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# Torrefied biomass fuels as a renewable alternative to coal in co-firing for power generation

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## Abstract

This study aims to assess the torrefaction of biomass as alternative renewable energy fuel to coal during co-firing. It was evaluated that torrefaction improves biomass grindability to such an extent that it can be used in coal mills with coal in co-firing without capital intensive modification. Torrefaction of beech wood was performed on a batch scale reactor at three different temperatures (200, 250 and 300 °C) with 30 min of residence time. The chemical structural changes in torrefied biomass were investigated with binding energies and FTIR (Fourier transform infrared) analysis. Monocombustion and co-combustion tests were performed to examine the combustion behaviour regarding flue gas emissions (CO, NO<sub>x</sub> and SO<sub>2</sub>) at 0.5, 1.5 and 2.5 m distance from the burner

opening along with fly ash analysis. The FTIR and binding energies showed that lignin hardly affected during light torrefaction while hemicellulosic material was significantly depleted. The Hardgrove grindability index (HGI) was calculated with three methods (DIN51742, IFK and ISO). The medium temperature torrefied biomass (MTTB) yields HGI value in the range of 32–37 that was comparable with HGI of El Cerrejon coal (36–41). A slight change in temperature enabled the torrefied beech wood to be co-milled with coal without capital intensive modification and improved grindability. Comparing the combustion behaviour of single fuels, low temperature torrefied biomass (LTTB) produces less amount of NO<sub>x</sub> (426 mg/m<sup>3</sup>), CO (0.002 mg/m<sup>3</sup>) and SO<sub>2</sub> (2 mg/m<sup>3</sup>) as compared MTTB and raw beech wood. In the case of co-combustion, it was found that blending of coal with raw biomass does not show stable behaviour. However, premixing of 50% of coal with 50% of torrefied biomasses (MTTB and LTTB) gives most stable behaviour and reduces NO<sub>x</sub> almost 30% and SO<sub>x</sub> up to almost 50% compared to coal. The fly ash contents analysis proved that K<sub>2</sub>O contents much decreased during co-firing of coal and torrefied fuels that could cause ash related issues during combustion of raw biomass.

**Keywords:** Renewable energy; CO<sub>2</sub> emissions; Torrefaction; Biomass; Hardgrove grindability index; Co-combustion; Emissions profile and Power plant.

## 1 Introduction

One of the current demands of global energy network is to mitigate its dependence on fossil fuels and to attain a sustainable environment scenario [1]. Among the developed renewable energy resources (solar, wind, geothermal and biomass) bioenergy is considered one of the largest and promising renewable energy in the world as well as close to CO<sub>2</sub>-neutral fuel [2]. It directly contributes to preserving the equilibrium of ecosystems by reducing the greenhouse effect [3] and

environmental pollution [4]. Moreover, biomass has been widely used for getting heat, power, chemical raw materials and electricity either by using thermochemical conversion (gasification, direct combustion and pyrolysis) or through biological routes (fermentation and anaerobic digestion) [5, 6].

Although with wide applications of biomass, there are some drawbacks associated with raw biomass including; high moisture content, hygroscopic behaviour, relatively low energy density, less grindability, larger volume, difficulty in handling, storage and transportation [7]. However, the efficiency of biomass utilisation can be improved by dewatering, drying, torrefaction, densification [8], size reduction with pulverisation as well as pelletisation [9]. Among the latest developments and conventional pre-treatment strategies of biomass, special attention was paid to the torrefaction because of large-scale implementation of biomass into bioenergy. Torrefaction is a thermal pre-treatment that involves heating the biomass at a moderate temperature between 200 and 300 °C under an inert atmosphere [10]. The torrefaction includes a reduction in moisture content markedly to <3% and increment in energy density, heating value and carbon content of the biomass by 15–20 wt% [4, 11]. Easier storage, delivery, ignitability, milling power and reactivity of the fuel can be improved to a great extent [12]. Additionally, the black torrefied biomass turns into uniform and brittle solid form having coal-like properties so that the energy is saved for milling. The cellulose and hemicelluloses contents decrease in torrefaction and biomass becomes concentrated and easy to grind [13].

Torrefaction has been performed by fluidised bed combustor, fixed bed reactor as well as rotary kiln [1]. All previous studies outlined different processing condition such as temperature, type of

reactor [14], biomass material and residence time for torrefaction [5]. Valix et al. [15] examined the dry torrefaction of sugar cane bagasse in an inert atmosphere and chemical torrefaction with H<sub>2</sub>SO<sub>4</sub> pre-treatment within a temperature range of 160–300 °C. All the issues regarding biomass feeding, handling and processing were demonstrated by using chemical torrefaction. Likewise, Rodrigues et al. [16, 17] focused on chemical torrefaction of sixteen woody biomasses from poplar short rotation coppice to portuguese round wood species at 265 °C for 105 min in the presence of nitrogen. Bach et al. [18] studied a combined process of torrefaction, CO<sub>2</sub> capture and gasification to improve the biomass gasification and quality of product gas.

According to Budde et al. [4], the torrefaction of rice straw exhibited excellent fuel properties at 275 °C while cotton stalk at 250 °C. Yilgin et al. [19] performed the torrefaction of beech wood sawdust at light (220 °C), mild (260 °C) and severe (300 °C) temperatures and concluded that mild temperature was the best optimum temperature to get higher calorific values. Jian et al. [20] explored the pyrolysis of dry torrefaction as well as wet torrefaction of beech wood and wheat straw. The wheat straw showed a significant chemical change in comparison to beech wood. Gucho et al., [21] investigated the torrefaction of miscanthus and beech wood using 240–300 °C temperature with a residence time of 15–150 min. The results concluded that beech wood showed significant improved grinding behaviour after torrefaction at 280 °C for 15 min, which is almost similar to the low type of coal. Besides that, torrefaction of different biomasses such as empty fruit bunch [7, 22], stem wood, bark and stump of Norway spruce [23] palm kernel shell [7], beech wood, pine, miscanthus, deciduous wood, coniferous [24], wheat straw [20], eucalyptus [25] and vine prunings [26] exhibited high heating values and energy density that were also found suitable for bioenergy applications.

Kopczynski et al. [8] investigated the co-combustion of raw fuels of willow, furniture waste wood, olive oil and torrefied biomass regarding emissions profile and ash behaviour. It was suggested that SO<sub>2</sub> emission significantly decreased by using torrefied biomass as a substitute for raw biomass. Similar findings were found by Xue et al., for co-combustion of coal with avocado and torrefied biomass. [27]. Mun et al. [28] explored the significant benefits of co-combustion of coal and torrefied biomass on the boiler's efficiency that was similar with reference to coal. Rentizelas et al., [29] noticed positive outcomes of co-combustion of torrefied biomass with coal regarding reduction in global warming and human toxicity. Co-combustion of various biomass material with coal have attracted the attention of researchers to lessen the CO<sub>2</sub>, SO<sub>x</sub> and NO<sub>x</sub> emissions because of low fuel nitrogen and CO<sub>2</sub>-neutral biomass [30]. However, there are limited types of biomasses that can be co-combusted with coal because of higher moisture content and poor grinding ability. The higher percentage of moisture in biomass has a direct effect on meeting the thermal loads in steam generating units [31].

An attempt has been made to fill the gap in knowledge regarding co-combustion of coal with torrefied biomass at different temperatures to examine the effect of torrefaction temperatures during co-combustion and ash behaviour. In addition, the Hardgrove Grindability Index (HGI) has long been used by the coal and utility industries as a determinant of power consumption in grinding and pulveriser capacity. There is a lack of research on HGI investigation of biomasses and this gap is covered by determining the HGI values with three different methods to compare the milling properties, particle size distribution, flue gas analysis during combustion and ash behaviour. This study focused on the preparation of torrefied biomass via torrefaction process. The structural

changes were studied by FTIR analysis as well as binding energies. The main aim of the current study is to check whether torrefaction improves fuel's grindability to such an extent that it can be used in coal mills with coal in co-firing without capital intensive modification. It is also examined either co-combustion of torrefied biomass with coal has improved the combustion behaviour regarding flue gas emissions. The flue gas emissions were studied at 0.5, 1.5 and 2.5 m distances from burner opening that were rarely reported by the published studies.

