Dependency of the Combustion Behavior of Energy Grass and Three Other Types of Biomass upon Lignocellulosic Composition

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The combustion characteristics of four kinds of biomass fuels (energy grass, sawdust, corn cob, and walnut shell) are investigated in this article. All the samples are heated from room temperature to 800°C at multiple heating rates of 10, 20, and 30°C/min. The effect of hemicellulose, cellulose, and lignin components on the pyrolysis and combustion processes of energy grass is explored by comparison to those of the other three types of biomass. The hemicellulose and cellulose content of samples could improve the devolatilization performance during biomass combustion. Furthermore, the comprehensive combustion index suggested herein indicates that the combustion performance of energy grass or walnut shell is limited by their high ash content or their low ratio of cellulose to lignin. Kinetic parameters are obtained by combining the isoconversional method (OFW and KAS models) and the method of master-plots. The apparent activation energy of the devolatilization stage is higher than that of the char oxidation stage, which is mainly influenced by the lignocellulosic composition. © 2017 American Institute of Chemical Engineers

Keywords: energy grass, combustion characteristics, kinetics, lignocellulosic compositions

INTRODUCTION

Biomass is an only renewable carbon source, gaining particular attention in energy generation for its neutral CO₂ conversion, low NOₓ and SO₂ emissions, and high content of volatiles [1]. Generally, biomass can be converted into heat or liquid fuel by three thermal conversion processes namely pyrolysis, gasification, and combustion [2]. Direct combustion is one of the most extensively employed technologies for commercial or industrial utilization of biomass, and is responsible for about 95–97% of the world’s bioenergy produced [3–5]. Thermal analysis is regarded as a useful and reliable tool to determine the thermal properties and kinetics of biomass during combustion [6,7]. The kinetic parameters are essential for the design, control, and optimization of industrial equipment [8]. Iso-conversional methods, such as Ozawa–Flynn–Wall (OFW) or Kissinger–Akahira–Sunose (KAS), are commonly used in numerous kinetic studies on biomass combustion without prior knowledge of reaction mechanisms [9–11].

Biomass is generally considered as an organic fuel derived from plants, including wood, agricultural wastes, herbaceous crops, and short-rotation energy crops [3,12]. Up to now, most studies have focused on the combustion of agricultural or woody biomass using thermogravimetric analysis (TGA), such as wood [13,14], pine sawdust [15], capsicum stalks [16], straw [17], sunflower [18], corn cob and stover [19], grape marc (i.e., skin, seed, and stalk) [20]. In comparison to other traditional biomass fuels, energy crops are a promising alternative that are cost-effective, and do not generally require particularly fertile soil good soil or high levels of fertilizer and pesticide application [21–24]. Energy grass (A. donax) is a kind of energy crop artificially cultivated and has following advantages: high calorific value (22.76 MJ/kg), high production (over 15 years after planting as a perennial plant), and lower land requirement (growing rapidly in sandy, saline-alkali, or industrial waste land) [25]. Because of the economical and environmental advantages of the combustion of energy grass, it is pertinent to investigate its thermal properties. However, previous studies on energy grass have been limited and have tended to focus on the combustion characteristics.

The chemical composition plays crucial role in the thermal conversion of biomass. Cellulose, a polysaccharide with the generic formula C₆H₁₀O₅, is the major component of biomass cell walls; hemicellulose is another cell wall component represented by the generic formula C₆H₁₀O₅; and lignin is the aromatic compound built from three highly cross-linked units [26–29]. So far, few investigations focused on the combustion characteristics related to the biomass components. Gani and Naurse [30] found that the cellulose and lignin content were important to evaluate the pyrolysis characteristics. Cheng et al. [31] and Kai et al. [32] used artificial biomass components (microcrystalline cellulose, xylan, and lignin) to explore the contribution of lignocellulosic components to the thermal process. They found that hemicellulose combusted easily and the weight loss of lignin covered a broad temperature range.

The aim of this work is to investigate the combustion characteristics of energy grass in comparison to those of sawdust, corn cob, and walnut shell. The combustion characteristics are
Definition of Characteristic Parameters

To clearly describe the pyrolysis and combustion processes, the following parameters are defined by thermogravimetric (TG) curves [21,34]:

1. DTGmax: the maximum rate of weight loss during thermal decomposition, indicating combustibility of the sample. DTGmax1 and DTGmax2 are introduced if there are two peaks in TG profile.

