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# Combustion behavior of coal pellets blended with Miscanthus biochar

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#### A R T I C L E I N F O

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### ABSTRACT

To achieve reductions in CO<sub>2</sub> emissions, replacing fossil fuels with biomass in thermal power generation is becoming increasingly prevalent. In general, the fuel nature and combustion characteristics of biomass are distinct from those of fossil fuels. Biomass is typically subjected to torrefaction to improve its grindability, hydrophobicity, and heating value (HV). However, the pretreatment process is accompanied by fuel property alteration and an energy penalty. This is strongly associated with the operating envelope and combustion stability of biochar cofiring with coal. Therefore, in this study, the Taguchi method was used to calculate the optimal torrefaction parameters for maximum energy yield and HV. Thermogravimetric and fuel characteristic analyses were performed to examine the pyrolysis features and combustion behavior of the studied fuels. In addition, a blend of 50% *Miscanthus* biochar and 50% Australia coal was produced and pressed into pellets. The pellets were placed into a free-drop furnace to observe their combustion behavior. The results demonstrated that the ignition temperature and burnout temperature of the blended fuels could be effectively reduced, and that their fuel conversion rates and combustion characteristic index could be enhanced. The results can be applied to coal cofiring in large-scale boilers in the future.

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## 1. Introduction

Climate change jeopardizes the survival of humans. However, total abdication of fossil fuel use to mitigate extreme increases in CO2 emission is highly unlikely. The Paris Climate Change Conference in 2015 engendered unprecedented accomplishment, including changes in European government policies, the U.S.-China joint agreement, and support from business and technology communities [1]. Specifically, China agreed to limit its emissions by 2030 or earlier, if possible, and the United States pledged to reduce its emissions by 26%–28% below the 2005 levels by 2025. The European Union has already pledged to reduce greenhouse gas (GHG) emissions by 40% by 2030. Similarly, Taiwanese authorities ambitiously declared to reduce CO<sub>2</sub> emissions by 50% below the 2005 levels by 2050. However, Taiwan possesses nearly no energy resources, and the country relies on imports for nearly 98% of its energy requirements. The gross power generation reached 225,792 GWh in 2016, backed by considerable

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fossil fuel consumption to generate electricity [2]. The share of hydroelectric power in Taiwan is 1.5%. Thermal power accounts for a maximum share of 77.3% (174,533 GWh). The country's energy consumption comprises 36.9% from coal, 4.4% from diesel fuel, and 36% from nature gas. Nuclear power accounts for 13.5%, whereas the share of renewable energy sources that include conventional hydropower, geothermal, solar, and wind power is 5.1%.

Taiwan authorities announced the new energy policy, which is aimed at phasing out nuclear energy by 2025. To meet energy policy commitments, Taiwanese authorities have an obligation to increase the contribution of renewable energy to 20% of electricity generation and meanwhile achieve the abatement of GHG emission. Biomass is considered an environmentally friendly fuel because of its advantage as a renewable and CO<sub>2</sub>-neutral fuel [3]. The thermal utilization of biomass fuels can contribute to the reduction of CO<sub>2</sub> emissions because the same amount of CO<sub>2</sub> released through combustion is extracted from the air during the growth of biomass feedstock. In addition, the utilization of coal with biomass, especially for the partial substitution of fossil fuels during combustion or gasification-based processes, is an essential approach to reducing emissions and avoiding methane release from landfill biomass [4–6]. The GHG effect of CH<sub>4</sub> is 25 times more





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potent than that of  $CO_2$  in terms of global warming impact [7]. Furthermore, cofiring of coal and biomass can reduce  $NO_x$  and  $SO_2$  emissions primarily because of a reduction in the total amount of nitrogen and sulfur in the blended fuels [8].

Currently, attention is shifting to biofuel options for energy generation because they do not require high-quality farmland and thus minimize the risk of deforestation or competition with food crops. Such options include biofuels produced from food or farm waste [9], thus representing second-generation biofuels produced from nonfood biomass or recovered organic materials such as wood, Miscanthus grass, switchgrass, crop residuals, forestry waste, and perennial grasses [10]. Growing trees and perennial grass on degraded land can facilitate the reduction of soil erosion, restoration of soil fertility, and prevention of the invasiveness of nonindigenous species. Accordingly, Miscanthus, considered a perennial energy crop, is widely available and easy to grow in Taiwan. Miscanthus does not require irrigation water and is not susceptible to pests or diseases. During photosynthesis, Miscanthus engages the C4 pathway, enabling efficient carbon fixation, thus rendering it a carbon-rich energy crop [11]. In particular, raw Miscanthus has considerable energy density that is slightly lower than woody biomass, and extensive drying or pyrolysis process can evidently improve its combustibility [12]. Compared with other energy crops, Miscanthus is advantageous for obtaining high productivity and carbohydrate containment [13].

