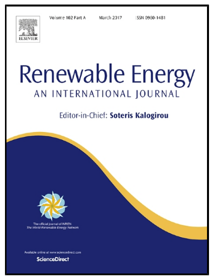
Accepted Manuscript



Co-firing combustion characteristics of different ages of *bambusa balcooa* relative to a high ash coal

M.O. Makwarela, S.O. Bada, R.M.S. Falcon

PII:	S0960-1481(16)31118-1
DOI:	10.1016/j.renene.2016.12.059
Reference:	RENE 8396
To appear in:	*Renewable Energy*
Received Date:	24 May 2016
Revised Date:	20 December 2016
Accepted Date:	22 December 2016

Please cite this article as: M.O. Makwarela, S.O. Bada, R.M.S. Falcon, Co-firing combustion characteristics of different ages of *bambusa balcooa* relative to a high ash coal, *Renewable Energy* (2016), doi: 10.1016/j.renene.2016.12.059

- Combustion of different ages of bamboo, coal and their blends was studied using TGA.
- Bamboo properties were enhanced by thermal treatment
- Raw bamboo has the highest fuel reactivity and lowest ignition temperature
- DTG curves indicate that Bamboo-biochar improves the reactivity of blends
- All samples tested exhibit lower burnout temperatures compared to coal

CO-FIRING COMBUSTION CHARACTERISTICS OF DIFFERENT AGES OF *BAMBUSA BALCOOA* RELATIVE TO A HIGH ASH COAL

M.O. Makwarela[1&2], S.O. Bada[1&2*] and R.M.S. Falcon[1]

[1]*School of Chemical and Metallurgical Engineering, Faculty of Engineering and the Built Environment, University of the Witwatersrand, P/Bag X3 Wits 2050 Johannesburg, South Africa.*

[2]*Department of Mineral Processing & Phyrometallurgy Division, Mintek, Johannesburg 2125, South Africa.*

Abstract

Bambusa balcooa samples of 1, 3 and 4 years old were subjected to torrefaction at 250 °C and 280 °C, and low temperature carbonization at 350 °C and 400 °C to establish their combustion, co-combustion and physicochemical properties. The combustibility of these raw and thermally treated bamboo materials was studied using thermogravimetric analysis (TGA).

The nitrogen content of the raw bamboo samples decreased with the plant's age and there was no correlation between the volatile matter content of the bamboo and the age of the samples. The calorific values (CV) for the raw bamboo samples ranging from 17 MJ/kg to 18 MJ/kg, while the torrefied and carbonized samples exhibited CVs ranging from 25 MJ/kg to 28 MJ/kg and 28 MJ/kg to 30 MJ/kg, respectively. The torrefied 4 year old sample has the highest mass and energy yield, whereas the carbonized 3 year old had the highest values. Both the raw and thermally treated bamboo had higher reactivities and lower ignition temperatures than the coal. The carbonized 4 year old bamboo is found to be more compatible to coal in terms of its combustion characteristic. Therefore, it's likely to be the preferred alternative source of fuel for co-firing with coal.

Keywords: Bamboo, Carbonisation, Combustion, Torrefaction, Reactivity.

Corresponding author: (Samson.Bada@wits.ac.za)

1. Introduction

South Africa is economically vulnerable to climate change because its economy is powered by electricity generated from coal fired power stations. There is a need to reduce the over reliance on fossil fuel energy not only because of greenhouse gas emissions but also to ensure energy security. Biomass "bamboo" has received significant attention with a positive prospect as a future energy source due to its fast growth rate, considerable strength and mass, low ash content and its ability to attain full maturity within five years, and as a carbon neutral renewable resource [1-4]. Studies have shown that biomass, along with solid waste can be converted into energy either by combustion, liquefaction or through gasification [5, 6]. In addition, recent investigations have also shown that biomass can be co-fired with coal in existing power plant with very little modifications [5, 7]. Co-firing biomass with coal shows a potential for reducing CO_2 and NO_x emission among other benefits. Even though bamboo has been used as an alternative fuel source, it must be noted that, like other woody biomass materials, this too has its drawbacks in its natural state. This includes poor physicochemical properties, high volatile matter contents and low energy densities.

Previous research has shown that these drawbacks can be addressed by thermal pre-treatment of the biomass by two mild pyrolysis processes, i.e. torrefaction and low temperature carbonization. [2, 7, 8-13]. The application of these techniques has a major influence on the chemical and physical properties of raw biomass. During these pre-treatment processes, biomass molecules are restructured, leading to losses in the hydrogen and oxygen content of biomass along with the decomposition of its cellulose and lignin functional groups. Ultimately, this biomass is converted into a densified solid with improved grindability and non-polar unsaturated products [12, 14, 15]. Bergman *et al* [9] stated that pre-treated biomass has energy densities similar to that of coal which could render it more suitable for co-firing. A study conducted by Rousset *et al* [2] found that, at torrefaction temperatures between 250 °C and 280 °C, hemicellulose and cellulose decomposes, yielding a biomass char that possesses a higher carbon content. Park *et al* [12] investigated the effect of thermal treatment on various biomasses and found that at carbonisation temperatures between 400 °C and 500 °C, the resulting char product has improved fuel properties such as higher fixed carbon, lower volatile matter and increased calorific value.

The species of bamboo utilized in this investigation is *Bambusa balcooa*, which was acquired from the Western Cape region of South Africa. *Bambusa balcooa* is known as a clumping bamboo and occurs as a naturalized species of bamboo in South Africa. It has a very thick wall culms, height within 15-20 m, and an internode of about 20-45 cm. Altogether, these are characteristic of species with a high yield biomass (tonne/ hectare/ yr). Hence, according to the report by Poppens et al [16] a well managed bamboo plantation may yield over 30 (t/ha/yr) dry matter biomass depending on the species. The use of bamboo for re-greening and rehabilitation of abandoned mined sites is due to its physicochemical and biological properties. The concept of bamboo cultivation can provide clean, efficient and economical alternative fuel source with sustainable community benefits. If grown successfully, a large number of abandoned mined sites such as asbestos, gold tailing dumps and coal mines, could be rehabilitated and promote job creation.

A detailed comparison of the physicochemical properties of some species of bamboo at different ages was conducted by Scurlock *et al* [17]. This author found that there was no correlation between the volatile matter, ash content, fixed carbon content and the age of the bamboo species utilized. All samples, regardless of their ages were found to have similar higher heating values, total carbon and hydrogen content. However, in this study, the characteristic combustion and co-combustion behavioural characteristics of bamboo "*Bambusa balcooa*" of different ages (1, 3 and 4) year were found to differ. The main objectives of this study were to quantify the differences in properties and behavioural characteristics between raw bamboo of different ages and thermally treated bamboo, as well as to compare their combustion features to coal along with their co-firing potential with coal.

The combustibility of these raw and thermally treated bamboo species, along with coal were investigated using thermogravimetric analysis. During the combustion and the co-combustion tests, the parameters measured included initiation devolatilisation temperature (IT_{VM}), peak temperature (PT) and burnout temperature (BT) based on the burning profiles generated from the differential thermogravimetric analysis (DTG).