2. Tc: the temperature which corresponds to the maximum degradation rate, which is an indicator of reactivity. A lower Tc indicates better ignition performance during the combustion process.

3. Tp: the initial temperature of the thermal conversion process (e.g., the ignition temperature for combustion). As defined by Biagini et al. [34], the initial temperature is determined by the tangential method and is derived from the earliest maximum degradation rate (DTGmax1). As shown in Fig. 1, a vertical line is drawn through point A (DTGmax1) intersecting with TG curve at point B. Subsequently an intersection between a tangent through point B and an extended TG initial horizontal line is made at point C, whose corresponding temperature is considered to be the beginning of thermal conversion process.

4. Te: the end temperature of thermal degradation (i.e., the burnout temperature for combustion), which is also determined through determination of the tangent, but derived from the latest degradation rate (DTGmax2). Te represents the completion of thermal degradation. Therefore, the vertical line is drawn through point D in Fig. 1, and the tangent line through point E is intersected with the extended TG final horizontal line.

5. Di: the ignition index [18], which is a measurement of ignition performance of combustion and described as Eq. (1):

\[ D_i = \frac{\text{DTGmax}}{T_p T_i} \]

6. S\text{c}: the comprehensive combustion index [16], which is used to evaluate general performance of combustion and can be defined as Eq. (2):

\[ S_c = \frac{\text{DTGmax}\Delta\text{DTGmean}}{T_i^2 T_e} \]

Kinetic Methods

As mentioned above, the OFW and KAS models are employed to determine activation energy of the combustion of biomass, and the master-plot method is used to determine the reaction mechanism herein.

The degree of conversion of biomass can be written as Eq. (3):

\[ \alpha = \frac{m_0 - m_i}{m_0 - m_f} \]

where \( m_0 \) and \( m_f \) represent the initial and final masses of the sample, respectively, while \( m_t \) is the mass at any time.

The fundamental rate equation is generally expressed as Eq. (4):

\[ \frac{d\alpha}{dt} = k(T)f(\alpha) \]

where \( t \) is the time, \( T \) is the temperature, and \( f(\alpha) \) is the reaction function. \( k(T) \) denotes the temperature-dependent rate constant, which is defined in terms of the Arrhenius equation:

\[ k(T) = A \exp \left( -\frac{E}{RT} \right) \]

where \( A \) is the pre-exponential factor, \( E \) is the activation energy, and \( R \) is the universal gas constant. At a constant
Table 1. The most common reaction mechanisms for solid-state processes [35].

| Proximate analysis* (wt %) | Ultimate analysis** (wt %) | Compositional analysis (wt %) |
|---------------------------|----------------------------|-----------------------------|
| Moisture | Vol | Ash | FC | C | H | O†† | N | S | Hemicellulose | Cellulose | Lignin |
| EG | 7.25 | 61.55 | 16.30 | 14.90 | 36.09 | 5.10 | 34.27 | 1.47 | 0.37 | 15.04 | 25.09 | 25.73 |
| SD | 7.65 | 76.80 | 0.95 | 14.60 | 44.72 | 6.37 | 39.86 | 0.65 | 0.10 | 22.53 | 42.02 | 34.42 |
| CC | 6.90 | 79.40 | 1.23 | 12.47 | 50.22 | 6.73 | 35.30 | 0.12 | 0.10 | 37.43 | 36.72 | 17.50 |
| WS | 7.20 | 73.54 | 1.97 | 17.29 | 50.65 | 6.27 | 33.92 | 0.28 | 0.11 | 21.62 | 18.90 | 48.73 |

*As received basis.
**Air dry basis.
††The content of FC is calculated by difference.

Substituting the value \( \alpha = 0.5 \) into Eq. (10) yields

\[
G(0.5) = \frac{AE}{\beta R} P(u_{0.5})
\]  

(12)

The following equation is easily derived from Eqs. (10) and (12):

\[
\frac{G(0.5)}{G(0.5)} = \frac{P(u)}{P(u_{0.5})}
\]  

(13)

where \( G(0.5) \) is constant for a given kinetic model, \( G(0.5)/G(0.5) \) denotes the theoretical value, while \( P(u)/P(u_{0.5}) \) is inferred from experimental data. Therefore, the appropriate mechanism function is obtained from Eq. (13). Different expressions of common reaction mechanisms are listed in Table 1 [35].