In decades, co-firing of coal with biomass for electricity generation has received increasing attention because its implementation can accommodate varying amounts of available biomass [14-16]. In addition, such cofiring does not require large investments in retrofitting an existing coal-fired power plant [16–18]. Lau et al. [19] pointed out that the optimum torrefaction temperature is determined to be at 250 °C, giving the torrefied oil palm frond a high heating value of 26.62 MJ/kg, while maintain an energy yield of 92.7%. Hu et al. [20] conducted a case study at Taipower, a major electricity supplier in the Taiwanese energy market. It concluded that Miscanthus is more economical than switchgrass in terms of the production cost and the land required to generate biopower for the same levels of biomass co-firing. The Drax power station in England is regarded as the cleanest and most efficient coal-biomass cofiring power generation system in the world; it can produce 4000 MW<sub>e</sub> to meet 7% of the UK electricity demand [21]. In the Netherlands, the Amer power station operates a waste-wood gasifier connected to a 600-MW<sub>e</sub> coal-fired power station with 42% net electric efficiency [22]. Although a biomass cofiring rate of more than 20% in coal-fired furnaces is currently feasible and technically achievable, the typical biomass share currently is below 5% and rarely surpasses 10% on a continual basis. A total 10% of biomass co-combustion could achieve CO<sub>2</sub> abatement from 45 million to 450 million ton per year by 2035 [23]. Low percentages of biomass can be co-fired easily [24]. Thus, it is applicable to a limited range of biomass types and to very low biomass to coal cofiring ratios that is typically less than 5% by mass [25]. However, when the percentage of biomass is increased, limitations are observed at distinct locations in the involved equipment and processes. The fundamental physical and chemical differences between biomass and coal represent limitations or require adjustments. For example, differences in the flow characteristics of biomass and coal necessitate distinct types of logistic installations. Milling characteristics are highly dissimilar because nearly all biomass types have a fiber structure and are extremely difficult to grind [26]. Moreover, combustion behavior is considerably disparate, not only because of differences in chemical composition but also because of differences in particle size. Air-fuel ratios must be adjusted for biomass.

The main difference between biomass and coal is in terms of their fuel properties and particle sizes, which can influence ignition and cofiring characteristics, rendering the task of designing burners and controlling the biomass co-combustion process difficult. Alternatively, high biomass shares in biomass co-combustion furnaces engender several technical challenges including sustained availability of biomass, low grindability of biomass, slagging, fouling, and corrosion [27]. Several technical constraints associated with biomass co-combustion application are predictable. For example, biomass particles are larger than coal particles, and the fibrous structure of biomass feedstock results in relatively high energy consumption during grinding. In addition, lignocellulosic biomass has high moisture content in raw material due to hydroxyl group that form hydrogen bonds to retain additional water [28], which ultimately affects the overall process efficiency. All such constraints originate from the inherent properties of biomass materials, which result in low thermal efficiency and high GHG emissions. Accordingly, upgrading the raw biomass feedstock to meet the requirements of current coal-fired furnaces prior to cofiring is necessary. Various thermochemical conversion technologies such as thermal pyrolysis or gasification may be used to convert raw biomass into biofuel [29], bio-oil [30], or syngas and improve combustion properties [31]. Biochar is the main product of torrefaction, a mild pyrolysis process performed in the temperature range of 200–300 °C under oxygen-free conditions [32]. Torrefaction facilitates the storage of solid fuel and increases its heating value (HV) [33].

In general, the pulverized coal/biomass combustion can be modeled as four-step process: drying, devolatilization, volatile combustion and char burning [34,35]. The coal/biomass particle undergoes the drying process. With an increase in the temperature, the inception of devolatilization process starts. During the devolatilization, obvious mass loss occurs due to the release of volatile matter. The quantity and composition of the volatiles depend on the coal and biomass ingredients and the particle size and temperature. The volatiles are burned out in the gas phase. After the devolatilization, only char and ash remain in the solid particle. Eventually, char oxides to carbon monoxide or carbon dioxide depending in the particle size and temperature, and ends up with ash [36]. For practical application, there are several studies that have discussed the direct co-combustion of alternative fuels in small-scale furnaces. Bhuiyan and Naser [37] numerically examine the co-firing of biomass with coal in an oxyfuel condition in a smallscale furnace, and optimize the biomass share and recycled ratio to achieve stable radiative, convective heat transfer and burnout performance. Gubba et al. [38] investigated the co-firing of straw and coal in a 300 MWe pulverized fuel fired boiler. The prediction of the temperature profile, NO<sub>x</sub> formation, and char burnout was in good agreement with the reported measurement. Dong et al. [39] discussed the co-firing of coal and product gas from biomass gasification in a 600 MWe tangential pulverized coal fired boiler. The result demonstrated a decrease in NO<sub>x</sub> emission of approximately 50–70%. Karampinis et al. [40] discovered that a decrease in NOx emission of up to 10% can be achieved when cardoon is cocombusted with coal. Agraniotis et al. [41] evaluated various coal and solid recovered fuel (SRF) co-combustion modes in a 600 MW<sub>e</sub> with regard to the evaluation of different co-combustion scenarios. Mikulčić et al. [42] studied different biomass co-combustion shares in a cement calciner, and numerically investigate the thermoschemical reaction occurring inside the calculated calciners and to make improvements. In addition, Hu et al. [43] pointed out that bio-char pellets had reduced ignition temperature, wider temperature range, and higher oxidation activity compared with the raw bio-char. The releasing and combustion of volatiles from the added organic binders led to a small peak before char combustion on the TG curves of the organic pellets.