## **2 Material and methods**

### **2.1 Fuel samples**

The raw beech wood (BW) biomass was used in the torrefaction experiments and EI Cerrejon coal (EC) was used as a standard reference for comparing different fuel properties as well as for coal/biomass co-combustion. For combustion experiments, the particle size of raw and torrefied biomass was  $\leq 250 \mu\text{m}$  to ensure complete combustion.

### **2.2 Fuel analysis**

Proximate analysis of the fuels used in the present was carried out according to DIN51718, 51719, 51720 method and ultimate analysis was made according to DIN ISO 10694 [9, 32]. The heating values (HHV) of all fuel samples were investigated using a calorimetric pump of IKA C4000 [33]. The elemental and proximate analyses along with calorific values for these fuels are represented in Table 1.

### **2.3 Torrefaction experiments**

A bench-scale reactor was used for torrefaction of beech wood as shown in Fig. 1. Almost 50 g of the raw material sample was torrefied at three different temperatures (200, 250 and 300 °C) under an inert atmosphere of N<sub>2</sub> for 30 min of residence time [20]. Consequently, 50 g of the raw material

sample was placed inside the rod in each batch and heated at desired torrefaction temperature under an inert atmosphere of N<sub>2</sub> for 30 min while heating at a rate of 50 °C/min. A small flow of nitrogen was maintained from one side to remove all oxygen traces and to avoid explosion while the flow of exhaust gasses and the liquid was collected from the opposite direction. After 30 min, the apparatus was switched off and the torrefied solid product was collected, weighed, and elemental analysis was performed that is reported in Table 1. The beech wood torrefied at 200 °C was named as low torrefied temperature biomass (LTTB) and torrefied at 250 °C was named as medium torrefied temperature biomass (MTTB).

## **2.4 FTIR**

The Fourier transform-infrared (FTIR) spectra were recorded using Perkin Elmer FTIR version 10.4.3 spectrometer in the range of 4,000-450 cm<sup>-1</sup>.

## **2.4 Combustion test**

The co-combustion experiments of biomass and coal were performed in a 20 kW<sub>th</sub> entrained flow combustion reactor (EFCR) that is shown in Fig. 2. The combustion reactor consists of an electrically heated ceramic tube with a diameter of 0.2 m and a length of 2.5 m. A constant wall temperature up to 1,300 °C was maintained by electrically heating around the reaction region, all analyses were performed at this temperature. A proper amount of various fuels (EI Cerrejon coal and torrefied Beech Wood) were injected into the reactor using fuel feeder at a rate of 0.5 g/min with the help of carrier air mixture using a central tube of a circular jet. The feeding unit temperature was 20 °C. The outer concentric cylinders of burner were used for injection of combustion air streams that are categorised into primary air and secondary air stream. The axial analysis of flue gas concentration was performed by a vertically movable probe that collected the flue gas and transported to standard flue gas analysers for analysis.

## 2.5 Standard flue gas analysis

Table 2 tabulated the standard measurements for the used equipments and calibration gasses employed for the calibration of analysers. Experiments related to combustion and co-combustion of EI Cerrejon coal, beech wood and torrefied beech wood were performed using atmospheric drop tube furnace BTS-VR. The general input parameters for various combustion settings are given in Table 3. All standard gaseous concentrations such as O<sub>2</sub>, NO<sub>x</sub>, CO and SO<sub>2</sub> were expressed on a dry basis. The flue gas was quenched immediately by maintaining the oil-cooled probe temperature to 180 °C. The flue gas was collected from the end region of the heated reaction tube at 2.5, 1.5 and 0.5 m distance from the burner opening [34]. After each experiment, ash is collected from the bottom of the oil-cooled probe for further investigated of ash behaviour analysis. For each experiment of different fuel, ash collecting filter was changed to avoid any contamination [16].

## 2.6 Grindability test

The grindability behaviour of beech wood and torrefied biomass samples were determined by hardgrove grindability index (HGI). The HGI values of all fuels were calculated in accordance with DIN 51742 Calibration, IFK Calibration and Indian Standard IS-4435-1979 Calibration [35]. Grindability experiment was carried out in Hardgrove laboratory grinder in accordance with ASTM D409 standard. Firstly, the torrefied fuel sample was milled to a size <4.75 mm and screened between the sieves of size 0.6 to 1.18 mm. Then, 50 g of the sample was removed and poured on grinding track of HGI equipment. The grinder was stopped after 60 rotations and the ground sample was screened for 10 min between sieves of size 0.75 and 0.6 mm. The grain particles were removed from the bottom, and screening was performed twice again for 10 min. After completion, the undersize and oversize samples were weight with 0.01 g accuracy.

The particle size distribution having D10, D50 and D90 were analysed. For a sieve analysis, the ground sample of 50 g was sieved for 10 min with mesh sizes of 32, 50, 63, 75, 90, 160, 200 and 353  $\mu\text{m}$ . The fabric used for sieve analysis was standardised DIN ISO 3310. After each sieving, the weight of sample on each sieve was measured and noted as a percentage of the original mass sample. The milling properties of torrefied biomass and coal were also compared using HGI. The ash fusibility temperatures were determined in accordance with CEN/TS 15404 method to investigate the ash melting behaviour of biomasses at 550 to 1,500  $^{\circ}\text{C}$  with a heating rate of 10  $^{\circ}\text{C}/\text{min}$ . The ash fusibility temperatures, including shrinking temperature (ST), start of sintering temperature (SbT), hemisphere temperature (HT) and flow temperature (FT) were determined within the given range [36].

### **3 Results and discussion**

#### **3.1 Effect of temperature on torrefaction**

The effect of temperature on torrefaction was investigated by a series of experiments. Beech wood biomass was torrefied for 30 min at three different temperatures (200, 250 and 300  $^{\circ}\text{C}$ ). After torrefaction, the elemental analysis of all three samples was performed as shown in Fig. 3. The results showed that when torrefaction temperature was increased from 200 to 300  $^{\circ}\text{C}$  there was an increment in nitrogen content of torrefied beech wood from 0.09 to 0.33% and carbon contents were increased from 48.55 to 73.78%. This may be explained by the decrease in mass yield with increment in temperature from 200 to 300  $^{\circ}\text{C}$  because of the devolatilisation of carbon, hydrogen and oxygen in hemicellulose during torrefaction. The sample becomes more densified due to weight loss during torrefaction.

A significant weight reduction and mass loss of H and O of the sample was observed due to the evaporation of moisture and hemicellulose. The hydrogen contents decreased evidently from 5.98 to 2.62% as temperature increased from 200 to 300 °C due to the release of volatiles and hydrocarbon at high temperature. While overall, no significant changes were observed in nitrogen and sulphur contents [20]. Similar findings have been reported by Pawlak-Kruczek et al., [14] that the carbon amount of torrefied *Leucaena* is enhanced while the oxygen amount is reduced by increasing torrefaction temperature. The light torrefaction at 200 °C was influenced by hemicellulose component of the biomass sample, while cellulose and lignin components were little affected [37]. In contrast, the lignocellulosic materials were significantly depleted in severe torrefaction at 300 °C.

That is why the two-materials named as low torrefied temperature biomass (LTTB) obtained at 200 °C and medium torrefied temperature biomass (MTTB) obtained at 250 °C were further used in combustion and co-combustion settings. Furthermore, it is reported above that increasing temperature resulted in decreased mass yield and increased densification of torrefied biomass and resulted in a solid with increased carbon content, decreased oxygen content and decreased volatiles. It is also highlighted the weight losses of biomass materials in a light torrefaction environment (200 °C), medium torrefaction (250 °C) and a severe torrefaction one (300 °C). It is also pointed out that severe torrefaction has a drastic impact on the depletion of lignin and cellulosic material that have little effect in the case of light and medium torrefaction.

### **3.2 Effect of binding energies on structural degradation**

Biomass mainly composed of lignin, hemicellulose and cellulose components. The torrefaction process and performance of a lignocellulosic material depends strongly on the thermal degradation

of these constituents. The binding energies are given in Table 4, clearly describe the degradation behaviour of these constituents. Firstly, the biomass constituents possess no nitrogen. Only available nitrogen in the biomass is primarily bound to proteins which are defragmented from peptides [20]. The wood chips are connected with melamine resins in which much amount of nitrogen is present. As C-N bond possesses low binding energy (285 kJ/mol) in comparison to N-H bond (389 kJ/mol) which is rather stable, so it defragmented easily during torrefaction or pyrolysis. The half of nitrogen atom in heterorings is easily released at a medium temperature (250 °C) while another half of aliphatic nitrogen atom as amine is released at low temperature (200 °C) in NH form.