**RESULTS AND DISCUSSION**

**Biomass Characterization**

The results of proximate, ultimate, and compositional analyses of biomass samples are shown in Table 2. It is essential to give a summary of chemical analysis due to the correlation with thermal performance of biomass [40]. It is obvious that energy grass (EG) has large amount of ash, whilst sawdust (SD), corncob (CC), and walnut (WS) have small content of ash. Lower ash content may be more beneficial to combustion process. Besides, the sequence of volatile content is CC > SD > WS > EG. Table 2 also shows C, H, O, N, and S content of biomass, herein the O content is calculated by difference. The content of N and S of EG is a little larger than those of the other three biomasses. In addition, some differences on lignocellulosic components among the biomass samples SD, CC, and WS are demonstrated with high content of cellulose, hemicellulose, and lignin, respectively.

**Pyrolysis Characteristics**

The pyrolysis process is the initial step of biomass combustion. As shown in Fig. 2a, EG (energy grass) undergoes the smallest weight loss, which is in agreement with the results of proximate analysis (Table 2). There are two peaks in the first stage of pyrolysis except for SD (sawdust) in Fig. 2b. One local maxima peak is observed at about 300°C and the main peak at around 350°C, which represents the thermal decomposition of hemicellulose and cellulose, respectively. This is consistent with the fact that hemicellulose decompose over the temperature range of 150–350°C, while cellulose...
break down occurs between 250 and 400°C [41]. It is worth noting that the first peak of CC (corn cob) is larger than that of WS (walnut shell) or EG mainly due to the higher content of hemicellulose. There is no shoulder peak for SD, indicating that the decomposition of hemicellulose is overlapped by that of cellulose and lignin. The pyrolysis characteristic parameters of the four types of biomass are summarized in Table 3. It is noted that the pyrolysis of EG starts and ends at 278.9°C and 406.5°C, respectively, which are lower than those of the three other types of biomass. The maximum weight loss rate of EG or WS is lower while that of SD or CC is higher, indicating the poorer reactivity of EG or WS. This observation is related to their volatiles content.

### Combustion Characteristics

Figure 3 shows the combustion profiles of the four types of biomass as a function of temperature at heating rates of 10, 20, and 30°C/min. It is evident that the combustion process can be divided into three stages responding to their DTG profiles. The first stage is dehydration from room
The weight losses for different types of biomass are approximately coincidental as all the samples contain a similar amount of moisture. The second stage is devolatilization at temperatures between 150 and 380°C, which moves to a slightly lower temperature versus pyrolysis in an inert atmosphere. The maximum devolatilization rate of combustion is a little higher than that of pyrolysis. This is because mild heterogeneous oxidation promotes the pyrolytic abstraction of volatile matter [39]. In addition, the main peak appears around 300°C and the shoulder peak of EG is not distinct during the combustion process, which is probably because the hemicellulose peak has merged with the cellulose peak. This phenomenon can be explained by the alkali ions causing a reduction in the decomposition temperature of cellulose [42]. The last stage is attributed to the oxidation of char in the temperature range of approximately 380−600°C.

A series of combustion parameters of the four types of biomass, including the ignition index and comprehensive combustion index, are listed in Table 4. It is noted that the ignition temperature of EG is lower than that of WS or SD. This might be attributed to the fact that the higher lignin content in woody plants delayed the ignition [16]. Moreover, in comparison to EG, CC ignites earlier and exhibits the highest reaction rate in the devolatilization stage, as the ignition performance is improved by higher cellulose and

![Figure 3. TG and DTG profiles of four types of biomass under air at heating rates of 10, 20, and 30°C/min. [Color figure can be viewed at wileyonlinelibrary.com]](image-url)