According to the preceding descriptions, most studies have focused on assessing the technical feasibility of biomass cofiring; however, few studies have examined the effect of biochar cofiring on flame characteristics. Therefore, the current study focused on the fuel properties of pulverized coal and Miscanthus floridulus biochar mixtures and their combustion phenomenon. Thermogravimetric analysis (TGA) was performed to observe the thermal behavior of the fuels. Furthermore, the blended fuels were pelletized in a cylindrical die under controlled conditions, and the corresponding combustion process and flue-gas emission were examined using a laboratory-scale free-drop furnace for single pellet combustion. The dominance of homogeneous and heterogeneous reactions could be further explained by matching the mass-loss rate and flue-gas emission of single pellet combustion. The purpose of this study is not to propose a new and innovative measurement approach, but to delineate the interrelation between biochar cofiring feature and torrefaction condition as well as optimize the appropriate torrefaction condition for Miscanthus as exemplified. Meanwhile, seeking a balance between the performance loss of biomass co-combustion and the energy loss of biomass pretreatment is the basic task to maximize the advantages of biomass cofiring.

#### 2. Experimental methods

#### 2.1. Sample preparation

Because of improvements in the feasibility of biomass cofiring utilization, torrefaction was employed as a pretreatment technology to convert raw biomass into biochar. The process of torrefaction transforms the chemical and physical properties of raw biomass into those similar to coal, which enables utilization with high substitution ratios of biomass in existing coal-fired boilers without any major modifications. Torrefaction is a thermochemical process conducted at 200–300 °C. Thus, the biomass partially decomposes, generating volatiles and resulting in a solid residual similar to charcoal-like biofuels. Loss of the strong nature of raw biomass is

mainly coupled with the breakdown of the hemicellulose matrix, which bonds the cellulose fibers to the raw biomass, reducing the length of the fibers during the depolymerization process. In general, torrefied biomass has several benefits such as a higher energy density, improved grindability, higher flowability, and uniformity. In particular, high pyrolysis temperatures favor the yield of liquid and gaseous products, which reduces energy recovery in biochar. Therefore, the pyrolysis temperature is a pivotal parameter for solid fuel production from biomass while maintaining the desired combustion properties.

Fig. 1 indicates the experimental apparatus for the torrefaction process. The feedstock was air-dried *Miscanthus floridulus* obtained from the Chiayi Agricultural Experiment Branch in Taiwan. Before the experiments, the biomass was crushed into a size smaller than 2.83 mm. In each experiment, approximately 10 g of *Miscanthus* was packed in a quartz cylindrical holder. The holder was placed in a tubular furnace and filled with nitrogen. The carry gas was controlled using a flowmeter and continuously delivered into the furnace. The furnace was heated to the target temperature and then maintained for a set time. Thus, volatile gas was generated, which was then delivered to the condensing system. After the furnace cooled, the material that remained in the holder was biochar.

For investigating the combustion behavior of fuels, maintaining a complete database of the thermochemical characteristics of the fuels is crucial. In this study, Australia pulverized coal and *Miscanthus floridulus* biochar were used as the fuel material. Three biomass blending ratios of biochar and coal, namely 0, 50, and 100 wt%, were used. Biochar with maximum HV and maximum energy yield (EY) was produced through torrefaction. Energy yield gives the fraction of the original energy in the biomass retained after torrefaction Energy yield gives the fraction of the original energy in the biomass retained after torrefaction, *that is*, energy yield = (energy in torrefied product)/(energy in raw biomass). The biochar produced using the tubular furnace in the absence of oxygen was further crushed and sieved to form particles smaller than 0.075 mm (200 mesh). The materials were subjected to proximate, elemental, and HV analyses to characterize their basic properties.



Fig. 1. Experimental setup for torrefaction.

The proximate analysis followed the ASTM standard. The higher heating value (HHV) of the sample was measured using a bomb calorimeter (Parr 6200).

#### 2.2. Thermogravimetric analysis

Thermogravimetric analysis (TGA) is an advanced technique that measures different substance masses as the temperature of a sample is changed over time. It is used to analyze decomposition and evaporation rates, oxidation and so forth. A typical TGA comprises of a precision balance with a sample pan located inside a furnace with a programmable control temperature. The temperature is generally increased at constant rate to incur a thermal reaction. In this study, a thermal analyzer (PerkinElmer, STA 8000) was used to simultaneously perform TGA and differential scanning calorimetry. The temperature range for the thermal analysis was set to 30–1000 °C, with a corresponding heating rate of 20 °C/min. In each run, approximately 15 mg of sample was used. Nitrogen and air were used as the carry gas, and the flow rate was fixed at 50 mL/ min for the pyrolysis and oxidation processes. Ignition and burnout temperatures are important properties of solid fuels. The ignition temperature  $(T_i)$  is defined as the minimum temperature at which fuel ignites spontaneously in an environment without an external source of ignition: the burnout temperature  $(T_b)$  is defined as the temperature at which the fuel conversion reaches 99%. In this study, Ti and Tb were calculated through intersection and conversion methods [44], respectively. The results obtained were used to determine the combustion characteristic index (S); a high S value implies that the fuel has better combustion performance. This index is expressed as follows [45].

$$S = \frac{\left(\frac{dW}{dt}\right)_{max} \cdot \left(\frac{dW}{dt}\right)_{mean}}{T_i^2 \cdot T_b}$$
(1)

where  $(dW/dt)_{max}$  and  $(dW/dt)_{mean}$  represent the maximum and average mass-loss rates, respectively.