2. Experimental

2.1. Materials

Samples of "*Bambusa balcooa*" of different ages and high ash coal were utilized in this investigation. The three different ages of bamboo were 1 year, 3 years and 4 years old, all sourced from the Western Cape, South Africa. These were used as the raw biomass materials. The stem, known as the culm, was blended from the top, middle and bottom, as well as the underground root, also known as rhizomes. The bamboo samples were then cut into blocks of approximately 25 X 25 X 10 mm in size to generate feed for the thermal treatment investigation. The coal used for the co-firing was sourced from the Free State, South Africa. This high ash coal was pulverized to 100% passing a 212 μm screen in a pulveriser for preparation and use in the tests, both alone and with bamboo samples.

2.2. Thermal treatment

The thermal treatment processes conducted on the raw *Bambusa balcooa* utilized in this investigation were known as torrefaction and low temperature carbonization. Torrefaction is a slight pyrolysis process carried out within the range of 200 ^{0}C to 300 ^{0}C under an inert environment, with the aim to produce a densified and carbon rich solid. The raw 1, 3 and 4 years bamboo were torrefied at 250 ^{0}C and 280 ^{0}C. The raw samples were further subjected to thermal treatment at 350 ^{0}C and 380 ^{0}C using low temperature carbonization process. The process was conducted at a higher temperature compared to torrefaction, and in an oxygen free environment. The thermal processes were carried out in a gas tight laboratory scale heated electric muffle furnace embedded with a glass tube reactor at a constant heating rate of 3 0C/min under argon gas at 0.5 l/min. Approximately 600 g of the respective raw bamboo samples was charged into the glass tube reactor and heated to the set temperature, and held for 40 minutes. After the treatment time, the samples were removed and covered with a container to prevent oxidation, and thereafter milled to -212 μm size fraction. Several blends of coal and bamboo were then prepared from the raw samples, torrefied (T250 ^{0}C and T280 ^{0}C) and low-carbonized (C350 ^{0}C and C 380 ^{0}C), and adding at 10%, 30%, 50% and 75% of coal by weight for the investigation.

2.3. Thermo-gravimetric analysis

The combustion behaviour of the raw and the thermally treated bamboo samples as well as when blended with coal in different proportions (25, 50 and 75% bamboo, the difference being coal), was studied using thermogravimetric analysis. The combustion tests were conducted in a Leco 701 thermogravimetric analyser (TGA), under an oxidising atmosphere using air. Approximately 100 mg of each sample (100% passing a 212 μm screen), of raw bamboo biomass, coal, pre-treated bamboo and all the different bamboo/coal blends, was used for the experiment. The differential thermogravimetric (DTG) curves, i.e. combustion profiles were obtained at a constant heating rate of 10°C/min, from 25°C to 850°C and held until there is constancy in weight loss. The differential thermogravimetric curves (DTG) indicating the rate of weight loss (%/min) with increasing temperature were used to directly evaluate the combustion properties including initiation devolatilisation temperature (IT_{VM}), peak temperature (PT) and burnout temperature (BT). The reactivity (R_m) of the combusting material was quantified using the same expression as that used by Bada *et al* [3] and is presented in Equation 1 below:

$$R_m = \frac{100 \times DTG_{max}}{PT} \quad (1)$$

Where DTG_{max} is the maximum weight loss rate (%/min) and PT is the corresponding peak temperature.

2.4. Fuel characterization, mass and energy yield

The proximate and the calorific value of the coal, raw and thermally treated bamboo samples were evaluated. The proximate analysis was conducted in accordance with the ASTM D-5142, utilizing approximately 1 g of each sample (coal and bamboo sample) in a TGA 701 Leco instrument. The calorific value was determined using a Leco AC500 bomb calorimeter in accordance with ASTM D5865-04. The system uses an electronic thermometer with an accuracy of 0.0001 ^{0}C to measure the temperature every six seconds, with the results obtained within 4.5 to 7.5 minutes. The raw bamboo samples were further characterized for their elemental constituents using a LECO CHN 628 with add on 628 S module, in accordance with the ASTM D3176-89.

The impact of the thermal treatment on mass and energy yield was also evaluated. The mass yield (η_M) and energy yield (η_E) obtained at different pre-treatment temperature were calculated using Equations 2 and 3, reported by Bada *et al* [3] and Park *et al* [11].

$$\eta_M = \left(\frac{M_t}{M_o} \right) \text{ dry basis} \quad (2)$$

$$\eta_E = \eta_M \left(\frac{GCV_t}{GCV_u} \right) \text{ dry basis} \quad (3)$$

Where M_0 and M_t are the initial biomass mass and final mass of the biomass after thermal treatment, respectively. The GCV_o and GCV_t are the initial biomass gross calorific values and final biomass gross calorific values after heat treated, respectively.

3. Results and discussions

3.1. Fuel characteristics of coal and bamboo samples.

The results of the ultimate and the proximate analyses for all the samples tested are presented in Table 1. The proximate and the ultimate analysis of the raw bamboo samples showed that the three raw fuels have a low ash content and an insignificant amount of sulphur. The nitrogen content in the raw bamboo samples was also low, suggesting that NO_x emissions might be minimized during the co-combustion of the fuel compared with coal as the percentage ratio of the biomass increases in the blend. These characteristics are seen in most commercial co-fired power plant and are essential for clean coal combustion conditions [5,18]. There was little difference observed from the proximate results of the three raw bamboo samples in terms of moisture content, fixed carbon and volatile matter, these ranged from 7.01 to 8.09 %, 18.03 to 19.25 % and 79.20 to 81.04%, respectively. The nitrogen content of the bamboo samples decreased with the age of the harvested plant, while there was no correlation between the total carbon content of the bamboo and the age of the samples. Similarly, there was no correlation between volatile matter and the age of the samples.

After torrefaction and low temperature carbonization treatment the fixed carbon and calorific values of all samples were observed to increase (see Table 1) while moisture and volatile matter content were reduced. Also in Table 1 fixed carbon for the 4 year old bamboo is shown to be more than triple its content from 19.25% to 63.64% after torrefaction at 280°C, and that increased further to 76.6% after treatment in the low carbonization temperature of 400°C. A similar result was observed in a study by Park et al [12] who found the fixed carbon content of a woody biomass to be more than tripled after torrefaction at 275°C. In terms of the sample's age and the effect of heat treatment, the older bamboo is observed to have a higher fixed carbon content at all treatment temperatures, with the exception of torrefaction at 280°C, where a slightly higher fixed carbon content was observed for a 3 year old bamboo sample. In conclusion, it has been shown that the 4 year old bamboo carbonized at 400°C has the highest fixed carbon content of all the samples heat treated.

Table 1: Fuel properties of raw and thermally treated bamboo.