| Sample | Heating rate (°C/min) | Temperature range (°C) | \( T_i \) (°C) | \( T_{p1} \) (°C) | \( DTG_{max1} \) %/min | Temperature range (°C) | \( T_{p2} \) (°C) | \( T_e \) (°C) | \( DTG_{max2} \) %/min | Char D (°C) | \( S_n \) (°C) |
|--------|----------------------|----------------------|--------------|--------------|----------------|----------------------|--------------|--------------|----------------|---------------|---------------|
| EG     | 10                   | 187−378              | 259.2        | 313.4        | −6.1          | 378−544              | 509.7        | 524.2        | −1.9          | 13.93         | 0.22          | 0.27          |
|        | 20                   | 193−383              | 270.2        | 313.5        | −13.1         | 383−577              | 506.8        | 541.6        | −3.7          | 14.64         | 0.47          | 1.20          |
|        | 30                   | 191−410              | 272.9        | 341.6        | −18.6         | 410−609              | 527.5        | 555.3        | −4.9          | 14.40         | 0.60          | 2.6           |
| SD     | 10                   | 156−379              | 296.0        | 331.6        | −12.0         | 379−516              | 486.2        | 505.0        | −3.8          | 1.47          | 0.46          | 0.63          |
|        | 20                   | 158−390              | 298.0        | 357.6        | −23.9         | 390−544              | 492.5        | 517.7        | −7.8          | 2.06          | 0.76          | 2.68          |
|        | 30                   | 151−427              | 310.7        | 349.3        | −34.0         | 427−591              | 511.0        | 564.9        | −7.3          | 2.38          | 1.10          | 5.44          |
| CC     | 10                   | 196−354              | 254.7        | 301.9        | −12.5         | 354−498              | 407.4        | 473.9        | −3.8          | 1.71          | 0.47          | 0.72          |
|        | 20                   | 188−362              | 266.3        | 306.1        | −30.4         | 362−543              | 411.4        | 485.5        | −6.3          | 3.13          | 1.20          | 4.10          |
|        | 30                   | 179−375              | 306.6        | 310.9        | −41.6         | 375−567              | 420.1        | 530.1        | −7.0          | 2.24          | 1.50          | 7.10          |
| WS     | 10                   | 197−357              | 274.7        | 321.3        | −9.5          | 357−506              | 468.2        | 489.5        | −4.8          | 4.45          | 0.35          | 0.52          |
|        | 20                   | 175−380              | 282.5        | 334.5        | −15.9         | 380−551              | 491.5        | 532.0        | −5.7          | 3.37          | 0.54          | 1.60          |
|        | 30                   | 170−391              | 288.2        | 343.4        | −25.2         | 391−600              | 499.3        | 576.5        | −6.4          | 5.21          | 0.72          | 3.50          |
hemicellulose content [43]. At a given heating rate, the reactivity (maximum weight loss rate, DTG\textsubscript{max}) sequence of devolatilization stage is CC > SD > WS > EG, which is consistent with the hemicellulose and cellulose content in fuels. The ignition index \(I_D\) of EG shows the worst ignition performance. Furthermore, the comprehensive combustion index \(S_n\) is introduced to evaluate the combustion performance. As shown in Fig. 4, \(S_n\) increases with elevated heating rate for each biomass. The higher \(S_n\) of CC and SD indicate better combustion performance, while \(S_n\) of WS and EG is lower. Comparing the difference of chemical composition among the four biomasses, the lowest \(S_n\) of EG may be attributed to the largest ash content. Both WS and CC exhibits a lower ash content than does EG. However, WS has a poorer combustion performance, which probably results from lower ratio of cellulose to lignin content (0.39) than that of CC (2.1). Therefore, to evaluate the combustion performance of biomass, both ash composition and the ratio of cellulose to lignin content should be taken into consideration.

Figure 3 presents the effect of heating rate on combustion performance. It can be seen that both the temperature ranges of the devolatilization and char oxidation stages are becoming wider with an increase in heating rate. As the heating rate increases from 10\(^\circ\)C/min to 30\(^\circ\)C/min, the maximum weight loss rates (DTG\textsubscript{max}) of EG, SD, CC, and WS increase from 6.1%/min, 13%/min, 11.5%/min and 9.5%/min to 18.6%/min, 34%/min, 41.6%/min, and 23.2%/min, respectively. Combining with Table 4, the ignition temperature \(T_i\) and end temperature \(T_e\) also move to higher values as the heating rate increases for all the samples, which results from a particle gradient temperature due to limited thermal conductivity. Similar results were also obtained in previous studies [34,44].