That is why nitrogen content was increased on torrefaction. The overall proportion of nitrogen in the torrefaction of biomass is 2–4% high so that large NH is formed. It was also analysed by Wang et al., [23] that the mass loss increased evidently with increasing torrefaction temperature to 275 °C, which is due to the degradation of hemicelluloses [16]. Secondly, C-C bond in aromatic rings of lignin possesses high binding energy (519 kJ/mol) in comparison to aliphatic C-C bond (348 kJ/mol) in hemicellulose and cellulose. Hence, their binding energies showed that lignin is thermally stable in chemical nature during torrefaction and not decomposed easily while hemicellulose and cellulose can be easily degraded at light (200 °C) and medium torrefaction (250 °C) temperatures.

### **3.3 Effect of torrefaction on energy properties of fuels**

The proximate analysis of raw biomass and torrefied fuels is shown in **Table 1**. The results indicate a clear difference in fixed carbon (FC), ash content (AC) and volatile matter (VM) contents of raw and torrefied biomass (LTTB and MTTB) in comparison with coal. The similarities of LTTB with

raw biomass suggested that only slight degradation or defragmentation occurred at low torrefaction temperature. The thermal decomposition of biomass constituents was directly affecting the moisture content. With increasing temperature from 200 to 250 °C, the moisture content of raw biomass was decreased from 5.41 to 2.38%. This reduction in moisture content is because of less availability of water bonding sites due to thermal degradation.

The dehydration process was involved in releasing moisture, therefore the volatile content was decreased significantly from 82% to 71% whereas increment in FC from 16% to 27% was observed on torrefaction at 200 to 250 °C. The positive variation in FC has improved the bioenergy properties of torrefied beech wood that exhibited low VM. In accordance with the above results, torrefied beech wood has the ability to burn slowly in comparison to raw biomass. The values of FC and VM were in agreement with the range of values obtained by Ndibe et al., [34] investigated the torrefaction characteristics of torrefied spruce. In addition, the ash content was found elementary characteristics that have a direct influence on the bioenergy properties of biomass. It has been reported that higher ash content enhanced the handling and maintenance cost of combustor along with a reduction in heating values. The ash content value for MTTB was found 1.15% that is slightly less than the ash content of raw biomass (1.16%), however, El Cerrejon has 14% ash content.

Moreover, MTTB has much less ash content that is suggesting it more suitable biomass for combustion. The ash content values are closely related to the literature within the range of 0.7 to 6.0% reported by Yelverton et al., [38] they performed torrefaction of four woody biomasses. Similar findings were reported in the published analysis of torrefied logging residue as well as

waste wood [39]. The ultimate analysis that is given in Table 1 indicates that carbon content in the solid product has increased at a medium temperature of torrefaction whereas the hydrogen and oxygen contents were decreased, resulting in the increased heating value of torrefied biomass. MTTB has shown the highest heating value that was 21,698 kJ/kg in comparison to raw biomass and LTTB that was comparable to El-Cerrejon having 28,134 kJ/kg heating value [40].

### 3.4 FTIR analysis

The effect of torrefaction on chemical structure of beech wood was investigated by performing FTIR analysis. The FTIR spectra of raw and torrefied beech wood (MTTB and LTTB) are given in Fig. 4. The interpretation of the FTIR band for raw and torrefied beech wood was made by a literature review [41]. The peaks indicate about the functional group evolution of the corresponding sample, however, their absorbance intensity indicates the transformation, degradation and chemical reactions of polymer components (lignin, hemicellulose, cellulose) of beech wood during torrefaction [20]. The spectra has similar peaks, but the absorbance intensity of the peaks was different. The broadband in the region of 3,300-3,400  $\text{cm}^{-1}$  and 2,880-2,923  $\text{cm}^{-1}$  indicated the stretching vibration of -OH and -CH for all samples. The intensity of peaks is reduced with increasing torrefaction temperature from 200 to 250 °C because of demethoxylation, dissociation of the side chain and dehydration reaction during torrefaction [42].

The C=O peaks observed at 1,720  $\text{cm}^{-1}$  are associated with carboxylic acid, aldehyde and ketone that are formed after decomposition of cellulose and hemicellulose. The peaks in the region of 1,450-1,610  $\text{cm}^{-1}$  were due to C-H deformation of cellulose component, methoxy stretching vibration of lignin as well as a ketonic component of hemicellulose. Furthermore, the intensity of these peaks is reduced significantly in the case of LTTB and MTTB, showing the thermal

degradation of holocellulose and lignin component. The peaks in the region of 1,160-1,270  $\text{cm}^{-1}$  are associated with C-O stretching vibration of the aromatic component of lignin as well as C-OH and C-O-C stretching vibration of hemicellulose and cellulose. The sharp peak at 1,025  $\text{cm}^{-1}$  is observed due to C-O, C-C-O and C=C stretching vibrations of biomass constituents [43]. Their absorbance intensity is stable at 200 °C torrefaction and then disappeared with increasing torrefaction temperature up to 250 °C. Lignin is thermally stable in comparison to cellulose and hemicellulose component and the C–O–C peak at 1,160  $\text{cm}^{-1}$  of lignin is retained in the case of LTTB and MTTB without any changes in absorbance intensity.

### 3.5 Hardgrove grindability index of fuels

HGI was determined from calibration line relating to the mean value of calculated mass passing through a  $>74 \mu\text{m}$  sieve to the certified HGI values of the standard test coals. The HGI values provide information for determining grinding power consumption and pulverised capacities [44]. Coal HGI ranges from 40–80 or even 90, higher the HGI easier to grind. A change from 47 to 50 in HGI is very negligible. The HGI has an inverse relation to grinding power and power consumption [35]. Three standard methods (DIN 51742, IFK and Indian standard (IS-4435-1979) were used to determine HGI values of raw biomass, torrefied biomass and coal. It is noticed from the HGI values of different fuels that determining HGI by different methods yields different results due to the difference in grindability characteristics of biomass.

Comparing HGI values of raw biomass with torrefied biomass and coal (Fig. 5), it can be clearly seen that raw biomass has lower HGI values in the range of 20–27. That means it is relatively tougher to grind and needs more grinding power consumption and less mill power capacity. Therefore, raw biomass is difficult to mill because of having a tenacious component like fibres.

The torrefied biomasses (LTTB and MTTB) need less grinding power in consumption and have more mill capacity due to higher HGI value ranging from 23 to 37. The results of HGI test show that torrefied biomass has HGI value ranging between a minimum of 23 and a maximum of 32 by DIN calibration, whereas IFK calibration showed a minimum HGI of 24 and maximum HGI of 33. Similarly, IS calibration giving a minimum HGI of 28 and a maximum of 37. These trends confirm that as the fuel becomes softer, the HGI value is higher and needs less power for grinding. By comparing MTTB and LTTB, it can be said that MTTB has high HGI values as compared to LTTB in all calibration methods. This could be due to increasing temperature the sample becomes more densified because of carbon, hydrogen and oxygen contents removal as a result of hemicelluloses devolatilisation.

There was a significant mass loss and an overall reduction in the weight of the sample due to evaporation of moisture and hemicellulose. Because of less mass, low power would be required for grinding. Comparing torrefied biomasses with coal, results show that HGI values of MTTB are only 3–4 digits less than HGI values of the referenced coal that was in the range of 37–41. Therefore, coal requires less power consumption with higher HGI to produce a product of the same fineness. Mun et al., [28] also used ASTM-D-409 method for HGI determination and found closest HGI values for blended torrefied biomass that was 46.9. The torrefied biomass had highest grindability among all blends of coal with raw palm kernel shell, wood pellets, walnut shell and empty fruit bunch.