The volatile matter content of the bamboo samples decreased with an increase in treatment temperature, irrespective of the age of the bamboo, as seen in Table 1 above. The volatile matter contents of 3 year and 4 year old bamboo samples decreased to about half when torrefied at 250°C, i.e. from 79% to 39% and 79% to 37% on a dry basis, respectively. The degree to which the bamboo samples tested in this study devolatilized was found to be more pronounced than samples reported by other authors using biomass materials such as *Bambusa vulgaris*, pine chips, logging residue chips, willow, eucalyptus and woody biomass [2, 11-13]. The ash content was also seen to increase as the treatment temperature increases. The raw and the thermally treated 1 year old bamboo had the lowest ash content (0.93-3.65%) at all treatment temperatures.

Table 2: Mass and Energy yield of thermally treated bamboo

The calorific value (CV) of the raw bamboo samples was found to be between 17.10 and 18.53 MJ/kg as shown in Table 2 above. Bada *et al* [3] reported similar results on the raw *Bambusa multiplex*. The CV of all raw bamboo samples (1, 3 and 4 year old) increased by at least 40% after being torrefied at 250°C and increased even further at higher thermal treatment temperatures. The CV value of the 4 year old bamboo increased from 17.63 MJ/kg to 26.38 MJ/kg and 30.24 MJ/kg after torrefied at 280°C and carbonized at 400°C, respectively. Similar results were reported by Phanphanich and Mani [11], Ibrahim *et al* [12] and Bada *et al* [3] on logging residue chips, Eucalyptus and *Bambusa multiplex*, respectively.

In terms of mass yields, the torrefied products in this study were found to have the highest mass yields of 51%, 40% and 39% for the 4, 3 and 1 year old bamboo samples relative to the carbonized products which exhibited lower mass yields as seen in Table 2. Ibrahim *et al* [13] obtained a higher mass yield of 68.76% on willow torrefied at 270 °C for 30 min. The lower mass yields noted in this study might be as a result of the impact of torrefaction (280 °C) on bamboo, which is similar to the results obtained by Rodrigues and Rousset [19]. In the case of carbonization, similar mass yield (32.8%) obtained by Park *et al* [12] on woody biomass at 350°C for 30 min was obtained. The energy yield was found to be consistently higher at torrefaction temperatures for all bamboo samples. The 4 year old bamboo sample had the highest energy yield of 74% and 68% after torrefied treatment at 250°C and 280°C, compared to other samples as shown in Table 2 above.

3.2. Combustion of coal, raw and thermally treated bamboo

Figure 1 below shows that the combustion of the raw bamboo samples occurs in stages. The first stage of the combustion profiles represents the initial weight loss which occurred as a result of the moisture being driven off (25 °C to 140 °C), this was seen in all the thermographs (Figures 1-8). After the moisture loss, a downward trend or negative deflection (weight gain) was observed due to the oxidation of the organic matter within the samples. As the curve rises above the zero line of the x-axis, the devolatilization stage begun and this point is known as the volatile matter initiation temperature (IT_{vm}). The IT_{vm} occurred within the temperature of (142°C to 200 °C) for the bamboo samples and above 230 °C for the coal, thereafter, complete char combustion above 400 °C for all samples (Figures 1-8). This is similar to the three distinctive stages observed by Bada *et al* [3] from the combustion of *Bambusa multiplex*. The combustion of the raw bamboo is rapid and occurs at lower temperatures when compared to that of coal. This is evident from the peak and burnout temperatures range of 224-250 °C and 460-475 °C for the three different bamboo ages in Figure 1. The coal is shown to have a peak combustion temperature of 406 °C and a burnout temperature of at least 90 °C higher than that of the raw bamboo. This difference is expected because coal has a higher fixed carbon content than all the raw bamboo samples.

Figure 1: DTG curves for coal and all the raw bamboo samples.

It may be noted in Figure 2a below that the maximum weight loss rate (%/min), i.e. DTG_{max}, of the raw 1 year old bamboo decreased by almost 60% after torrefied at 250 °C and it decreased even further at higher treatment temperatures as shown in the same Figure. The 3 and 4 year old bamboo samples also show similar trends as seen in Figure 2b and 2c. The decrease in volatile matter contents of the thermally treated samples and the consequent increase in their fixed carbon contents is considered to be responsible for the changes in their burning profiles, all of which brings the combustion profiles of the bamboo samples closer to that of coal.

The respective combustion profiles of the 1 year old bamboo samples treated at different temperatures show two distinctive peaks. The same number of peaks is noted for the 3 year old samples, although the low carbonized bamboo at 400 °C was less pronounced. These results are identical to the observation made by Park et al [12] on the combustion profile of low temperature carbonized woody biomass. The PT and BT of the torrefied and carbonized bamboo samples are also observed to increase as the thermal treatment temperature increases. Bada et al [3] reported a similar observation on *Bambusa multiplex*. The 4 year old low carbonized bamboo at 400 °C has only one peak with a similar combustion profile to coal. This sample also has the highest burnout temperature compared to other bamboo samples, signifying a coal like nature. The major difference to coal, however, is that all bamboo samples devolatilise and ignite at lower temperatures compared to coal. In general, it would appear that the burnout temperatures of the raw and the thermally treated bamboo samples are influenced by the increase in fixed carbon content.

Figure 2: DTG curves for thermally treated bamboo and coal (a:1yr; b:3yr and c:4yr)

According to both Table 2 and Figure 2 above, the reactivity of the raw bamboo samples may be seen to be 4 times faster than that of coal. This is considered to be related to the higher volatile matter content, lower fixed carbon and the lower mass density of the raw bamboo relative to coal. This finding is in agreement with that achieved by Kastanaki and Vamvuka [20] when studying the reactivity of coal, olive and kernel char. The reactivities of the thermally treated bamboo samples T250, T280, C350 and C400 were also found to be higher than that of coal, but were lower than that of the raw bamboo sample. In summary, raw bamboo samples ignite easily at low temperatures and are more reactive than the thermally treated bamboo samples and the coal used in this study. In terms of reactivity, 1 year old raw bamboo is the fastest burning fuel than all other fuels tested.

3.3. Co-combustion profiles of raw bamboo and coal

Raw bamboo (1, 3 and 4 year old) and coal were co-combusted in a TGA furnace. The blends studied were composed as follows: (i) 75% raw bamboo + 25% coal, (ii) 50% raw bamboo + 50% coal and (iii) 25% raw bamboo + 75% coal, for each respective age of the bamboo. The co-combustion profiles of 1 year, 3 year and 4 year old raw bamboo with coal are presented in Figure 3a, b and c, respectively.

Figure 3: DTG curves of co-combustion of raw bamboo/coal (3a:1yr; 3b:3yr and 3c:4yr)

It may be noted that for the blends of raw bamboo (1, 3 and 4 year old) and coal, the maximum rate of mass loss (DTG_{max}) decreased significantly with the decrease in the proportional weight percentage of bamboo in the bamboo/coal blend (Figure 3a, b and c). This is considered to be due to the decrease in volatile matter and low density materials in the blend. In contrast, as the weight percentage of the coal in the blend increases, the DTG profiles were seen to move away from that of the raw bamboo and closer to the coal's profile. A blend containing (25% raw bamboo + 75% coal) was found to have the highest burnout temperatures compared to other blends seen in Figures 3a, 3b and 3c. The blends containing (75% raw bamboo + 25% coal) may be seen to have similar burning profiles to that of the raw bamboo combusted alone, and similar high combustion reactivities. It must also be noted that the peak temperature of all blends occurred in the lower temperature region compared to that of coal. Coal is shown to have similar reactivity to samples with (25% raw bamboo + 75% coal).