**Kinetic Analysis of Combustion**

**Isoconversional Method**

OFW and KAS models are used to analyze the kinetics due to their ability to give a relatively accurate value of activation energy that is independent of the reaction mechanism [9]. Two stages of thermal degradation are investigated assuming

![Figure 4](https://wileyonline-library.com)

**Figure 4.** Profile of combustion index for the four types of biomass. [Color figure can be viewed at wileyonlinelibrary.com]

![Figure 5](https://wileyonline-library.com)

**Figure 5.** Plots used to determine the value of \(E\) for energy grass for each stage for both OFW and KAS models. [Color figure can be viewed at wileyonlinelibrary.com]
single-step reactions for the solid-state process. Taking energy grass (EG) as an example, Figure 5 shows that the plot of In $\beta$ and In $(\beta/T^2)$ versus $1/T$ with respect of conversion rate both give an approximately linear relationship.

The activation energy of EG can be obtained by determining the slope of the fitted lines. The other three types of biomass (SD, CC, and WS) are also divided into two stages, and activation energies are acquired using the above method. Almost all the samples present an excellent linear dependency such that correlation coefficients are >0.99. In this study, the average values of $E$ are calculated by OFW and KAS models as they are appropriate to assess the kinetic parameters of thermal process. As listed in Table 5, the average $E$ value of devolatilization stage is higher than that of char oxidation stage. With respect to the lignocellulosic composition of biomass, this might arise from the fact that lignin, whose decomposition rate is lower than cellulose and hemicellulose components, is condensed to char [45]. There is little difference among activation energies ($E$) of the four types of biomass in devolatilization stage, but for the char oxidation stage, samples of EG and CC show higher $E$ than do SD and WS. This might be attributed to the fact that cellulose with the highest $E$ has an obvious effect on global kinetics and the $E$ value of hemicellulose was higher than that of lignin [46]. SD and WS contain large amounts of lignin, which explains their lower $E$ in the char oxidation stage.

**The Method of Master-Plots**

The average activation energy ($E$) is calculated by the isoconversional methods, and then $P(n)$ is obtained using Eq. (11). Figure 6a shows the $P(n)/P(n_{0.5})$ versus $\alpha$ of the devolatilization and char oxidation stages (EG) at different heating rates. It is revealed that the master-plots of $P(n)/P(n_{0.5})$ against $\alpha$ are in very close agreement for the different heating rates. Similar profiles are obtained for the other three samples, indicating that the kinetics of biomass thermal degradation can be approximated as a single-step reaction model. In addition, the theoretical master plots of $G(0.5)/G(\alpha)$ versus $\alpha$ are compared with the experimental curves $P(n)/P(n_{0.5})$ in Fig. 6b. It is found that the EG-oxidation stage matches the theoretical master plot of the first-order model $F_1$, while the experimental master plot of EG-devolatilization stage lies between $F_2$ and $F_3$ models. Furthermore, the $F_{2.2}$ model is the most appropriate to describe the devolatilization stage of energy grass by plotting more $F_n$ models, as shown in Figure 6c. Similarly, the kinetic models of the other types of biomass (SD, CC, and WS) are determined by comparing the experimental and theoretical master-plots (Fig. 6d). The pre-exponential factor ($A$) is estimated by the intercept of the fitted straight lines (Eqs. (8) and (9))

![Figure 6. Plots of $P(n)/P(n_{0.5})$ versus $\alpha$ (a) and energy grass (b); comparison between theoretical and experimental master-plots of EG at a heating rate of 20°C/min (c); determination of the $F_n$ model for energy grass (d); experimental master-plots of $P(n)/P(n_{0.5})$ versus $\alpha$ (SD, CC, and WS) and corresponding kinetic models of $G(0.5)/G(\alpha)$ versus $\alpha$. [Color figure can be viewed at wileyonlinelibrary.com]](image-url)
Table 6. Kinetic parameters and mechanisms for four types of biomass.