In the current study, HGI test of raw and torrefied beech wood with three different methods made this study novel from all other published. Hence, it can be concluded that medium temperature

torrefied beech wood biomass could be used with coal in co-firing in the same installation equipment without any significant modifications or changes in the installation and grinding. Ohliger et al., [45] analysed that raw beech wood has poor grindability and moderate HGI value. The HGI results reported that grinding ability and milling capacity was improved significantly on torrefaction but less than Rhenish lignite. Similarly, Zhang et al., [1] observed the torrefaction of poplar sawdust and analysed the grinding behaviour by a particle distribution method.

In general, coal mills break up coal by a brittle fracture mechanism and most of the biomasses have poor grinding properties. Consequently, some larger and coarse biomass particles cannot be milled properly and therefore this can lead to limit the co-firing possibility. That is the reason why beech wood does not exhibit good grinding properties with lower HGI values and less carbon content in comparison to coal. But on torrefaction biomass can be easily milled and involved in the superior breaking of the fibrous chain (lignin, cellulose and hemicellulose) during grinding. It has been reported that HGI value becomes higher with the growth of carbon content [46]. This carbon content is increased on torrefaction and by increasing the torrefaction temperature. Apart from it, power consumption might be increased with increasing co-firing biomass ratio.

### **3.6 Effect of milling and particle size distribution**

The particle size distribution (PSD) is the relative amount of particles retained and sorted according to size. PSD is also termed as grain size distribution. Sieve analysis was performed to find out the percentage of different particle sizes retained within the fuel and to determine the distribution of finer as well as the coarser, particles [21]. The particle distribution having less than 75  $\mu\text{m}$  particle diameter were 70% while 99.5% particle distribution was found for  $>300 \mu\text{m}$  particle diameter that is the suitable particle size range for torrefied biomass [47]. Biomass

particles greater than 300  $\mu\text{m}$  were not burned completely in the given residence time and can be obtained as unburned carbon. All fuel samples were milled to a particle size of less than 250  $\mu\text{m}$  to enable complete burnout by using biomass crusher. The particle size distribution given in Fig. 6 shows that only 1.99% of the raw biomass passes through 50  $\mu\text{m}$  sieve and it improves the passage of biomass up to 7.3% that further increases up to 22.16% as the temperature of torrefied biomass increases from low to medium (200–250  $^{\circ}\text{C}$ ). In all cases, there is an improvement in the grindability characteristics of torrefied biomass as the percentage of fines increases for the samples subjected to the torrefaction process [45].

Gil et al., [33] reported that torrefied chestnut woodchips showed good grindability behaviour at 280  $^{\circ}\text{C}$  with 22 min of residence time that increased the amount of finer particles. Similarly, comparing the grindability characteristic of MTTB and LTTB at different sieve sizes, it can clearly be noted from Fig. 6 that only 20.04% of LTTB sample passes through 75  $\mu\text{m}$  sieve while in the case of MTTB it is 33.92%. In addition, the sieve of 200  $\mu\text{m}$  passes only 67.45% of LLTB that enhanced up to 80.25% in the case of MTTB. Compared with coal, it can be seen that 97.65% of MTTB particles show passage through 353  $\mu\text{m}$  sieve, which was 99.82% in the case of El Cerrejon with the same sieve size. It can be concluded that the particle distribution of MTTB is closest to coal and higher than LTTB.

The results of particle size distribution suggested that grindability characteristics are improved to a great extent if the raw biomass is pre-treated like torrefaction. It can also be observed that particle size decreases significantly with the rise in torrefying temperature. Reduction of large particles is obtained with an increment in torrefaction temperature that produces a major fraction of fine

particles in the range of  $200 \mu\text{m} < d < 353 \mu\text{m}$ . All trends are in good agreement with the study of Wang et al., [23] they reported the distribution of spruce bark particles having diameter  $< 0.063 \text{ mm}$  that was increased with an increment in temperature from 225 to 300 °C.

The cumulative particle distribution data at 10, 50 and 90% was used to determine the particle diameter of  $D_{10}$ ,  $D_{50}$  and  $D_{90}$ . The summary of sieve analysis presented in Table 5 is the particle diameter of the samples that determines whether a particle passes through the sieve opening. It is observed from the sieve analysis that particle dimensions are greatly reduced on torrefaction and produced more fine particles. The raw biomass has a higher particle size diameter almost 70  $\mu\text{m}$  that was reduced to 58  $\mu\text{m}$  in low torrefaction while further reduction is observed at medium temperature torrefaction by 10% cumulative distribution ( $D_{10}$ ). The particle size of MTTB (32  $\mu\text{m}$ ) was found to be comparable with coal particle size (38  $\mu\text{m}$ ) for combustion test. The particle distribution  $D_{90}$  showed that a suitable range of particle diameter for combustion is less than 300  $\mu\text{m}$ . Furthermore, it can be concluded that the decrease in particle size is mainly due to the reduction of the particle length. In overall, torrefied biomass produced relatively narrower or uniform particle size ranges as compared to untreated biomass [34].

### **3.6 Combustion reactivity**

Combustion reactivity was studied by measuring oxygen consumption concentrations from furnace entry-level to furnace exit level (2.5 m distance from burner). The combustion of different fuels (100% of Beech wood, EI Cerrejon, LTTB and MTTB) and co-combustion of 50% EI Cerrejon with raw biomass (Beech wood) and torrefied biomass (LTTB and MTTB) were performed to evaluate the consumption of oxygen and emissions of CO, NO<sub>x</sub> and SO<sub>2</sub>. Fig. 7 (a)

indicates the oxygen concentrations based on the measurement distances from the entrance level of the burner to 0.5, 1.5 and 2.5 m distance for all combustion settings.

The slowest oxygen consumption was found for beech wood combustion and co-combustion of beech wood and EI Cerrejon. The fastest oxygen consumption was observed for single coal combustion and cases involving torrefied beech wood either MTTB or LTTB (both combustion and co-combustion) [28]. The combustion of EI Cerrejon appears fastest in comparison to the combustion of MTTB or LTTB and co-combustion (50% EI Cerrejon+MTTB/LTTB) processes. The reason is that the introduction of torrefied biomass increased the combustion reactivity, therefore less time is required for its combustion while raw biomass usually contained larger particle size that burns out slowly and required more time for complete combustion [34].

### **3.7 Emissions profiles of CO, NO<sub>x</sub> and SO<sub>2</sub>**

Fig. 7 (b-d) presents the emissions results during the combustion of 100% EI Cerrejon and beech wood on a thermal basis while co-combustion of 50% of EI Cerrejon with 50% of beech wood and torrefied biomass (LTTB and MTTB).

#### **3.8.1 CO emissions**

During flue gas analysis, the average highest concentration of CO appears during combustion of LTTB that was 3,048 ppm as given in Fig. 7 (a). It is noted that the highest CO released was found at 0.5 m distance from burner. It also indicates that raw biomass needs area to be burned completely, which provide complete combustion at 2.5 m distance from the burner. Moreover, the CO emission profiles show a significant reduction in moving from 0.5 to 2.5 m distance from the burner. It can be further noted that in the case of co-combustion of 50% EI Cerrejon and 50% beech wood, the amount of CO is increasing as the oil probe moves from 1.5 m distance to 2.5 m

distance which is also an unusual behaviour because of raw biomass. The CO content is considered as the first indicator for examining the combustion behaviour for various fuel settings [34].

The CO emission was significantly less in the case of EI Cerrejon combustion that was 404 ppm. CO released was 2,238 ppm comparing to the beech wood combustion. While in comparison with torrefied biomass (LTTB and MTTB) CO content was much increased. The lowest CO emission for EI Cerrejon was due to the presence of finer and homogeneous particles in coal as compared to the coarse particles in raw biomass. Similarly, comparing MTTB and LTTB, lesser CO release was noticed during MTTB combustion that was 1,054 ppm while 3,048 ppm CO release was observed during LTTB combustion. This less emission in the case of MTTB is because of improved homogeneity of biomass as well as finer particle distribution.

The co-combustion of 50% EI Cerrejon and 50% beech wood release only 130 ppm of CO that decreased to 37 ppm until the distance becomes 1.5 m from the burner while its concentration is increasing up to 179 ppm at 2.5 m distance that is an unstable behaviour due to raw biomass. The co-combustion of 50% EI Cerrejon with 50% MTTB or 50% LTTB release 2,373 ppm and 913 ppm CO respectively. These co-combustions release greater CO as compared to coal because of introducing torrefied biomass that may still possess coarse particles [48]. Comparing these CO emissions with other published results such as Kopczynski et al., [8] reported >70 ppm volumetric fraction of CO. Moreover, Lasek et al., [37] recorded up to 2,300 ppm while Varol et al., [49] reported >160 ppm of CO.