3.4. Co-combustion profiles of the thermally treated 1 year old bamboo and coal

Torrefied and low temperature carbonized 1 year old bamboo samples were blended with coal at different weight ratios and co-fired. As seen in figure 4a below, the profiles of all blends of 1 year old T250 and coal are similar, but coal alone exhibits a burning profile different from the other fuels. The 1 year old T250 and its respective coal blends show two different peaks, which are probably due to the release of the large amount of volatiles in the first peak and carbon-rich lignin combustion in the second peak. This trend was also observed in the profiles of the 1 year old T280, C350 and C400 blended with coal (Figures 4b-4d). The burning profile of (75% T250 + 25% coal) sample closely matches that of 100% T250 alone (Figure 4a), with both thermographs having a peak temperature of about 193°C and a burnout temperature of about 491°C. In Figure 4b, 4c and 4d, the blends of (75% + 25% coal) were seen to be far higher in reactivity compared to other thermally treated samples. These samples are seen to posses higher volatile matter content compared to other samples with an increased carbon content, thereby reduced reactivity. In addition, these blends (75% + 25% coal) burnout temperatures also occurred within the low temperature zone similar to the 1 year 100% (T280, C350 and C400) samples. The (25% C400 + 75% coal) blends in Figure 4d was seen with a DTG profile closest to that of coal. A similar observation was made by Bada *et al* [21] on the co-firing of thermally treated *Bambusa balcooa* at 400 °C with high ash coal, and the thermograph obtained shows a close co-combustion compatibility with coal. Furthermore, the reactivity of all the samples in the Figures was observed to decrease as the coal proportion in the blend increases, hence this leads to a higher burnout temperature for all the (25% bamboo + 75% coal) samples than that of coal.

Figure 4: DTG curves of co-fired thermal treated 1year old bamboo/coal (4a; 4b; 4c and 4d)

3.5. Co-combustion profiles of the thermally treated 3 year old bamboo and coal

The co-combustion profiles of the torrefied 3 year old bamboo samples T250 and T280 with coal are shown in Figures 5a and 5b, respectively. In Figure 5a, it can be seen that all blends of T250 with coal have a similar burning profiles and lower peak compared to that of a 100% T250 sample. As the percentage coal in the blend increases, the profiles are seen to move closer to that of coal. The blend of (75% T280 + 25% coal) in Figure 5b was seen with the highest peak, followed by that of (50% T280 + 50% coal). In all 3 year bamboo fuels co-fired with coal, the blends containing (75% bamboo + 25% coal) were seen to have maximum weight loss rate (%/min) DTG profiles closest to that of the respective 100% bamboo sample fired solely.

Figure 5a & 5b: DTG curves for co-combustion of 3 year T250 & T280/coal

Figure 6a & 6b: DTG curves for co-combustion of 3 year C350 & C400/coal

From Figure 6b above, the 3 year old bamboo sample (25% C400 + 75% coal) showed a single peak combustion profile and a relatively similar burning profile to coal, suggesting coal-like burning characteristics. The same observation was made by Park *et al* [12] on blends of thermally treated woody biomass and coal. All samples co-fired with coal in the proportion of (25% bamboo + 75% coal) were seen to ignite at the high temperature region with higher burnout temperatures compared to the other blends. In respect to reactivity, all samples (Figures 5a, 5b, 6a & 6b) co-fired with coal in the proportions of (75% bamboo + 25% coal) were seen to ignite at low temperatures. In all co-firing tests conducted, bamboo appears to aid in the ignition of coal at lower temperatures.

3.6. Co-combustion profiles of the thermally treated 4 year old bamboo and coal

The combustion profiles of the blends of torrefied 4 year old bamboo and coal are shown in Figures 7a and 7b, below. As is the case for the other blends of treated 1 year old and 3 year old bamboo samples, the DTG profile of the 4 year old sample with 75% coal (i.e. 25% T250 + 75% coal) was the closest match to that of coal as seen in Figure 7a below. The same observation was made in Figure 7b for the blend of (25% T280 + 75% coal). In addition, as the weight percentage of coal increases in the blends, the initiation devolatilisation temperatures (IT_{vm}) and burnout temperatures (BT) are seen to increase in all samples (Figures 7a & 7b). These observations can be attributed to the higher fixed carbon and lower volatile matter content of the bamboo and the coal in the blends. Bada *et al* [3] also reported the same observations for the co-combustion of torrefied *Bambusa multiplex* and coal.

Figure 7a & 7b: DTG curves for co-combustion of 4 year T250 & T280/coal

The respective maximum weight loss rate (%/min) DTG profiles in Figure 8a for the co-combustion of 4 year old C350 with coal shows a peak, which indicate volatile release at temperature between 200 ^{0}C and 220 ^{0}C for the 50% and 75% bamboo inclusion, but little if any in the 25% C350 + 75% coal sample below. These peaks signify the presence of some volatile matter left in the blends after treatment at 350 ^{0}C. The near-single peak and the highest initiation devolatilisation temperature (IT_{VM}) observed for the (25% C350 + 75% coal) blend indicate a combustion behaviour close to coal. Moreover, there is minimal difference in terms of BT between the profiles of all the blends in Figure 8a.

Figure 8a and 8b: DTG curves for co-combustion of 4 year C350 and C400/coal

Figure 8b above shows an illustration of the combustion of 100% carbonized 4 year old bamboo (C400) and its co-combustion with coal under different weight proportions. All samples in this Figure report a single peak, with PT, BT and combustion profiles closely similar to coal. The same observation was made by both Park *et al* [12] and Bada *et al* [21] on the co-combustion of low carbonized woody biomass and *Bambusa balcooa* with high ash coal, respectively. Only sample (75% C400 and 25% coal) presents a profile with an initiation devolatilisation temperature (IT_{vm}) similar to that of the 100% C400 bamboo sample. From the observations made in all the burning profiles, it can be concluded that 4 year old C400 bamboo material has combustion properties similar to coal and that it is therefore likely to be the most compatible fuel that could be co-fired with coal for power generation, especially in a pulverized fuel boiler. Furthermore, given that the blend with the highest proportion of C400 had better reactivity, it is possible that the bamboo blended with coal could improve the overall burning efficiency in a co-fired power station.