| Sample                        | $E$ (KJ/mol) | Model                  | $f(x)$                        | $A$ ($\text{s}^{-1}$) |
|-------------------------------|--------------|------------------------|-------------------------------|-----------------------|
| EG-devolatilization stage     | 153.2        | $F_1$                  | $1 - \alpha$                  | 9.24E+15              |
| EG-char oxidation stage       | 129.0        | $F_2$                  | $(1 - \alpha)^{1.2}$          | 2.34E+08              |
| SD-devolatilization stage     | 115.5        | $F_1$                  | $1 - \alpha$                  | 7.68E+09              |
| SD-char oxidation stage       | 90.3         | $F_2$                  | $2(1 - \alpha)^{1/2}$         | 8.27E+03              |
| CC-devolatilization stage     | 172.8        | $F_2$                  | $1 - \alpha$                  | 2.79E+19              |
| CC-char oxidation stage       | 159.6        | $D_1$                  | $1.5 [(1 - \alpha)^{1/3} - 1]^{-1}$ | 7.49E+15 |
| WS-devolatilization stage     | 132.4        | $D_2$                  | $1 - \ln(1 - \alpha)^{1/1}$   | 9.70E+09              |
| WS-char oxidation stage       | 81.6         | $D_1$                  | $1.5 [(1 - \alpha)^{1/3} - 1]^{-1}$ | 3.35E+03 |

based upon the determined $E$ and $G(x)$. The average $A$ value and corresponding kinetic models are summarized in Table 6. It is evident that $A$ in the devolatilization stage is much higher than that of char oxidation stage for all samples in this study.

CONCLUSIONS

In this work, the combustion characteristics of energy grass are investigated in comparison with sawdust, corn cob, and walnut shell using TGA. The kinetic parameters of combustion are obtained by combining the iso-conversional and master-plots methods. The main results can be summarized as follows:

- Compared with the pyrolysis under nitrogen, the devolatilization stage of combustion moves to a slightly lower temperature, and the maximum devolatilization rate is higher under air.
- Lignocellulosic composition plays an important role in the ignition performance. Ignition index increases with increasing hemicellulose and cellulose content of biomass.
- The comprehensive combustion index can be used to describe the combustion performance of biomass. Poor combustion behavior of energy grass is largely due to high ash content, but for walnut shell, this can be attributed to the low ratio of cellulose to lignin content.
- The apparent activation energy of the devolatilization stage is higher than that of the char oxidation stage for the four types of biomass studied. Compared with sawdust and walnut shell, energy grass and corn cob show higher activation energy.
- The reaction mechanism of devolatilization and char oxidation stages can be expressed by the master-plot method for the four types of biomass.

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LITERATURE CITED

1. Fernandez-Lopez, M., Pedrosa-Castro, G.J., Valverde, J.L., & Sanchezsilva, L. (2016). Kinetic analysis of manure pyrolysis and combustion processes, Waste Management, 58, 230–240.
2. Yurdakul, S. (2016). Determination of co-combustion properties and thermal kinetics of poultry litter/coal blends using thermogravimetry, Renewable Energy, 89, 215–223.
3. Vassilev, S.V., Baxter, D., & Vassileva, C.G. (2013). An overview of the behaviour of biomass during combustion: Part I. Phase-mineral transformations of organic and inorganic matter, Fuel, 112, 391–449.
4. Kocabas-Ataklı, Z.Ö., Okyay-Öner, F., & Yürüm, Y. (2014). Combustion characteristics of Turkish hazelnut shell biomass, lignite coal, and their respective blends via thermogravimetric analysis, Journal of Thermal and Analytical Calorimetry, 119, 1725–1729.
5. Jones, J.M., Bridgeman, T.G., Darvell, L.I., Gudka, B., Samson, A., & Williams, A. (2012). Combustion properties of torrefied willow compared with bituminous coals, Fuel Processing Technology, 101, 1–9.
6. Wang, J., & Zhao, H. (2015). Pyrolysis kinetics of combustion tubings under non-isothermal and isothermal conditions, Energy Conversion and Management, 106, 1048–1056.
7. García, R., Pizarro, C., Álvarez, A., Lavín, A.G., & Bueno, J.L. (2015). Study of biomass combustion wastes, Fuel, 148, 152–159.
8. Ceylan, S. (2015). Kinetic analysis on the non-isothermal degradation of plum stone waste by thermogravimetric analysis and integral master-plots method, Waste Management Research, 33, 345–352.
9. Álvarez, A., Pizarro, C., García, R., & Bueno, J.L. Lavín, A.G. (2016). Determination of kinetic parameters for biomass combustion, Bioresource Technology, 216, 36–43.
10. Tahmasebi, A., Kassim, M.A., Ju, Y., & Bhattacharya, S. (2013). Thermogravimetric study of the combustion of Tetraselmis suecica microalgae and its blend with a Victorian brown coal in $\text{O}_2/\text{N}_2$ and $\text{O}_2/\text{CO}_2$ atmospheres, Bioresource Technology, 150, 15–27.
11. Moliner, C., Bosio, B., Arato, E., & Ribes, A. (2016). Thermal and thermo-oxidative characterisation of rice straw for its use in energy valorisation processes, Fuel, 180, 71–79.
12. Demirbas, A. (2004). Combustion characteristics of different biomass fuels, Progress in Energy and Combustion, 30, 219–230.
13. Lopez-Gonzalez, D., Fernandez-Lopez, M., Valverde, J.L., & Sanchezsilva, L. (2013). Thermogravimetric-mass spectrometry analysis on combustion of lignocellulosic biomass, Bioresource Technology, 143, 562–574.
14. Senneca, O. (2012). Kinetics of pyrolysis, combustion and gasification of three biomass fuels. Study of main combustion characteristics for biomass fuels used in boilers, Fuel Processing Technology, 103, 16–26.
15. Zhao, J.L., Niu, S.L., Li, Y.J., Han, K., & Lu, C. (2015). Thermogravimetric analysis and kinetics of combustion of raw and torrefied pine sawdust, Journal of Chemical Engineering Japan, 48, 320–325.
16. Wang, X., Si, J., Tan, H., Niu, Y.Q., Xu, C., & Xu, T.M. (2012). Kinetics investigation on the combustion of waste capsicum stalks in Western China using thermogravimetric analysis, Journal of Thermal and Analytical Calorimetry, 109, 403–412.
17. Greenhalf, C.E., Nowakowski, D.J., Bridgwater, A.V., Titiloye, J., Yates, N., Riche, A.B., & Shield, I. (2012). Thermochromical characterisation of straws and high
yielding perennial grasses, Industrial Crop Production, 36, 449–459.