#### 2.3. Single pellet combustion

To investigate the combustion behavior of fuel pellets made from the mixture of coal and biochar, approximately 800 mg of fuel powder was placed in a cylindrical die, employed 2 ton compression with the pelletizer, and held for 30 s. After pressing, the pellet size was nearly  $\psi$ 12 mm  $\times$  6 mm. A free-drop furnace was used to determine the combustion characteristics of a single pellet; the schematic of the system is shown in Fig. 2. The furnace comprises two heating plates at a distance of 4.5 cm, and the proportional-integral-derivative-controlled electrical wall heaters can reach up to 900 °C with a 220-V/2-kW power supply. Preheated air was continuously delivered into the furnace from the bottom at a fixed flow rate of 3.5 l/min. The sample was dropped through the transmission tube to the stainless mesh platform, which was connected to the quartz holder. The furnace has an observation window at the front for recording the combustion process with a video camera, and the weight change of the sample can be measured by the electronic scale in real time (once per second). In addition, a gas analyzer (MRU VarioPlus) was used to measure the gas emission (including O<sub>2</sub>, CO<sub>2</sub>, CO, and NOx) generated from the pellet during the entire heating process. Combustion experiments were performed at furnace temperatures of 600 °C and 800 °C. The fuel can be ignited if the environmental temperature is sufficiently high so that the ignition delay time, total combustion time, and flame patterns can further be measured.



Fig. 2. Schematic of experimental apparatus.

#### 3. Results and discussion

#### 3.1. Optimization of torrefaction condition

To find the optimum conditions for the torrefaction process, the Taguchi method was used to conduct the minimal number of experiments, similar to a previous study [46]. The Taguchi methods are statistical methods to analyze the influential factors with limited experiment runs. The most important feature of the Taguchi method is the use of an orthogonal-array experimental design with a single analysis of variance. The Taguchi method is not a full factorial one that can probe the precise optimal conditions, but it provides the best tendency by performing less experimental data, and it is more practical and feasible than a full factorial approach in view of application. Furthermore, the Taguchi method can also examine the interactions between the factors to optimize the output response. Accordingly, it prevails in the optimization of industrial processes. The signal-to-noise (S/N) ratio is regarded as an evaluation of the stability of performance of an output characteristic and used to assess the quality characteristics deviating from the desired value. The algorithm for S/N ratio includes logarithmic and inverse, and there are three types of exact equation depending upon the optimization goal [47]. In general, the HV of the biofuel is an essential property to assess the substitution ratio of biofuel in coal-firing power plants. The torrefaction process can evidently improve the HV of biomass, but the pretreatment process is somehow accompanied with energy penalty. It leads to sacrifice of biomass-substituting benefit in coal-firing furnace. Alternatively, the EY indicates the percentage of the original energy of the raw biomass that is retained after torrefaction. The EY is defined as [13].

$$EY = \frac{mass of \ product \times HV \ of \ product}{mass \ of \ biomass \ feed \times HV \ of \ feed}.$$
 (2)

Accordingly, pursuing a torrefied sample with high HV entails compromising EY. To investigate the effect of the torrefaction process on the combustion characteristics of coal cofiring with biochar, the-larger-the-better (LTB) characteristics in the Taguchi method were used to screen the optimal torrefaction conditions for obtaining maximum EY and maximum yield of HV [48]. The S/N ratio for the LTB characteristics is defined as:

$$\frac{S}{N_{LB}} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] = -10\left[\frac{\overline{1}}{\overline{y^2}}\left(1+\frac{3s^2}{\overline{y^2}}\right)\right]$$
(3)

where n is the number of tests and  $y_i$  is the value of the EY or the HV. In the torrefaction process, the parameters of reaction temperature, residence time, and N<sub>2</sub> flow rate were considered.

Table 1 shows the torrefaction control factors and their levels. Three parameters, namely torrefaction temperature, residence time, and nitrogen flow rate, were selected for the torrefaction process. The control factors were assumed to be independent of each other, and each factor had three levels. Therefore, the  $L_9(3^3)$  orthogonal array was used. The original 27 experiments with different conditions were reduced to 9 experiments, as shown in Table 2. Each experiment was repeated several times and the average was taken to ensure the accuracy of the results. Table 3 presents the HV and EY of biochar; the corresponding S/N ratio can be calculated by Eq. (3).

Because the experimental design was orthogonal, separating the effect of each torrefaction factor at different levels was practical. After the S/N value of each experiment is obtained and listed in Table 3, the effect of each factor can then be determined by averaging certain experimental values. The mean S/N ratio for each level of the other parameters could be calculated: this is summarized in the S/N response table for best EY and best HV of biochar, as presented in Table 4. For example, the effect of factor A at level 1 in Table 4 can be determined by conducting the average of the S/N ratios of experiment number 1 to 3 due to having identical Torrefied temperature of 200 °C in Table 3. Similarly, the effect of factor B at level 1 in Table 4 can be determined by averaging the S/N ratios of experimental number 1, 6 and 8 with identical residence time of 60 min. Based on the analysis results, the optimal conditions could be obtained. The optimal set of operating conditions for the maximum EY was a torrefaction temperature of 200 °C, residence time of 60 min, and nitrogen flow rate of 100 sccm; moreover, the optimal set of operating conditions for the maximum HV was a torrefaction temperature of 300 °C, residence time of 120 min, and nitrogen flow rate of 50 sccm. The large difference in the S/N rates implies the importance of parameters in the torrefaction process. The torrefaction temperature appears to be the most significant variable, followed by the residence time and finally the nitrogen

Table 1

Torrefaction control factors and levels.