4. Conclusions

Torrefication and carbonization were established as a suitable process to enhance the fuel properties of different ages of raw bamboo as a source for co-firing with coal. The calorific value of 1 year, 3 year and 4 year old bamboo plants was increased by low temperature carbonization from 18.53 MJ/kg to 28.54 MJ/kg for 1 year old bamboo, 17.10 MJ/kg to 30.17 MJ/kg for 3 year old bamboo and 17.63 MJ/kg to 30.24 MJ/kg for 4 year old bamboo. The fixed carbon for all ages of bamboo was increased to over 66% (db) from low temperature carbonization, matching high quality coal. The *nitrogen content* of the bamboo samples was noted to decrease with the age of the harvested plant, but there was no correlation between the *total carbon content* of the bamboo and the age of the samples. The raw bamboo sample had the highest fuel reactivity and the lowest devolatilisation, peak and burnout temperatures compared to all heat treated fuels. All the bamboo samples, raw and heat treated, were found to exhibit lower initiation (IT_{VM}), peak and burnout temperatures compared to coal. Moreso, the DTG curves of the 4 year old carbonized samples (C400) closely matched that of coal. Hence, a *blend of carbonized 4 year old bamboo (C400) with coal* resulted in a DTG profile characterized by a single peak, and with the most compatible combustion characteristic with coal.

Acknowledgements

The authors thankfully acknowledge the financial support of the NRF (National Research Foundation), SARChl Clean Coal Technology and the University of the Witwatersrand. Thanks to Mr Adrian Sutton of Hortus Capensis (Pty) Ltd, Western Cape for providing the bamboo plant materials utilized in this study.

References

[1] Yao, F. Wu, Q. Lei, Y. Guo, W. Xu, Y. VC BN GV C Thermal decomposition kinetics of natural fibres: activation energy with dynamic thermogravimetric analysis. Polym Degrad Stabil. 2008, 93, 90-98.

[2] Rousset, P. Aquiar, C. Labbe, N. Commandre, J.M. Enhancing the combustible properties of bamboo by torrefaction. *Bioresour. Technol*. 2011, 102, 8225-8231.

[3] Bada, S. O. Falcon, R.M.S. Falcon, L.M. Investigation of combustion and co-combustion characteristics of raw and thermally treated bamboo with thermal gravimetric analysis. *Thermochim Acta*. 2014, 589, 207-214.

[4] Basu, P. Sadhukhan, A.K. Gupta, P. Rao, S. Dhungana, A. Acharya, B.; An experimental and theoretical investigation on torrefaction of a large wet wood particle. *Bioresour. Technol*. 2014, 159, 215-222.

[5] Gil, M.V. Casal, D. Pevida, C. Pis, J.J. Rubiera, F. Thermal behaviour and kinetics of coal/biomass blends during co-combustion. *Bioresour. Technol*. 2010, 101, 5601-5608.

[6] Fang, X. Jia, L. Experimental study on ash fusion characteristics of biomass. *Bioresour. Technol*. 2012, 104, 769-774.

[7] Ohliger, A. Forster, M. Kneer, R. Torrefaction of beechwood: A parametric study including heat of reaction and grindability. *Fuel.* 2013, 104, 607-613.

[8] Zhijia, Liu. Wanhe, Hu. Zehui, Jiang. Bingbing, Mi. Benhua, Fei. Investigating combustion behaviors of bamboo, torrefied bamboo, coal and their respective blends by thermogravimetric analysis. *Renew Energ*. 2016, 87, 346-352.

[9] Bergman, P.C.A. Boersma, A.R. Zwart, R.W.R. Kiel, J.H.A. Torrefaction for biomass co-firing in existing coal-fired power stations. *Energy Research Centre of the Netherlands*, 2005, ECN-C-05-013.

[10] Kargbo, F.R. Xing, J. Zhang, Y. Property analysis and pre-treatment of rice straw for energy use in grain drying: A review. *Agric. Biol. J. N. Am*. 2010, 1, 195-200.

[11] Phanphanich, M. Mani, S. Impact of torrefaction on the grindability and fuel characteristics of forest biomass. *Bioresour. Technol*. 2011, 102 (2), 1246–1253.

[12] Park, S.W. Jang, C.H. Baek, K.R. Yang, J.K. Torrefaction and low temperature carbonization of woody biomass: Evaluation of fuel characteristics of the products. *Energy*. 2012, 45, 676-685.

[13] Ibrahim, R.H.H. Darvell, L.I. Jones, J.M. Williams, A. Physicochemical characteristics of torrefied biomass. J Anal Appl Pyrolysis. 2013, 103, 21-30.

[14] Uslu, A. Faaij, A.P.C. Bergman, P.C.A. Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. *Energy*. 2008, 33, 1206-1223.

[15] Bridgeman, T.G. Jones, J.M. Williams, A. Waldron, D.J. An investigation of the grindability of two torrefied energy crops. *Fuel*. 2010, 89 (12), 3911-3918.

[16] Poppens, R. Van Dam, J. Elbersen, W. Analyzing the potential of bamboo feedstock for the biobased economy, Netherlands, January 2013, Record Number 503535

[17] Scurlock, J.M.O. Dayton, D.C. Hames, B. Bamboo: an overlooked biomass resource? *Biomass Bioenergy*. 2000. Vol. 19: 229-244.

[18] Dayton, D. A Summary of NO_x Emissions Reduction from Biomass Cofiring. A Report prepared for the National Renewable Energy Laboratory, Colorado, May 2002, Report NREL/TP-510-32260.

[19] Rodrigues, T.O. Rousset, P. Effects of torrefaction on energy properties of Eucalyptus grandis wood. *Cerne, Lavras*. 2009, 15, 446-452.

[20] Kastanaki, E. Vamvuka, D. A comparative reactivity and kinetic study on the combustion of coal-biomass char blends. *Fuel*. 2006, 85, 1186-1193.

[21] Bada, S.O. Falcon, R.M.S. Falcon, L.M. Characterization and co-firing potential of a high ash coal with Bambusa balcooa. Fuel. 2015, 151, 130-138.

.

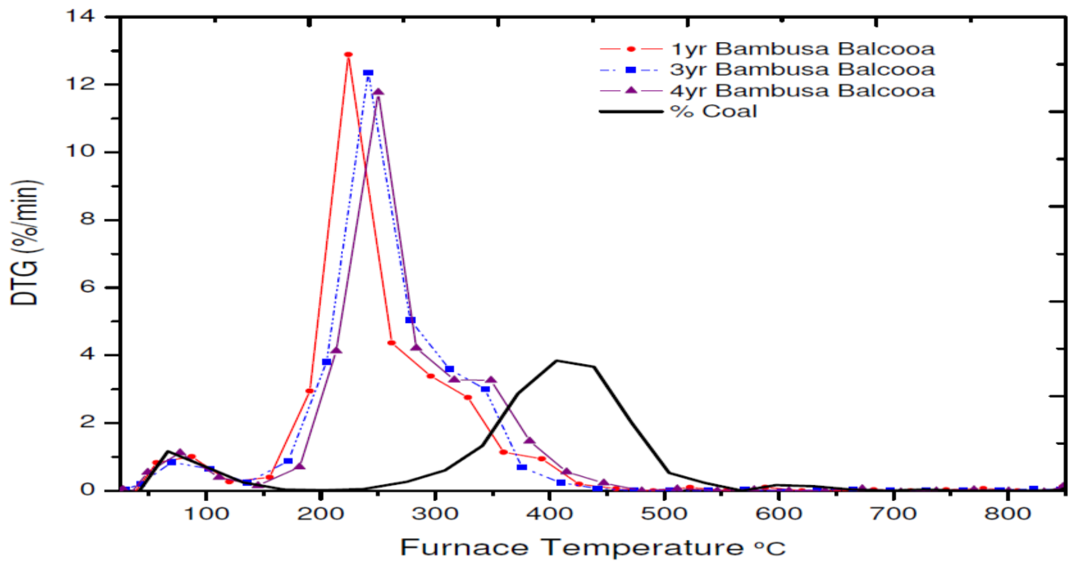


Figure 1: DTG curves for coal and all the raw bamboo samples.