18. López, R., Fernández, C., Gómez, X., Martínez, O., & Sánchez, M.E. (2013). Thermogravimetric analysis of lignocellulosic and microalgae biomasses and their blends during combustion, Journal of Thermal and Analytical Calorimetry, 114, 295–305.

19. Sittisun, P., Tippayawong, N., & Wattanasiriwech, D. (2015). Thermal degradation characteristics and kinetics of oxy combustion of corn residues, Advances in Materials Science Engineering, 2015, 1–8.

20. Valente, M., Brillard, A., Schönrenbeck, C., & Brilhac, J. (2015). Investigation of grape marc combustion using thermogravimetric analysis. Kinetic modeling using an extended independent parallel reaction (EIPR), Fuel Processing Technology, 131, 297–303.

21. Qin, K., & Thunman, H. (2015). Diversity of chemical composition and combustion reactivity of various biomass fuels, Fuel, 147, 161–169.

22. Ertem, F.C., Neubauer, P., & Junne, S. (2017). Environmental life cycle assessment of biogas production from marine macroalgal feedstock for the substitution of energy crops, Journal of Cleaner Production, 140, 977–985.

23. Collazzo, G.C., Broetto, C.C., Perondi, D., Junges, J., Dettmer, A., Filho, A.A., Foletto, E.L., & Godinho, M. (2017). A detailed non-isothermal kinetic study of elephant grass pyrolysis from different models, Applied Thermal Engineering, 110, 1200–1211.

24. Scordia, D., Van den Berg, D., Van Sleen, P., Alexopoulou, E., & Cosentino, S.L. (2016). Are herbaceous perennial grasses suitable feedstock for thermochemical conversion pathways? Industrial Crop Production, 91, 350–357.

25. Guan, Y.J., Ma, Y., Zhang, K, Chen, H.G., Xu, G., Liu, W.Y., & Yang, Y.P. (2015). Co-pyrolysis behaviors of energy grass and lignite, Energy Conversion and Management, 95, 132–140.

26. Dorez, G., Ferry, L., Sonnier, R., Taguet, A., & Lopez-Cuesta, J.M. (2014). Effect of cellulose, hemicellulose and lignin contents on pyrolysis and combustion of natural fibers, Journal of Analytical and Applied Pyrolysis, 107, 323–331.

27. Balogun, A.O., & McDonald, A.G. (2016). Decomposition kinetic study, spectroscopic and pyrolytic analyses of Isobetulia doka and Pinus ponderosa, Biology of Conservation, 6, 315–324.