### 3.8.2 *NOx emissions*

NO<sub>x</sub> emissions occurred due to the presence of fuel nitrogen during combustion and co-combustion. The overall NO<sub>x</sub> emissions are depending on different factors including; temperature, residence time, volatiles amount and burner configurations [34]. Fig. 7 (c) indicates that the high amount of NO<sub>x</sub> was observed for EI Cerrejon combustion that was 730 ppm at 2.5 m distance from the burner because of the already bound high amount of fuel nitrogen. Beech wood produces remarkably less amount of NO<sub>x</sub> as compared to coal. Overall combustion behaviour of beech wood is not stable, but mostly the combustion of EI Cerrejon is stable. For torrefied beech wood (MTTB and LTTB), the NO<sub>x</sub> emissions were 269 ppm and 251 ppm respectively that representing only a little fraction of NO<sub>x</sub> emissions comparatively to EI Cerrejon (730 ppm). The increment of NO<sub>x</sub> in MTTB was due to devolatilisation of O, H and C content during torrefaction at high temperature and maybe because of the large amount of NH bond production as it is more stable compared to C-N in heterorings. Eddings et al., [48] analysed the reduction in NO<sub>x</sub> in raw pinewood combustion that is enhanced on torrefaction at high temperature [33].

The NO<sub>x</sub> released during co-combustion of coal and beech wood increases till distance from the burner becomes 1.5 m and from there it starts decreasing up to 450 ppm till 2.5 m distance from the burner. Comparing with only EI Cerrejon combustion, NO<sub>x</sub> amount was 450 ppm instead of 730 ppm that is almost half. While comparing with beech wood combustion, NO<sub>x</sub> amount was 252 ppm and here in the case of co-combustion NO<sub>x</sub> was 450 almost double ppm. Additionally, co-firing of 50% EI Cerrejon with 50% MTTB or 50% LTTB yields 555 ppm and 533 ppm NO<sub>x</sub> respectively. In comparison to EI Cerrejon, the NO<sub>x</sub> contents are reduced during co-combustion of coal with torrefied biomass while in comparison to beech wood, the NO<sub>x</sub> contents are enhanced.

Therefore, higher volatile yield and low nitrogen amount in torrefied beech wood compared to coal resulted in lower emissions. Furthermore, Thanapal et al., reported about 12% reduction in NO<sub>x</sub> emissions for torrefied mesquite in comparison to coal while in the present study, the NO<sub>x</sub> reduction is up to 30%.

### **3.8.3 SO<sub>2</sub> emissions**

Fig. 7(d) also indicates the SO<sub>2</sub> emissions during all combustion and co-combustion settings. The highest concentration of SO<sub>2</sub> was released by EI Cerrejon combustion that was 593 ppm at 0.5 m distance from burner. This highest emission was due to already bound high amount of fuel sulphur. The SO<sub>2</sub> emission was significantly decreased compared with beech wood combustion from 593 to 13.47 ppm. These SO<sub>2</sub> emissions were further decreased substantially in the case of torrefied biomass and produce negligible SO<sub>2</sub> that was 1.98 ppm for MTTB and 1.07 ppm for LTTB. The SO<sub>2</sub> reduction was observed because the amount of fuel sulphur as well as combustible sulphur, was decreased due to torrefaction [37]. Co-firing of EI Cerrejon with raw biomass and torrefied biomasses (LTTB and MTTB) produces remarkably less amount of SO<sub>2</sub> as compared to coal. The co-combustion of 50% coal and raw biomass releases 78–266 ppm SO<sub>2</sub> while the release of SO<sub>2</sub> was 329 ppm and 269 ppm during co-firing of 50% EI Cerrejon with 50% MTTB and 50% LTTB respectively.

The SO<sub>2</sub> concentration was reduced to half in the case of co-combustion of torrefied fuels and coal in comparison to EI Cerrejon due to presence of less sulphur content in torrefied biomass [50]. Torrefied beech wood already has a negligible amount of fuel sulphur that was in the range of 0.017-0.018% from fuel analysis given in Table 1. The SO<sub>2</sub> has been significantly reduced in the case of MTTB and LTTB combustion. In case of co-combustion, the reduction was not only due

to the replacement of 100% of coal input with 50% torrefied beech wood and 50% El Cerrejon but was also due to sulphur capturing in ash. Lasek et al., [37] reported the SO<sub>2</sub> emission of 2 ppm for torrefied willow and 1,184 ppm for polish hard coal that is a positive agreement with the present study, where SO<sub>2</sub> emissions were 1.98 ppm for MTTB, 1.07 for LTTB and 593 ppm for El Cerrejon that is a significant reduction in SO<sub>2</sub> amounts.

### ***3.8.4 Comparison of flue gas emissions at the furnace exit***

To compare flue gas emissions (CO, NO<sub>x</sub> and SO<sub>2</sub>) of different combustion and co-combustion settings, it was corrected to 6% O<sub>2</sub> in the flue gas, the data is shown in Fig. 8. It can be seen from the comparison of different fuels' emissions that El Cerrejon produces almost double NO<sub>x</sub> and SO<sub>2</sub> as compared to raw biomass as well as torrefied biomasses (LTTB and MTTB). In the case of monocombustion of all fuels, El Cerrejon produces 1,231 mg/m<sup>3</sup> of NO<sub>x</sub>, 1265 mg/m<sup>3</sup> of SO<sub>2</sub> and 17.5 mg/m<sup>3</sup> of CO. In contrast, LTTB releases about 426 mg/m<sup>3</sup> of NO<sub>x</sub>, 2 mg/m<sup>3</sup> of SO<sub>2</sub> and a negligible amount of CO. This significant emission reduction was due to light torrefaction of biomass at low temperature 200 °C. But the co-combustion of coal with raw biomass and torrefied biomass (LTTB and MTTB) reduces the NO<sub>x</sub> to almost 30% and SO<sub>2</sub> releases to about half of the coal emission [34]. Under the current scenario of environmental pollution [51, 52], there is a need to develop renewable fuels [53, 54] and sustainable energy technologies [55, 56] to reduce CO<sub>2</sub> emissions [30, 57] and control global warming [58]. Consequently, torrefied biomass is an excellent renewable fuel that could be used as an alternative to coal for co-firing in power plants.

## **4 Fly ash analysis**

Ash is an inorganic incombustible part of the fuel that is left after complete combustion, containing a bulk of mineral fraction of original biomass. During the process of combustion, the ash from the flue gas in the oil probe was collected and was analysed for multiphase carbon to determine the

degree of fuel conversion during tests. The multiphase carbon analysis of all fly ash samples is presented in Fig. 9, which was taken under different configurations showed complete combustion of fuels in all type of settings. Achieving complete combustion was a prerequisite for a good comparison of the flue gas emissions in different configurations. Elemental analysis of the ashes of different fuels shows that total organic carbon (TOC) in El Cerrejon is higher than the total organic carbon in raw biomass and torrefied biomasses (MTTB and LTTB). It may be explained because the biomass is considered as a near CO<sub>2</sub>-neutral fuel and contains almost negligible CO<sub>2</sub> emission as compared to coal. However, NO<sub>x</sub> contributions to the GHG footprints should also be watched [59].

That is why the world is now focusing on replacing the coal with biomass to reduce CO<sub>2</sub> emissions. Results also show that the MTTB that was prepared at 250 °C contains 0.4% of TOC while LTTB prepared at 200 °C contains only 0.1% of TOC. Therefore, it can be concluded that by increasing torrefaction temperature, total organic carbon content increases from 0.1 to 0.4%. It may be explained because the mass becomes more densified at high torrefaction temperatures with increment in fineness of fuel particles and more ash is collected at the lower portion of the combustion chamber due to higher weight loss [29]. The increment in TOC was reported because of 1.15% ash contents were found for MTTB, while 1.12% ash content for LTTB from fuel analysis as given in Table 1. The co-combustion of coal and torrefied biomasses (LTTB and MTTB) improves the TOC content from 0.75 to 1.05% because of introducing torrefied biomass. However, this content is decreased up to 0.1% in the case of co-combustion with 50% coal and 50% raw beech wood because biomass has a negligible amount of carbon.