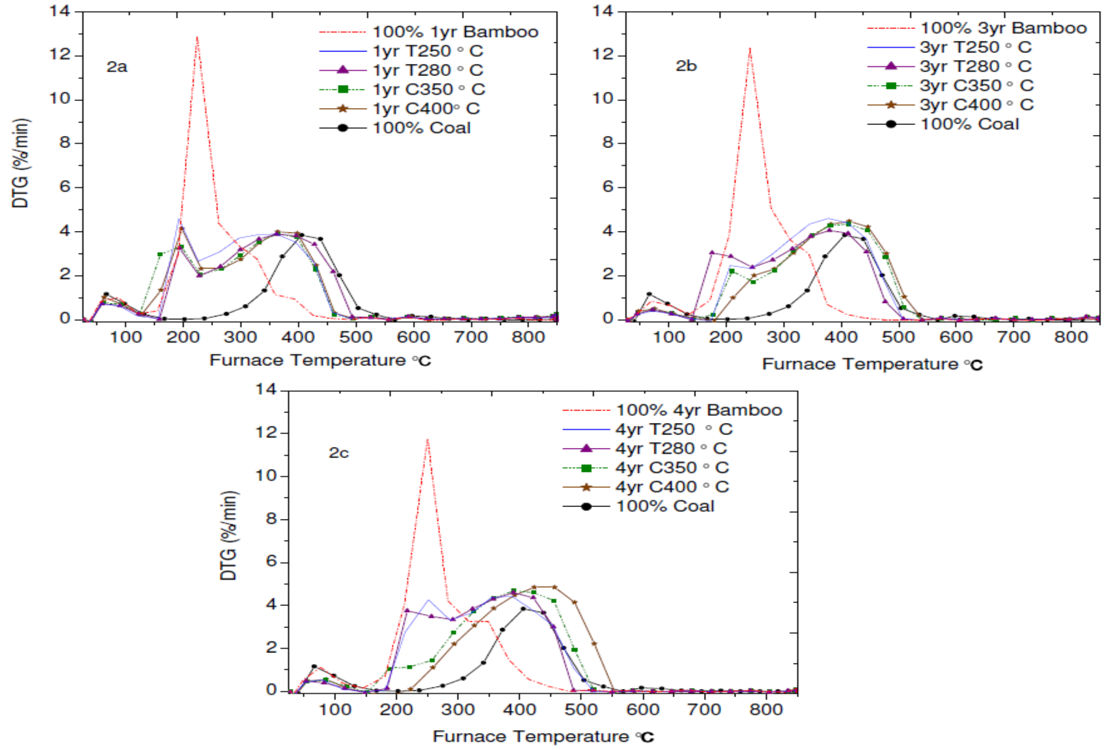


Figure 2: DTG curves for thermally treated bamboo and coal (a:1yr; b:3yr and c:4yr)

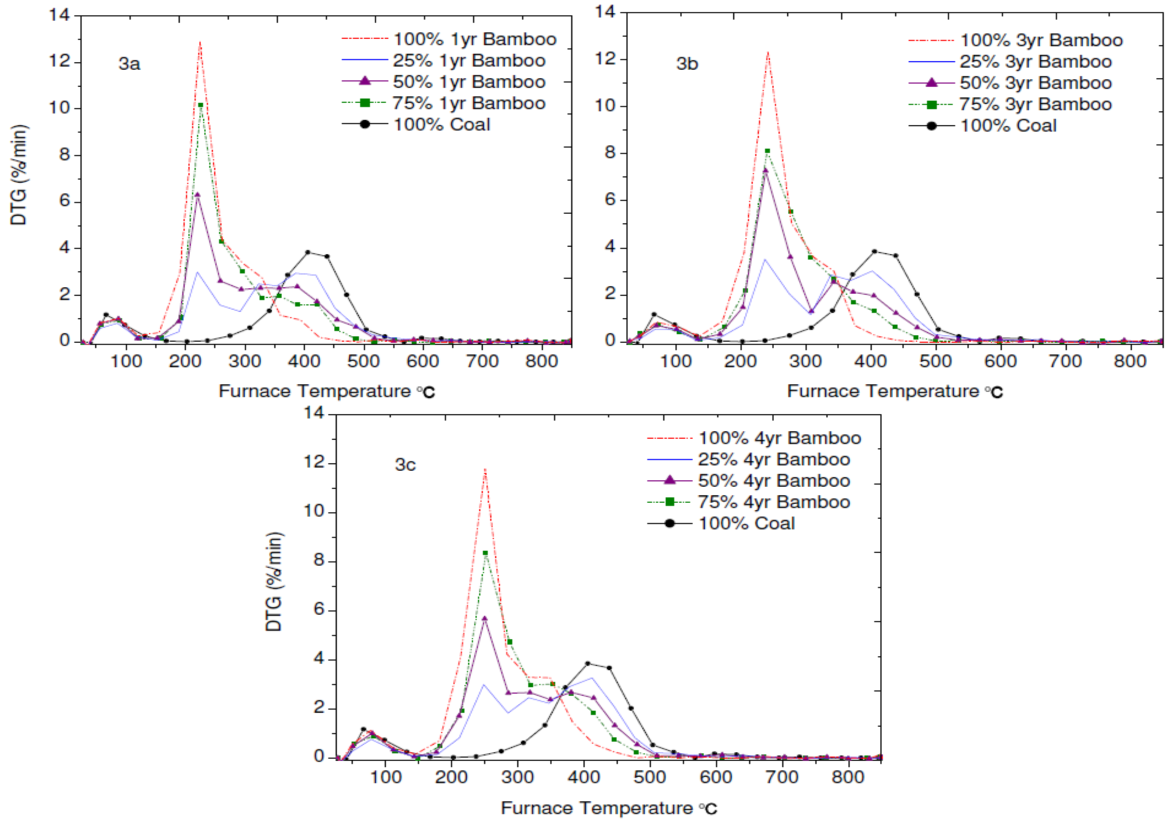


Figure 3: DTG curves of co-combustion of raw bamboo/coal (3a:1yr; 3b:3yr and 3c:4yr)

