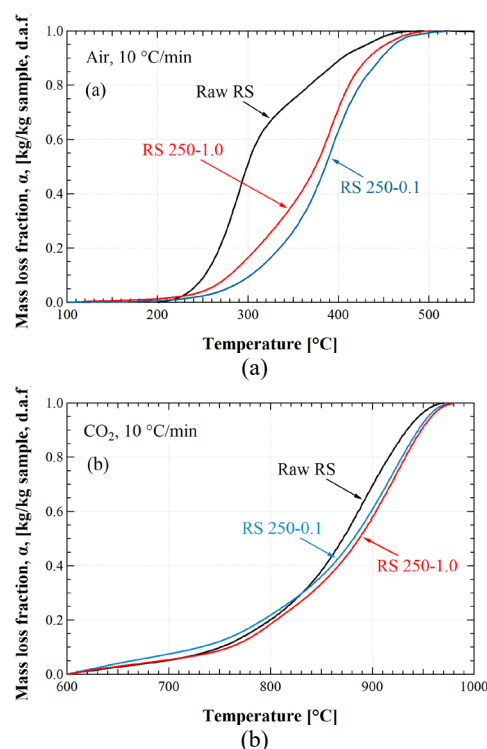


Figure 7. Mass loss fraction of RS and Upgraded RS during (a) combustion and (b) CO₂ gasification at a constant heating rate of 10°C/min

Figure 8 illustrates a linear plot and the resulting equation from the relationship between $\ln\left(\frac{-\ln(1-\alpha)}{T^2}\right)$ and $\frac{1}{T}$ for the combustion reaction of RS, which can be divided into two temperature ranges: 175-342°C and 342-507°C. Figure 9 presents a linear plot and the resulting equation from the relationship between $\ln\left(\frac{-\ln(1-\alpha)}{T^2}\right)$ and $\frac{1}{T}$ For the CO₂ gasification reaction of RS, the char gasification step is the focus at 600-980°C.

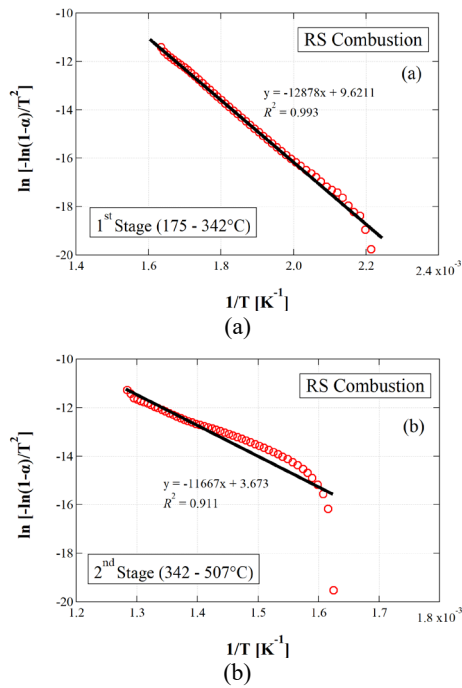


Figure 8. The linear relationship between $\ln\left(\frac{-\ln(1-\alpha)}{T^2}\right)$ and $\frac{1}{T}$ for the combustion of raw RS: (a) first-stage reaction (175–342°C) and (b) second-stage reaction (342–507°C)

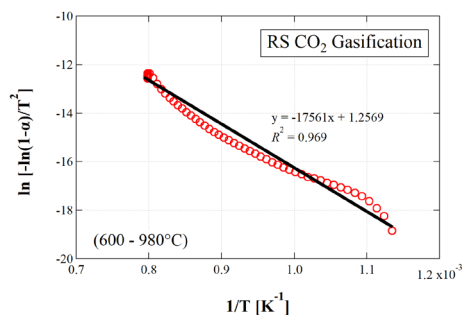


Figure 9. The linear relationship between $\ln\left(\frac{-\ln(1-\alpha)}{T^2}\right)$ and $\frac{1}{T}$ for the CO₂ gasification of raw RS in the temperature range of 600–980°C

Based on the global kinetic model used in this study, the kinetic parameters are summarized in Table 4 and Table 5, presenting the values obtained for the combustion and CO₂ gasification processes, respectively. The analysis of the kinetic parameters for the combustion process revealed R^2 values greater than 0.90 for both stages, indicating that the values obtained are accurate and reliable. With R^2 values ranging from 0.98 to 0.99 for the first stage of decomposition, it was found that Upgraded RS had an activation energy between 52-55 kJ/mol, which is lower than the activation energy of RS at 107 kJ/mol. However, when comparing the activation energies of Upgraded RS prepared at different pressures, they were found to be similar despite their different calorific values. The pre-exponential factor of Upgraded RS was also found to range from 7.8×10^{-4} to 1.01 s^{-1} and 6.4×10^{-4} to 1.56 s^{-1} . For the second stage reaction, only RS is present, with an activation energy of approximately 97 kJ/mol. Previous studies on biomass combustion have reported activation energy values typically ranging from 60 to 160 kJ/mol, depending on the feedstock type, devolatilization stage, and kinetic modeling approach used (Shen *et al.*, 2009b; Chen *et al.*, 2015). The lower E_a observed for the Upgraded RS in this study suggests improved combustibility under the applied treatment conditions, although differences in model assumptions and reaction stages must be taken into account. From the results, it can be preliminarily concluded that RS upgraded by a pressurized air oxidation process has a significantly faster combustion rate than raw RS.