### 3.8 Ash melting behaviour

Ash melting behaviour of biomasses and coal employed to determine the ash fusibility temperatures (IDT, ST, HT and FT) [36]. It can be seen from Table 6 in all possible configurations of combustion and co-combustion the IDT was increased after low and medium torrefaction of raw biomass as well as for all combinations of coal and torrefied fuels (50% El Cerrejon + 50% MTTB/LTTB). All mixtures of fuels after torrefaction showed IDT greater than 830 °C. Vassilev et al., [60] proposed a wide range of IDT (670–1565 °C) for 87 varieties of biomasses and coal. The ash melting behaviour is closely related to ash contents that contain various oxides including; MgO, Na<sub>2</sub>O, CaO, K<sub>2</sub>O, Fe<sub>2</sub>O<sub>3</sub>, Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub> and little amount of TiO<sub>2</sub> as shown in Fig. 10. Niu, Tan [61] suggested that IDT is increased due to the presence of a large amount of CaO, Fe<sub>2</sub>O<sub>3</sub>, MgO and Al<sub>2</sub>O<sub>3</sub> while IDT is decreased with an increment of K<sub>2</sub>O in ash composition.

In this study, IDT value decreases in following order: El Cerrejon (1240 °C) > El Cerrejon + MTTB (980 °C) > El Cerrejon + LTTB (950 °C) > El Cerrejon + Beech wood (920 °C) > MTTB (840 °C) > LTTB (980 °C) > Beech wood (790 °C). It is concluded that all these IDT trends depend on the flue gas emission and mineral composition in ash. To get more information about ash melting, the hemisphere temperature is considered more informative characteristics of ash fusion temperature. The range of ashes of hemisphere temperatures for all fuels is almost 1,200–1,450 °C that can be categorised into moderate HT in accordance with Vassilev et al., [62] study. This temperature is decreased on the co-combustion of coal and torrefied fuels. It may be explained due to significant reduction up to 3% in K<sub>2</sub>O content during co-combustion. The potassium content is much problematic during combustion of single fuels, but during co-combustion it decreases.

Therefore, IDT temperatures are higher in the case of co-combustion of El Cerrejon and torrefied biomasses while the other melting temperature characteristics including; ST, HT and FT are not presented a similar trend. These temperatures are reduced during co-combustion of coal and torrefied biomasses (LTTB and MTTB) as compared to mono-combustion. The reduction in all these temperatures is because of the torrefied biomass substitution and the particle size dimension. The obtained ranges of these melting temperatures are larger than 1,250 °C. These ranges are considered as suitable values for the combustion in fluidised bed combustor. It is observed that slagging, corrosion and fouling is increased by introducing raw biomass in coal during co-combustion.

The sodium and potassium contents in biomass have a direct effect on agglomerate formation during co-combustion. Agglomeration, as well as slagging is enhanced due to the formation of eutectics that have melting points lower than their individual components [63]. The oxides in fly ash that are displayed in Fig. 10 indicate that the SiO<sub>2</sub> is most predominant oxide in all used fuels. CaO, as well as K<sub>2</sub>O oxides are additionally considered next predominant oxides that are greater in raw and torrefied biomass as compared to El Cerrejon combustion and all co-combustion configurations. Eddings et, McAvoy [48] also observed in fly ash analysis of pine wood and torrefied types that K<sub>2</sub>O is decreased significantly on torrefaction of pine wood. Torrefied biomass contains 12–13% K<sub>2</sub>O that reduced up to 3.8% during co-combustion of fuels while El Cerrejon was just 1.32%. Because biomass has more alkaline earth metals compared to coal that may cause slagging and fouling. The K<sub>2</sub>O content in less amount is also responsible for the increment of IDT temperature that can be seen in El Cerrejon and prevents from slagging [64].

The CaO content is rich in raw biomass, almost 38% while its content is decreased in the case of torrefied biomass and co-combustion with torrefied biomasses. The torrefaction reduced the fusion temperatures, especially softening temperatures in comparison to raw biomass that has high CaO content that makes it does not melt or hardly melt at physical operating temperatures. The MgO content in the ash of biomass and torrefied biomass combustion is high in the range of 3–5% that is significantly decreased during separate coal combustion. Different ash component and minerals affect the ash fusibility temperatures in ash melting behaviours. The Na<sub>2</sub>O content also has a direct effect in reduction ash fusion temperatures for biomass and especially in those ash samples that have a larger amount of CaO. These characteristics temperatures and ash contents provide the first indication of the fuel quality for combustion in fluidised bed combustor [36].

## **5 Conclusions**

Torrefaction of beech wood was performed using batch scale reactor at three different temperatures (200, 250 and 300 °C) with 30 min of residence time. The chemical structural changes on torrefaction were investigated by FTIR analysis as well as binding energies. The HGI values with three different methods like DIN51742, IFK and ISO standard have shown that MTTB yields HGI value as 32.75 and LTTB yields HGI value as 23.78. The difference in HGI values of coal and MTTB is almost 3–4 values, so by a minor change in torrefaction temperature biomass could be co-milled with coal in already existing pulverisers without any significant loss of mill capacity. During combustion of a single fuel, LTTB produces less amount of NO<sub>x</sub> (426 mg/m<sup>3</sup>), CO (0.002 mg/m<sup>3</sup>) and SO<sub>2</sub> (2 mg/m<sup>3</sup>) as compared to MTTB. The torrefying biomass at high temperatures increases nitrogen content, therefore, it is recommended that biomass should not be torrefied at high temperatures. In the case of co-combustion, it is found that premixing of coal with torrefied

biomass gives the most stable behaviour and reduces the NO<sub>x</sub> almost 30% and SO<sub>x</sub> up to 50% compared to coal. The ash melting behaviour showed that initial deformation temperature of co-combustion of torrefied fuels with coal was higher in comparison to raw biomass and coal. The fly ash contents analysis proved that K<sub>2</sub>O content is much decreased during co-firing of coal and torrefied fuels that may be problematic issues during combustion of raw biomass. However, a further specific examination regarding slagging, fouling as well as agglomeration is required. Future study may include the usage of co-combustion of coal and torrefied beech wood at large scale implementation of bioenergy.

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## List of Tables

**Table 1.** Ultimate, proximate analysis and calorific values of coal and other biomass fuels.

Fuels	Ultimate analysis <sup>a</sup>					Proximate analysis <sup>c</sup>				GCV	NCV
	C (%)	H (%)	N (%)	O <sup>b</sup> (%)	S (%)	M <sup>d</sup> (%)	VM (%)	FC (%)	Ash <sup>d</sup> (%)	kJ/kg	kJ/kg
Beach wood	46.80	6.40	<0.30	42.50	0.021	5.41	82.00	16.84	1.16	19429	17374
El Cerrejon	78.50	5.98	1.57	13.48	0.47	2.25	31.00	55.00	140	28134	27205
LTTB	49.90	6.32	<0.30	40.10	0.017	3.00	77.88	21.00	1.12	21058	19690
MTTB	53.30	6.18	<0.30	36.70	0.018	2.38	71.85	27.00	1.15	21698	20352

M: moisture, VM: volatile matter, FC: fixed carbon, GCV: gross calorific value, NCV: net calorific value, LTTB: low torrefied temperature biomass, MTTB medium torrefied temperature biomass

- a. On a dry basis except as denoted in the table.
- b. Calculated by the difference.
- c. On a dry basis except for moisture which is on an as-received basis.
- d. As the received basis.