	Level 1	Level 2	Level 3
Temperature (°C)	200	250	300
Residence time (min)	60	90	120
N <sub>2</sub> flow rate (sccm)	50	100	150

Table 1	2
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Experimental layout using an L<sub>9</sub>(3<sup>3</sup>).

Experiment No.	Temperature (°C)	Residence time (min)	N2 flow rate (sccm)
1	200	60	50
2	200	90	100
3	200	120	150
4	250	90	50
5	250	120	100
6	250	60	150
7	300	120	50
8	300	60	100
9	300	90	150

flow rate. This conclusion is similar to the results from the article of Wilk and Magdziarz [49].

#### 3.2. Thermogravimetric analysis

The TGA is a method of thermal analysis in which the mass of a sample is measured over time as the temperature changes. Table 5 presents a summary of the physical and chemical properties, as determined through evaluation processes including proximate and ultimate analysis, and fuel parameters of Australia coal, raw Miscanthus, and torrefied Miscanthus obtained under best-EY and best-HV conditions of torrefaction. Proximate analysis, including moisture content (M), volatile matter (VM), fixed carbon (FC), and ash (ash), is the prevailing approach to determine the quality of solid fuels. The volatile matter and fixed carbon are two pivotal thermochemical parameters associated with combustion behavior and gas emission. Australia coal was observed to have remarkably low moisture (1.42%) and volatile matter (29.63%) but high fixed carbon content (50.51%). The corresponding HV of fossil coal was determined to be 6122 kcal/kg. By contrast, Miscanthus as a type of biomass had a high volatile matter content (82.21%), which may cause problems when directly combusted because it reduces energy efficiency and produces harmful emissions. The energy content of raw Miscanthus was observed to be 3827 kcal/kg, approximately 60% of the HV of fossil fuels. Regarding biochar samples under the best-EY and best-HV torrefied conditions, the moisture content in these two cases was evidently reduced to <2%. Owing to the relatively low reaction temperature and short residence time, the biochar under the best-EY torrefied condition maintained high volatile matter content (77.2%) and enhanced the fixed carbon content (8.41%) slightly compared with raw Miscanthus. The corresponding HV slightly increased to 4042 kcal/kg. Nonetheless, when the reaction temperature and resident time increased under the best-HV torrefied condition, the volatile matter decreased to 52.84%, whereas the fixed carbon content increased to 31.54%. The corresponding HV increased to 5061 kcal/kg, approaching the HV of coal. The fixed carbon increased with an increase in the reaction temperature and residence time of the process.

The differences between the elemental composition of raw and torrefied biomass under the studied conditions are shown in

 Table 3

 HV and EY of biochar with the corresponding S/N ratio.

Experiment No.	HV (cal/g)	EY (%)	S/N ratio for best HV	S/N ratio for best EY
1	4104.4	94.41	72.26	-0.499
2	3978.3	91.29	71.99	-0.792
3	4144	95.93	72.35	-0.361
4	4268	85.83	72.60	-1.327
5	4270	87.52	72.61	-1.158
6	4271.2	87.93	72.61	-1.117
7	5061.6	69.74	74.09	-3.13
8	4947.9	73.16	73.89	-2.715
9	4728.4	69.15	73.49	-3.204

Table 4					
S/N resp	onse tabl	e for b	oest EY a	nd best	HV.

Table 4

	For best EY			For best HV		
	L1	L2	L3	L1	L2	L3
<ul> <li>(A) Temperature (°C)</li> <li>(B) Residence time (min)</li> <li>(C) N<sub>2</sub> flow rate (sccm)</li> </ul>	-0.551 -1.444 -1.652	-1.2 -1.774 -1.554	-3.016 -1.55 -1.561	72.2 72.92 72.99	72.61 72.7 72.83	73.82 73.01 72.82

5												
	Proxima	ate analysis (	wt. %)		Ultimate	Ultimate analysis (wt. %)		Atomic ratio		HHV		
	М	VM	FC	Ash	С	Н	0	Ν	S	H/C	O/C	(kcal/kg)
Australia coal	1.42	29.63	50.51	18.44	73.30	4.17	5.25	1.14	0.52	0.68	0.05	6122
Raw Miscanthus	4.91	82.21	5.85	7.03	44.85	6.55	48.06	0.04	_	1.75	0.80	3827
Biochar-best EY	0.96	77.20	8.41	13.43	45.99	6.15	47.64	0.22	_	1.62	0.78	4042
Biochar-best HV	1.08	52.84	31.54	14.54	58.05	3.62	38.00	0.33	_	0.74	0.49	5061

 Table 5

 Physical and chemical properties of Australia coal, raw Miscanthus, and biochar with various torrefied conditions.

Table 5. These differences are explained by the O/C and H/C ratios of the studied samples. Typically, the O/C and H/C ratios of Australia coal are smaller than those of raw *Miscanthus*. The O/C and H/C ratios of biochar with best-EY are close to those of raw *Miscanthus*, whereas the ratios of biochar with best-HV are similar to those of Australia coal.

The increase in the reaction temperature and residence time of torrefaction shifts the torrefied biomass away from the raw biomass toward coal because of the increased carbon content and calorific value. Torrefaction deteriorates the hemicellulose content ( $200-275 \,^{\circ}$ C) and partial cellulose content ( $275-350 \,^{\circ}$ C), removing OH radicals from the torrefied sample and resulting in the reduction of O and H atoms.