For the analysis of the kinetic parameters of the CO₂ gasification process, R^2 values as high as 0.96-0.97 were obtained from calculations within the 600-980°C temperature range (see Table 5), indicating high reliability of the fitted model. Upgraded RS exhibited a significantly faster gasification rate than raw RS, with its activation energy (E_a) ranging from 129-134 kJ/mol, compared to approximately 141 kJ/mol for raw RS. Reported E_a values from previous studies range from ~127 kJ/mol for torrefied Kenaf at 250°C (based on model-free analysis) to 196-299 kJ/mol for high-temperature steam gasification of various biomass feedstocks (Lee *et al.*, 2021). Despite differing kinetic models and reaction regimes, the comparatively lower E_a here suggests enhanced reactivity via pressurized air oxidation. This reduction may be attributed to an increased number of carbon-free active sites formed during the upgrading process. Although higher treatment pressure slightly decreased the gasification rate, the overall results suggest that pressurized air oxidation not only improves the heating value but also

enhances the thermal reactivity of biomass. The decrease in activation energy implies that the thermal conversion reactions - both combustion and gasification - can occur more readily, making the process more energy-efficient.

Surface Area Analysis of Biomass and Upgraded Biomass

Table 6 presents the BET-specific surface area and pore characteristics of Upgraded RS prepared under varying compaction pressures. The data exhibit a clear trend: increasing pressure significantly enhances both surface area and total pore volume, from 1.16 m²/g and <0.01 cm³/g in raw RS to 17.02 m²/g and 0.02 cm³/g at the highest pressure. This structural evolution suggests the development of a more porous and reactive surface, which likely improves thermal conversion performance by promoting gas–solid interactions and increasing the number of active reaction sites. Similar trends have been reported, where low-temperature pressurized oxidation effectively enhanced microporosity and surface area in biomass-derived carbons (Shang *et al.*, 2018, Mysyk *et al.*, 2012). These improvements may partly explain the accelerated combustion and gasification rates observed in the upgraded biomass.

Conclusions

This study demonstrates that biomass upgrading through low-temperature pressurized air oxidation significantly enhances the fuel properties and

thermal conversion behavior of rice straw. The Upgraded RS exhibited increased carbon content, reduced oxygen content, and a higher heating value (HHV), particularly under elevated pressure conditions. BET analysis indicated an increase in surface area and pore volume, which may contribute to the improved reactivity of the Upgraded RS. These structural enhancements correlate with faster combustion and CO₂ gasification rates, as shown by lower activation energies compared to raw RS. Although higher treatment pressure slightly reduced the reaction rate, the overall thermal reactivity remained superior. These findings suggest that pressurized air oxidation is a promising pretreatment method for improving the efficiency of biomass in thermochemical conversion applications such as combustion and gasification. While pressurized air oxidation introduces additional process control requirements and may involve more sophisticated equipment than conventional torrefaction, its marked improvement of biomass reactivity and fuel quality could offer greater benefits in applications demanding high thermal efficiency.

Table 6. Specific surface area (S_{BET}), total pore volume, and mean pore diameter of Upgraded RS prepared at various conditions

Sample	Specific surface area (S_{BET}) (m ² /g)	Total pore volume (cm ³ /g)	Mean pore diameter (nm)
RS	1.16	< 0.01	8.62
RS250-0.1	11.62	0.03	3.31
RS250-1.0	17.02	0.02	3.50

Table 4. Kinetic parameters obtained from the combustion of RS and Upgraded RS using the global kinetic model

Sample	First stage reaction			
	Range of temperature (°C)	Pre-exponential factor (k_0) (s ⁻¹)	Energy activation (E) (kJ/mol)	R^2
Raw RS	175 – 342	$6.4 \times 10^{-4} - 1.56$	107.07	0.99
RS 250-0.1	177 – 650	$7.8 \times 10^{-4} - 1.01$	52.27	0.98
RS 250-1.0	174 – 590	$9.3 \times 10^{-4} - 1.64$	54.62	0.98
Sample	Second stage reaction			
	Range of temperature (°C)	Pre-exponential factor (k_0) (s ⁻¹)	Energy activation (E) (kJ/mol)	R^2
Raw RS	342 – 507	0.02 – 1.22	96.99	0.911
RS 250-0.1	-	-	-	-
RS 250-1.0	-	-	-	-

Table 5. Kinetic parameters obtained from CO₂ gasification of RS and Upgraded RS using the global kinetic model

Sample	Range of temperature (°C)	Pre-exponential factor (k_0) (s ⁻¹)	Energy activation (E) (kJ/mol)	R^2
Raw RS	600 – 980	$1.13 \times 10^{-3} - 0.50$	146.00	0.97
RS 250-0.1	600 – 980	$1.64 \times 10^{-3} - 0.37$	129.89	0.94
RS 250-1.0	600 – 980	$1.11 \times 10^{-3} - 0.29$	133.58	0.96

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