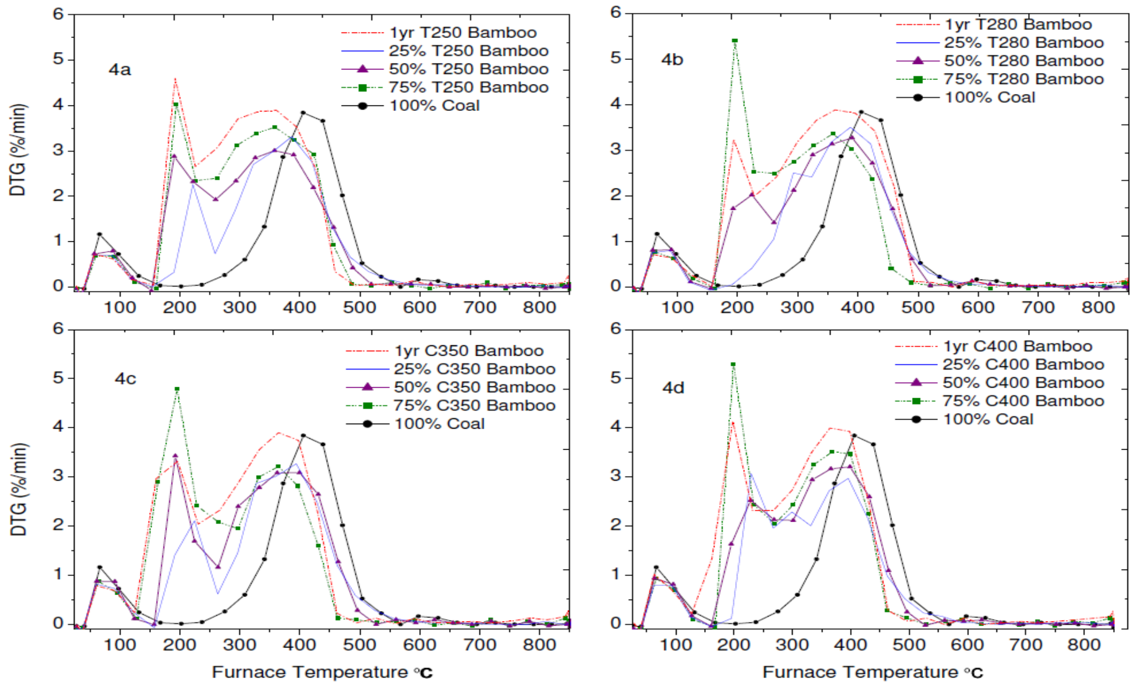


Figure 4: DTG curves of co-fired thermal treated 1year old bamboo/coal (4a; 4b; 4c and 4d)