The pyrolysis profiles for the fuels studied are shown in Fig. 3. which illustrates the mass loss of the fuel samples with temperature and their corresponding time derivative of the mass loss (DTG). As expected, two main mass losses were observed for all fuels. The first mass loss at below 140 °C was derived from moisture evaporation, followed by a larger mass loss observed within the 200-660 °C range because of the volatile matter being released. The remaining residue was char (Fig. 3a). When the surrounding temperature reached 1000 °C, the residual mass rate of Australia coal was 70.24%, and the residual mass rates of the biochar with the best-EY and best-HV were 28.24% and 47.81%, respectively (Fig. 3a). A higher total mass loss was observed for the fuels with higher volatile content: the biochar with the best-EY torrefaction condition. However, the values of the residual mass rate for the biocharblended coal samples were between those of Australia coal and biochar with specific torrefied conditions. The differences in their pyrolysis behavior could be obtained from the DTG curves (Fig. 3b). The curve for Australia coal presented a single peak with a flat tailing section at higher temperatures. The curves for the studied samples with the best-EY and best-HV torrefaction conditions demonstrated a single peak with a shoulder at higher temperatures. The difference in maximum mass loss between the two torrefied biochar samples was because of thermal degradation of their basic organic components such as hemicellulose, cellulose, and lignin. Mass loss occurs because of the release of carbon dioxide, methane, and water. The shoulder at higher temperatures was attributed to the decomposition of cellulose, and the main peak at lower temperatures was due to hemicellulose. Lignin decomposes very slowly over a broad temperature range, resulting in an unresolved band with a flat tailing section at higher temperatures. In addition, peak height and peak temperature (T<sub>max</sub>) are considered as a measure of the reactivity of the fuel.  $T_{\text{max}}$  is the temperature at which the rate of mass loss is maximum. Therefore, fuels with the lowest peak temperatures are considered most reactive. The peak temperatures of the studied fuels were 467 °C for Australia coal, 335 °C for the biochar with the best-EY torrefaction condition, and 341 °C for the biochar with the best-HV torrefaction condition. Australia coal was determined to be the least reactive of the fuels. whereas the biochar with best-EY torrefaction was the most reactive. In particular, Australia coal was observed to have a high carbon content and the lowest volatile contents, and the inception of maximum mass loss shifted to the high-temperature zone. Regarding the mass-loss rate of the coal-blended biochar, the curve of the weight loss rate had two humps, linearly superposing the mass-loss rate of coal and torrefied biochar. This indicates that no chemical reaction occurred between the coal and torrefied biochar when the blended fuel was subjected to pyrolysis.

Fig. 4 illustrates the TG and DTG profiles for the studied fuels under air atmospheres. The major mass loss of Australia coal was observed in the temperature range of 320-900 °C, and the maximum mass loss occurred at 594 °C, which is higher than those



Fig. 3. Plot of (a) mass loss with temperature and (b) time derivative of mass loss DTG results from pyrolysis-TGA analysis of the studied fuels, Australia coal, biochar obtained under the best-HV and best-EY torrefation, and 50% biochar–50% coal under nitrogen atmosphere.



**Fig. 4.** TGA and DTG curves of (a) Australia coal, (b) biochar with best-EY torrefaction, (c) biochar with best-HV torrefaction, (d) 50% coal–50% biochar with best-EY torrefaction, and (e) 50% coal–50% biochar with best-HV torrefaction in ambient air.

of the other studied fuels. This was caused by the high carbon content of Australia coal, necessitating a higher surrounding temperature for carbon combustion. When the surrounding temperature reached 1000 °C, the oxidation process of Australia coal became easy, and the residual mass rate was 19.44% (Fig. 4a). According to the TGA curve of the biochar with the best-EY torrefaction condition, the main mass losses occurred in the temperature ranges of 220-360 °C and 360-500 °C (Fig. 4b). The peak temperatures in the two temperature ranges were 303 and 386 °C. When the surrounding temperature reached 360 °C, the residual mass rate was 41.42%. These results suggest that more than half of the fuel was released as volatile gas. The combustion process was accomplished at 500 °C and the corresponding residual mass rate was 13.54%, which is lower than that of Australia coal. Furthermore, according to the TGA curve of the biochar with best-HV torrefaction condition, the main mass losses occurred in the temperature ranges of 240–320 and 320–560 °C (Fig. 4c). The peak temperatures in the two temperature ranges were 283 and 376 °C. These temperature ranges are higher in the biochar with the best-HV torrefaction condition than in that with the best-EY torrefaction condition, and this is because the increase in torrefaction temperature leads to an increase in the carbon content of torrefied fuels, resulting in the main mass loss presenting at higher temperatures. Fig. 4d and e demonstrate the TGA and DTG curves of coal blended with biochar with various torrefaction parameters.

To compare the combustion characteristics of the studied fuels, their ignition temperature ( $T_i$ ), burnout temperature ( $T_b$ ), and combustion characteristic index (S) were calculated, as shown in Table 6. The ignition temperature of Australia coal was the highest (446.8 °C), and that of the biochar with the best-EY torrefaction condition was the lowest (265.5 °C). Similarly, the burnout

#### Table 6

Ignition temperature, burnout temperature, and combustion characteristic index for five studied fuels.