**Table 2.** Equipments and techniques for standard flue gas analysis.

<b>Gas component</b>	<b>Manufacturer technique</b>	<b>Manufacturer</b>	<b>Calibration gas</b>
O <sub>2</sub>	Paramagnetism	Rosemount	3 vol% in N <sub>2</sub>
CO	NDIR	Rosemount	200 ppm in N <sub>2</sub>
NO <sub>x</sub>	Chemiluminescence	ECO Physics	800 ppm in N <sub>2</sub>
SO <sub>2</sub>	Infrared	Siemens	700 ppm in N <sub>2</sub>

**Table 3.** Input BTS-VR parameters for different combustion settings.

<b>Parameter</b>	<b>Values at STP</b>
Wall Temperature (°C)	1,300
Air ratio	1.15
Transport air (m <sup>3</sup> /h)	1.50
Primary air (m <sup>3</sup> /h)	2.08
Secondary air (m <sup>3</sup> /h)	3.12
Total burner air flow rate (m <sup>3</sup> /h )	6.70
Residence time (Minutes)	0.70

**Table 4.** Thermal kinetics and binding energies of various bonds in biomass.

<b>Bonds</b>	<b>Binding energy (kJ/mol)</b>	<b>Bonds</b>	<b>Binding energy (kJ/mol)</b>
<b>C=C</b>	615	<b>C-H (methane)</b>	415
<b>C-C (aromatic)</b>	519	<b>N-H</b>	389
<b>C-H (-CH<sub>3</sub>)</b>	507	<b>C-O</b>	364
<b>O-H</b>	465	<b>C-C</b>	348
<b>C-H (-CH<sub>2</sub>-)</b>	444	<b>C-O</b>	331
<b>N=N</b>	419	<b>C-N</b>	285

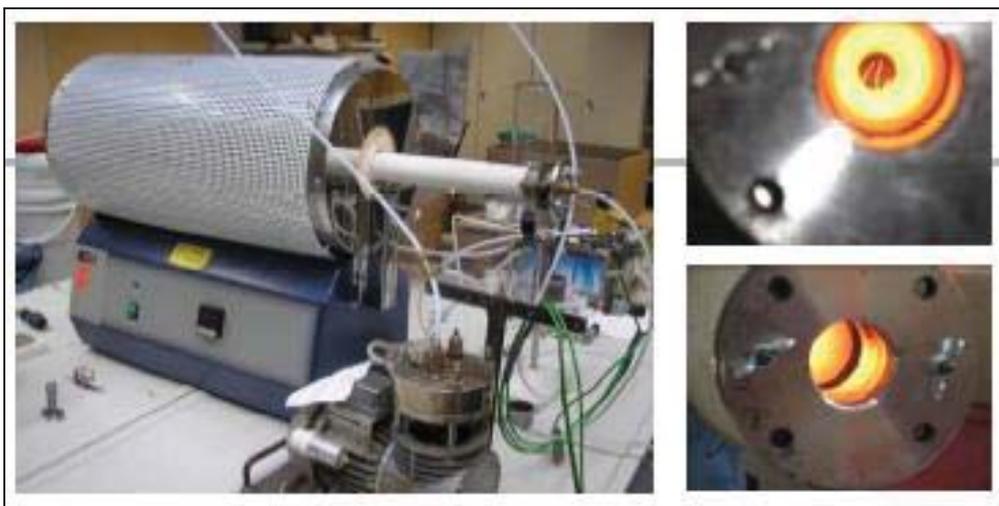
**Table 5.** Summary of fuels' sieve analysis.

<b>Diameter</b>	<b>Beech wood</b>	<b>El Cerrejon</b>	<b>LTTB</b>	<b>MTTB</b>
D <sub>10</sub> (μm)	70	38	58	32
D <sub>50</sub> (μm)	188	50	150	120
D <sub>90</sub> (μm)	300	87	300	250

**Table 6.** Ash fusion temperatures for different combustion and co-combustion settings.

<b>Tempertures (°C)</b>	<b>Beech wood</b>	<b>El Cerrejon</b>	<b>LTTB</b>	<b>MTTB</b>	<b>EC+ Beech wood</b>	<b>EC+ LTTB</b>	<b>EC+ MTTB</b>
initial deformation (IDT)	790	1,240	830	840	920	950	980
softening (ST)	1,440	1,260	1,310	1,350	1,310	1,220	1,240
hemisphere (HT)	1,420	1,270	1,390	-	1,320	1,220	1,240
flow (FT)	-	1,290	1,400	1,370	1,320	1,220	1,240

## List of Figures



**Fig. 1.** Horizontal tube furnace setup for batch torrefaction experiments.

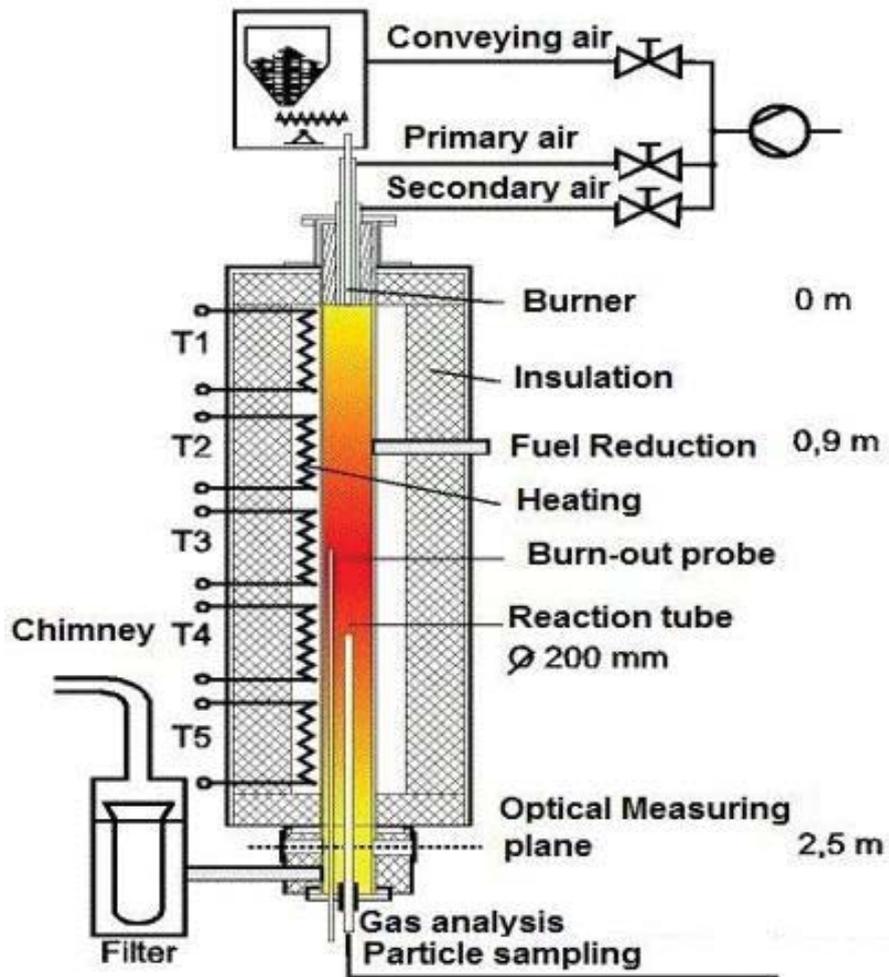


Fig. 2. Atmospheric entrained flow combustion reactor setup.

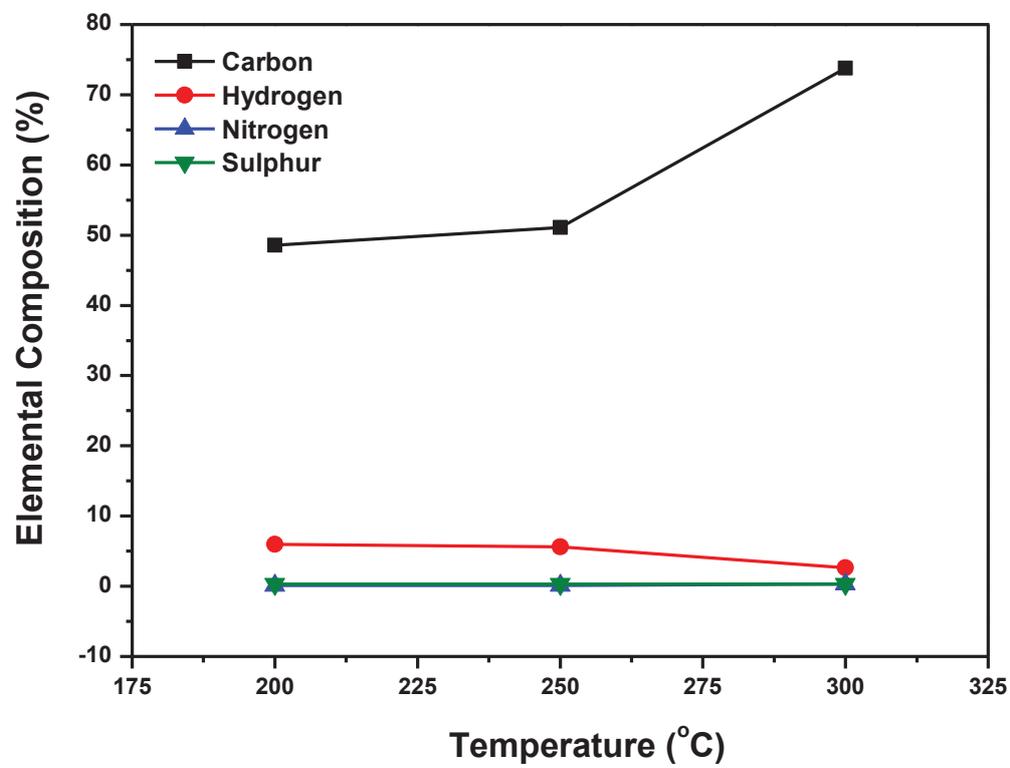


Fig. 3. Elemental analysis of beech wood at different torrefaction temperatures.