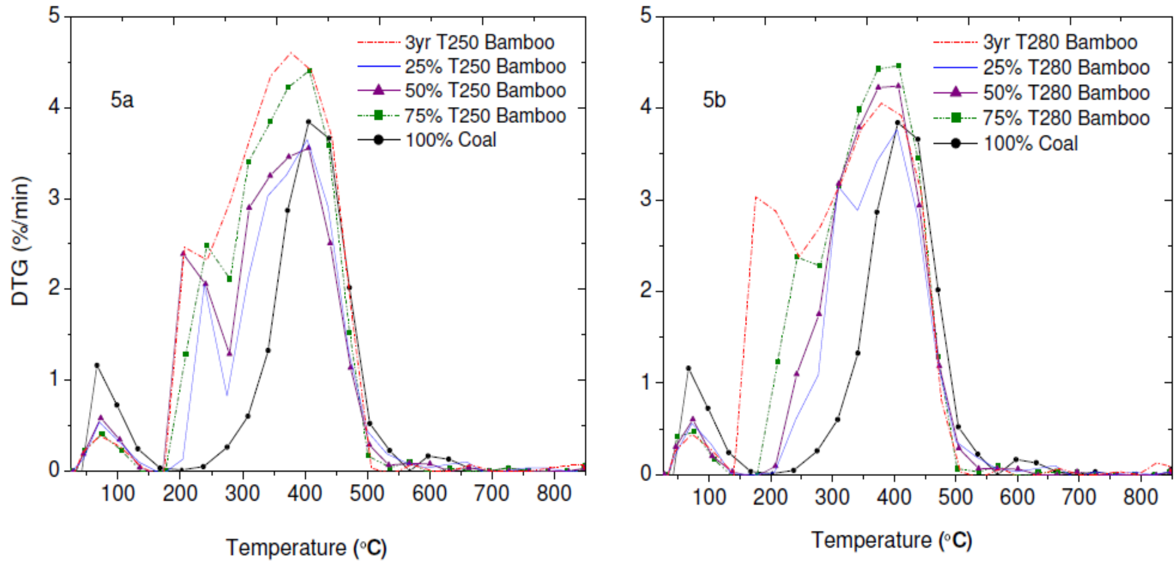


Figure 5a & 5b: DTG curves for co-combustion of 3 year T250 & T280/coal

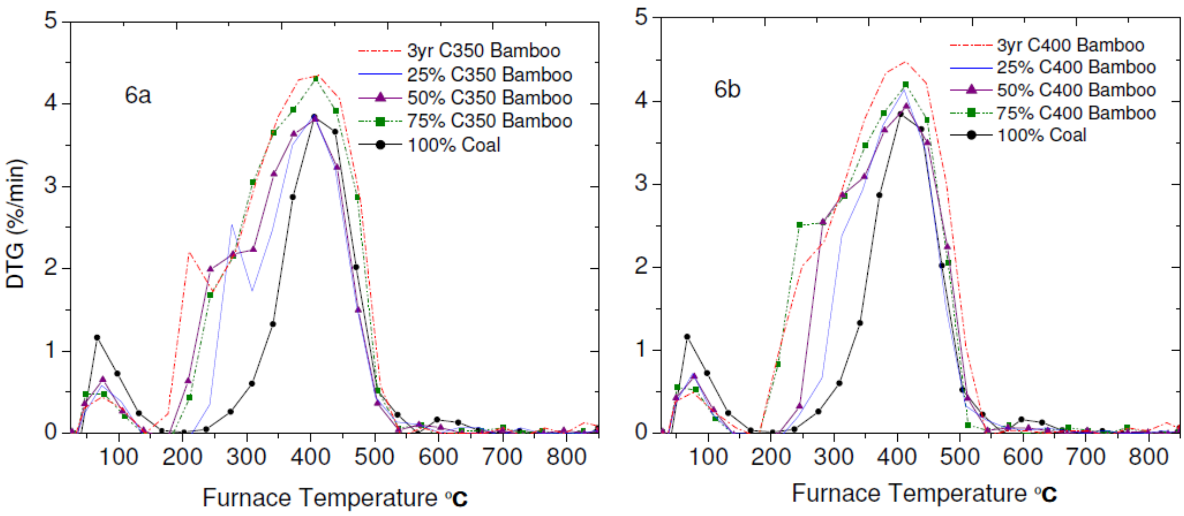


Figure 6a & 6b: DTG curves for co-combustion of 3 year C350 & C400/coal

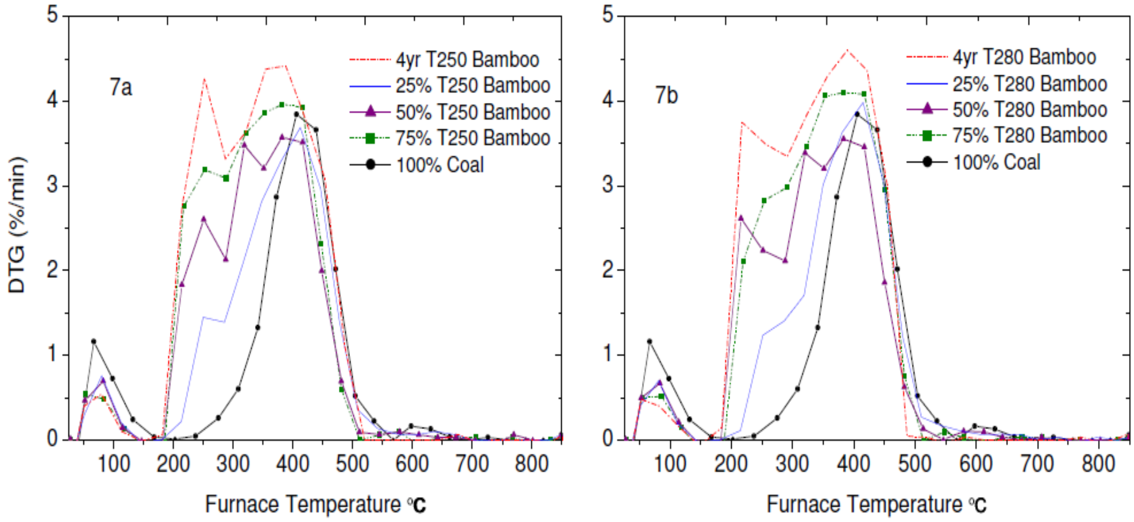


Figure 7a & 7b: DTG curves for co-combustion of 4 year T250 & T280/coal

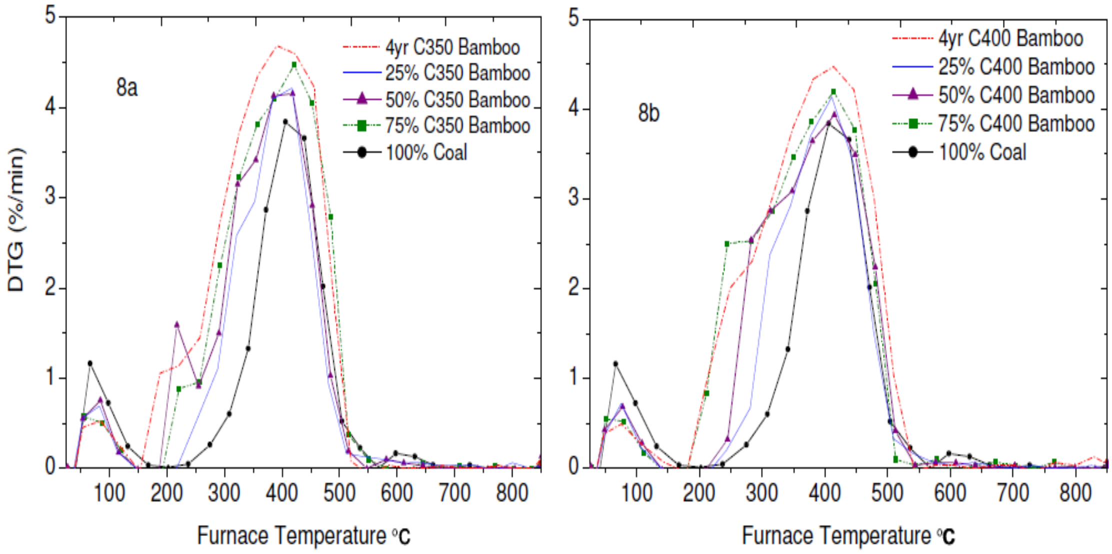


Figure 8a and 8b: DTG curves for co-combustion of 4 year C350 and C400/coal

Table 1: Fuel properties of raw and thermally treated bamboo.

Sample ID	Nitrogen	Total carbon	Hydrogen	Total sulphur	Oxygen		
1 year bamboo	0.88	44.91	6.17	0.07	39.14		
3 year bamboo	0.41	46.76	6.22	0.02	37.21		
4 year bamboo	0.32	46.52	6.26	0.03	37.37		
Coal	1.07	38.58	5.13	0.58	3.64		
	M (%)	FC (%)	VM (%)	Ash (%)	FC db.%	VM db.%	Ash db.%
1 year bamboo	7.97	16.59	74.58	0.86	18.03	81.04	0.93
1 year T250	1.26	45.58	50.72	2.44	46.16	51.36	2.47
1 year T280	0.92	50.21	46.41	2.47	50.67	46.84	2.49
1 year C350	2.52	66.91	27.02	3.56	68.64	27.72	3.65
1 year C400	1.99	68.55	26.88	2.58	69.94	27.43	2.63
3 year bamboo	7.01	16.97	73.64	2.37	18.25	79.20	2.55
3 year T250	3.05	52.32	38.33	6.30	53.97	39.54	6.50
3 year T280	3.18	64.60	25.10	7.13	66.71	25.92	7.36
3 year C350	3.30	66.34	22.13	8.25	68.60	22.88	8.53
3 year C400	4.14	68.46	18.90	8.50	71.42	19.72	8.87
4 year bamboo	8.09	17.69	72.81	1.41	19.25	79.22	1.53
4 year T250	1.41	57.76	37.25	3.59	58.58	37.78	3.64
4 year T280	1.62	62.61	31.63	4.15	63.64	32.15	4.21
4 year C350	2.07	71.62	21.62	4.69	73.14	22.08	4.78
4 year C400	2.62	74.59	17.75	5.04	76.60	18.23	5.18
Coal	6.28	29.64	19.36	44.72	31.63	20.66	47.72

M: Inherent Moisture; FC: Fixed carbon; VM: Volatile matter; and db: Dry basis and O: Oxygen by difference [100-(M+Ash+S+H+C+N)]

Table 2: Mass and Energy yield of thermally treated bamboo

Sample ID	Mass loss (%)	η_M	η_E	*Rm* (%/min/K)	CV (MJ/Kg)
Raw 1 year	-	-	-	2.59	18.53
1 year T250	60.7	0.39	0.55	0.99	25.94
1 year T280	67.7	0.32	0.48	0.61	27.78
1 year C350	69.6	0.30	0.47	0.61	28.51
1 year C400	70.9	0.29	0.45	0.63	28.54
Raw 3 year	-	-	-	2.40	17.10
3 year T250	59.8	0.40	0.64	0.71	27.34
3 year T280	64.4	0.36	0.59	0.61	28.39
3 year C350	68.7	0.31	0.55	0.63	29.76
3 year C400	69.4	0.31	0.54	0.65	30.17
Raw 4 year	-	-	-	2.25	17.63
4 year T250	48.6	0.51	0.74	0.67	25.46
4 year T280	54.5	0.46	0.68	0.69	26.38
4 year C350	67.6	0.32	0.54	0.71	29.16
4 year C400	70.3	0.30	0.51	0.66	30.24
Coal	-	-	-	0.55	12.70

n_M: Mass yield; n_E: Energy yield; CV: Calorific value; R_m: Reactivity