Fuel	T <sub>i</sub> (°C)	$T_b (^{\circ}C)$	S x 10 <sup>7</sup>
Coal	446.8	887.3	0.871
Biochar (best EY)	265.5	488.8	49.7
Biochar (best HV)	272.9	504.8	25.9
50% Coal+50% Biochar (best EY)	272.7	639.7	6.8
50% Coal+50% Biochar (best HV)	317.2	644.9	3.63

temperature of Australia coal was the highest (887.3 °C), and that of the biochar with the best-EY torrefaction condition was the lowest (488.8 °C). The ignition temperature and burnout temperature of coal blended with biochar was within the temperature ranges of coal and the corresponding biochar. A higher S value implies higher reactivity. This is because fuels with high S values are prone to release volatile gas and ignite at lower temperatures, thus affording them lower ignition and burnout temperatures and a higher massloss rate. This results in good combustion characteristics.

#### 3.3. Single pellet combustion

To understand the combustion behavior of solid fuels, the three studied fuels, namely Australia coal, 50% coal-50% biochar with the best-EY torrefaction condition, and 50% coal-50% biochar with the best-HV torrefaction condition, were selected for investigation. Fig. 5 shows the combustion process of the three selected solid fuels at a surrounding temperature of 600 °C. The combustion process of a solid fuel involves several stages including heating, drying, pyrolysis/devolatilization, volatile burning, char burning, and ash formation. Each stage has the corresponding characteristic time, and the fuel nature and composition are essential to combustion behavior. Nevertheless, at a high surrounding temperature, the release rate of volatile matter is increased. As shown in Fig. 5, the biochar with the best-EY torrefaction condition was easy to ignite and had the longest flame length because of the higher volatile content. By contrast, the combustion behavior of the biochar with the best-HV torrefaction condition was similar to that of Australia coal because of further carbonization during pretreatment. Fig. 6 presents the typical mass-loss history and flue gas emission of a single pellet of 50% coal-50% biochar with the best-EY torrefaction condition at a surrounding temperature of 600 °C. The process of gas combustion was induced after 9 s (Fig. 6a). However, the diffuse flames heated the fuel pellet and released volatile matter for gas combustion by inducing the pyrolysis process. The main mass loss of the fuel pellet occurred at the volatile combustion stage and ended after approximately 112s because of the completion of devolatilization. Thereafter, the surrounding oxygen diffused to the surface of the fuel pellet, triggering a surface reaction of the solid fuel. This stage, called char combustion, is time-consuming, and the reaction rate depends on the diffusivity of oxygen molecules.



Fig. 5. Combustion process of three selected solid fuels at a surrounding temperature of 600 °C...

However, the diffusivity of oxygen molecules is almost constant at stable surrounding temperatures. The results demonstrate that the mass loss of char combustion constantly declines until ash exists (approximately 883 s in this study).

Fig. 6b illustrates the detected gas emission in flue gas at a constant sampling rate (1 Hz). In the synchronizing time scale, the results showed a reduction in oxygen and an increase in carbon monoxide before the gas phase ignition. In addition to devolatilization, inception of partial oxidation  $(2C(s)+O_2 \rightarrow 2CO)$  was observed. Oxygen diffused to the surface of the pellet and induced the heterogeneous reaction for conversion to CO. After 9 s, gas combustion was induced, and  $O_2$  and CO evidently were reduced.

However, the amount of CO was increased considerably during volatile combustion. This process can be explained through the classical two-film model of carbon combustion. The volatile matter is quintessential gas to support gas reaction and produce products such as  $H_2O$  and  $CO_2$ . However,  $CO_2$  inwardly diffuses to the surface of the fuel pellet and heterogeneously induces the Boudouard reaction ( $C(s) + CO_2 \rightarrow 2CO$ ) to yield CO. CO diffuses outward and supports the gas reaction in terms of  $O_2$  consumption and  $CO_2$  production. Awaiting the completion of volatile combustion (approximately 112 s), the homogeneous reaction ceases because of the termination of devolatilization; however, the heterogeneous reaction remains dominant via partial oxidation ( $2C(s) + O_2 \rightarrow$ 



Fig. 6. (a) Mass-loss history and (b) flue-gas emission of single pellet of 50% coal-50% biochar with best-EY torrefaction at a surrounding temperature of 600 °C.

2CO) and the Boudouard reaction (C(s) + CO<sub>2</sub>  $\rightarrow$  2CO). Accordingly, the CO<sub>2</sub> concentration is rarely detected, but the CO concentration is abundant. Until the timeout of the char combustion, CO concentration sharply decreases and O<sub>2</sub> concentration recedes back to 21%. Regarding the NO<sub>x</sub> emission, the amount of NO<sub>x</sub> was increased considerably during volatile combustion but reduced significantly during char combustion. The peak value of NO<sub>x</sub> emission is approximate 180 ppm at 15% O<sub>2</sub> in the stage of volatile burning, but the averaged value of NO<sub>x</sub> emission is less than 10 ppm at 15% O<sub>2</sub> in the stage of char combustion. In general, NO<sub>x</sub> emission is certainly low.