28. Lopez-Velaquez, M.A., Santes, V., Balmaseda, J., & Torres-Garcia, E. (2013). Pyrolysis of orange waste: A thermo-kinetic study, Journal of Analytical and Applied Pyrolysis, 99, 170–177.

29. Gai, C., Dong, Y., & Zhang, T. (2013). The kinetic analysis of the pyrolysis of agricultural residue under non-isothermal conditions, Bioresource Technology, 127, 298–305.

30. Gani, A., & Naruse, I. (2007). Effect of cellulose and lignin content on pyrolysis and combustion characteristics for several types of biomass, American Journal of Physiology-Registry I, 32, 649–661.

31. Cheng, K., Winter, W.T., & Stipanovic, A.J. (2012). A modulated-TGA approach to the kinetics of lignocellulosic biomass pyrolysis/combustion, Polymer Degradation and Stability, 97, 1606–1615.

32. Kai, X., Yang, T., & Huang, Y. Li, R.D. (2011). The Effect of biomass components on the co-combustion characteristics of biomass with coal. 2011 Second International Conference on Digital Manufacturing & Automation; 1274–1278.

33. Sluiter, A., Hames, B., Ruiz, R., Scarlata, C., Sluiter, W.J., Tempelton, D., Crocker, A., & Sluiter, M.D. Determination of structural carbohydrates and lignin in biomass. Laboratory analytical procedure (LAP) 2008b;National Renewable Energy Laboratory (NREL).

34. Biagini, E., Fantei, A., & Tognotti, L. (2008). Effect of the heating rate on the devolatilization of biomass residues, Thermochimica Acta, 472, 55–63.

35. Chen, C., Ma, X., & He, Y. (2012). Co-pyrolysis characteristics of microalgae Chlorella vulgaris and coal through TGA, Bioresource Technology, 117, 264–273.

36. Zou, S.P., Wu, Y.L., & Yang, M.D. (2010). Pyrolysis characteristics and kinetics of the marine microalgae Dunaliella tertiolecta using thermogravimetric analyzer, Bioresource Technology, 101, 350–365.

37. Doyle, C.D. (1962). Kinetic analysis of thermogravimetric data, Journal of Applied Polymer Science, 6, 120.

38. Pérez-Maqueda, L.A., Criado, J.M., Gotor, F.J., & Málek, J. (2002). Advantages of combined kinetic analysis of experimental data obtained under any heating profile, Journal of Physical Chemistry A, 106, 2862–2868.

39. Senneca, O., Chirone, R., & Salatino, P. (2002). A Thermogravimetric study of nonfossil solid fuels. 2. Oxidative pyrolysis and char combustion, Energy Fuels, 16, 661–668.

40. Balogun, A.O., Lasode, O.A., & McDonald, A.G. (2014). Thermo-analytical and physico-chemical characterization of woody and non-woody biomass from an agroecological zone in Nigeria, BioResources, 9, 5099–5113.

41. Chandrasekarann, S.R., & Hopke, P.K. (2012). Kinetics of switch grass pellet thermal decomposition under inert and oxidizing atmospheres, Bioresource Technology, 125, 52–58.

42. Sebestyen, Z., Leszovits, F., Jakab, E., & Várhegyi, G. (2011). Correlation between heating values and thermogravimetric data of sewage sludge, herbaceous crops and wood samples, Journal of Thermal and Analytical Calorimetry, 110, 1501–1509.

43. Pang, C.H., Gaddipatti, S., Tucker, G., & Lester, E, Wu, T. (2014). Relationship between thermal behaviour of lignocellulosic components and properties of biomass, Bioresource Technology, 172, 312–320.

44. Taş, S., & Yürüm, Y. (2011). Co-firing of biomass with coals, Journal of Thermal and Analytical Calorimetry, 107, 293–298.

45. Milne, T. (1979). Pyrolysis-The thermal behavior of biomass below 600 C. A survey of biomass gasification, United States, 2, 95–132.

46. Sanchez-Silva, L., Lopez-Gonzalez, D., Villasenor, J., Sánchez, P., & Valverde, J.L. (2012). Thermogravimetric-mass spectrometric analysis of lignocellulosic and marine biomass pyrolysis, Bioresource Technology, 109, 163–172.