Regarding the effect of surrounding temperature on the combustion behavior of solid fuels, single pellet combustion was conducted at two surrounding temperatures, 600 and 800 °C. The mass-loss history of the three studied single pellets under various surrounding temperatures is illustrated in Fig. 7. The mass-loss rate under an identical surrounding temperature for the 50% coal–50% biochar blend with the best-EY torrefaction condition was greater than that for the 50% coal–50% biochar blend with the best-HV torrefaction condition, and in turn greater than that of coal. An increase in the surrounding temperature was accompanied by an increase in the mass-loss rate of the studied fuels, especially during volatile combustion. The higher surrounding temperature was assumed to accelerate the thermal decomposition and devolatilization process of the solid fuel. Table 7 shows the characteristic time and ash content of the three studied fuels (A: Australia coal, B: 50% coal-50% biochar with the best-EY torrefaction condition, C: 50% coal-50% biochar with the best-HV torrefaction condition) at surrounding temperatures of 600 and 800 °C. The order of ignition delay  $(t_i)$  in the studied fuels was A > C > B, that for burnout time of gas combustion ( $t_{flame}$ ) was B > C > A, and that for burnout time of char combustion  $(t_{char})$  was A > C > B. In summary, the order of total combustion time  $(t_{total})$  was A > C > B. These results thus indicate that the fuel nature impacts the combustion behavior of solid fuels. Specifically, Australia coal had a high content of fixed carbon, resulting in longer char combustion and shorter gas combustion. By contrast, the biochar with the best-EY torrefaction condition possessed high volatile matter and low fixed carbon, resulting in short char combustion and longer gas combustion. According to adiabatic thermal explosion theory, the ignition delay of gas reaction can be expressed as [50,51].

$$t_{i} = \frac{c_{\nu,g} \left( T_{0}^{2} / T_{a} \right)}{q_{c} Y_{F,0} B \cdot exp(-T_{a} / T_{0})}$$
(4)

where  $c_{v,g}$  is the heat capacity of the surrounding gas,  $T_0$  is the



Fig. 7. Mass-loss history of three studied single pellets of under the surrounding temperatures of 600 and 800 °C.

## Table 7 Characteristic time and ash content of three studied fuels at surrounding temperatures of 600 °C and 800 °C.

T (°C)	Fuel	$t_i(s)$	t <sub>flame</sub> (s)	$t_{char}\left(s ight)$	t <sub>total</sub> (s)	Ash (wt. %)
600	A	30	73	1489	1592	20.97
	В	9	103	721	833	15.50
	С	24	88	1087	1199	18.84
800	Α	4	70	1255	1329	18.67
	В	1	82	658	741	15.29
	С	2	80	1024	1106	18.01

initial temperature,  $q_c$  is the heat release of volatile combustion per unit mass,  $Y_{F,0}$  is the initial mass fraction of volatile matter, and  $B \cdot exp(-T_a/T_0)$  is the reactivity of volatile matter and oxidizer. Table 5 shows that a higher amount of volatile matter in the studied solid fuels could shorten the ignition time. Therefore, the ash content in the coal blended with biochar could be reduced, thereby lowering the cost of ash removal and furnace maintaining.

#### 4. Conclusions

The Taguchi method was used to screen the optimal pretreatment conditions for the best EY and largest HV. The produced biochar was blended with Australia coal, and the blended fuels were subjected to TGA to investigate their combustion features. The studied fuels were pelletized as tablets and dropped into a singlepellet furnace to observe the combustion process and gas emission of the single pellet at various surrounding temperatures. The following results were obtained:

- 1. The Taguchi method was used to probe the optimal set of torrefaction condition. The influence extent order of control parameter is torrefied temperature (high), residence time (intermediate) and nitrogen flow rate (low). The optimal set of torrefaction parameters for the fuel pretreatment of miscanthus can be found by examining the S/N ratios. Consequently, the optimal set of torrefaction condition for the maximum EY is a torrefaction temperature of 200 °C, residence time of 60 min, and nitrogen flow rate of 100 sccm. Furthermore, the optimal set of operating condition for the maximum HV is a torrefaction temperature of 300 °C, residence time of 120 min, and nitrogen flow rate of 50 sccm.
- 2. During thermal pyrolysis, the biochar engaged in the thermal degradation of hemicellulose and cellulose content. Australia coal was observed to have a high carbon content; thus, the main mass loss of coal tended to occur in a higher temperature range. In addition, observing the pyrolysis features of the blended fuels revealed high superposition of coal and the biochar with specific torrefaction conditions.
- 3. On the basis of the calculated S index, biochar with best-EY torrefied condition had a relatively low ignition temperature and a low burnout temperature, resulting in a higher S index value. In the contrary, biochar with best-HV torrefied condition had a relatively high ignition temperature and burnout temperature, resulting in a smaller S index value. It points out that different optimization standards lead to distinct combustion characteristics.
- 4. To compare the characteristic time of the three studied fuels at surrounding temperatures of 600 °C and 800 °C, results reveal that the fuel nature impacts the combustion behavior of solid fuels. The order of ignition delay time in the studied fuels was A > C > B, that for burnout time of gas combustion was B > C > A, and that for burnout time of char combustion was A > C > B. In summary, the order of total combustion time was A > C > B.

5. A single pellet with high volatile matter was easily ignited; however, the volatile combustion process was longer. By contrast, a pellet with high fixed carbon content had longlasting char combustion. In general, when the surrounding temperature increases, the process of thermal pyrolysis and devolatilization can be accelerated.

Undoubtedly, biochar cofiring technology applied in thermal power plant can reduce the energy dependence of fossil fuel and increase fuel diversity for coal-fired power system. This study demonstrated the concept of torrefied *Miscanthus* biochar cofired with coal, ushering a feasible and reliable approach to utilize indigenous biomass feedstock and reduce the fossil fuel consumption in power generation system simultaneously.

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