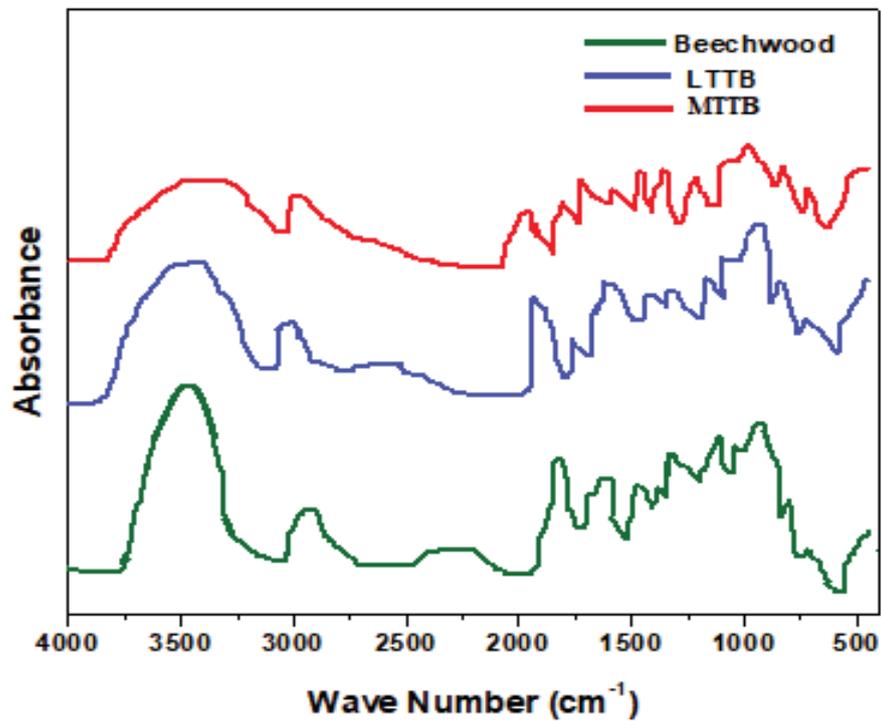
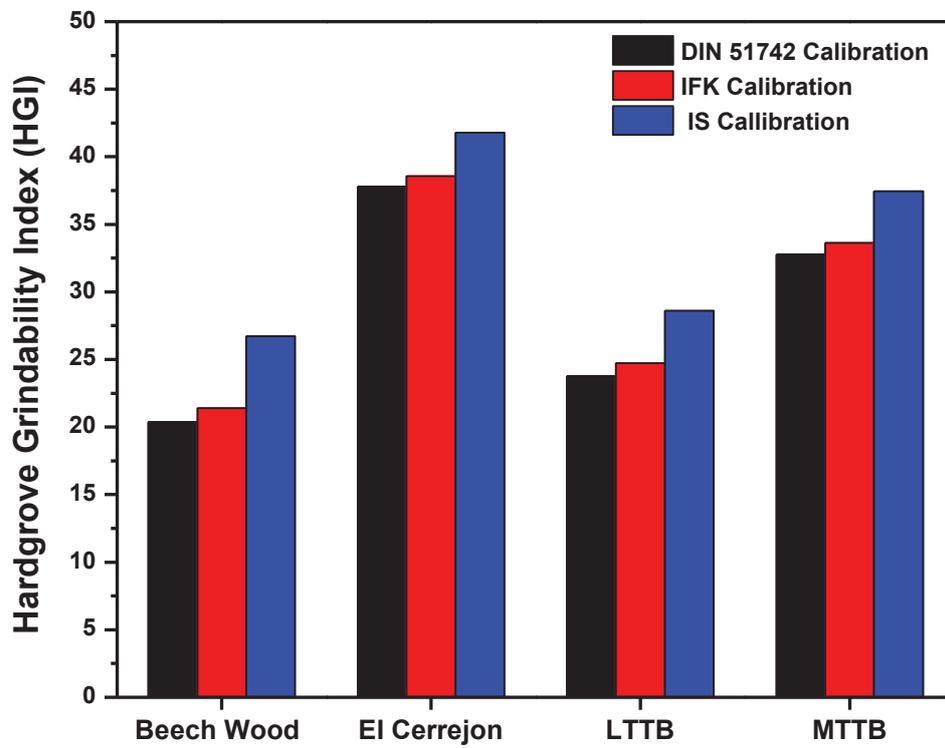
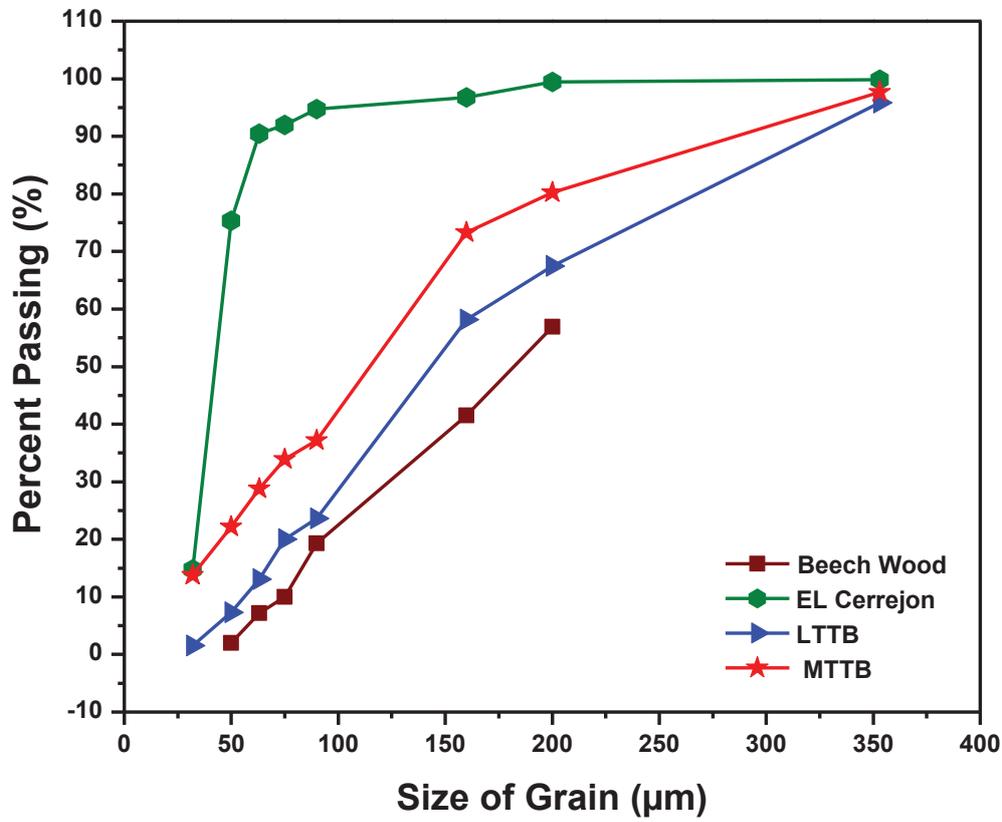


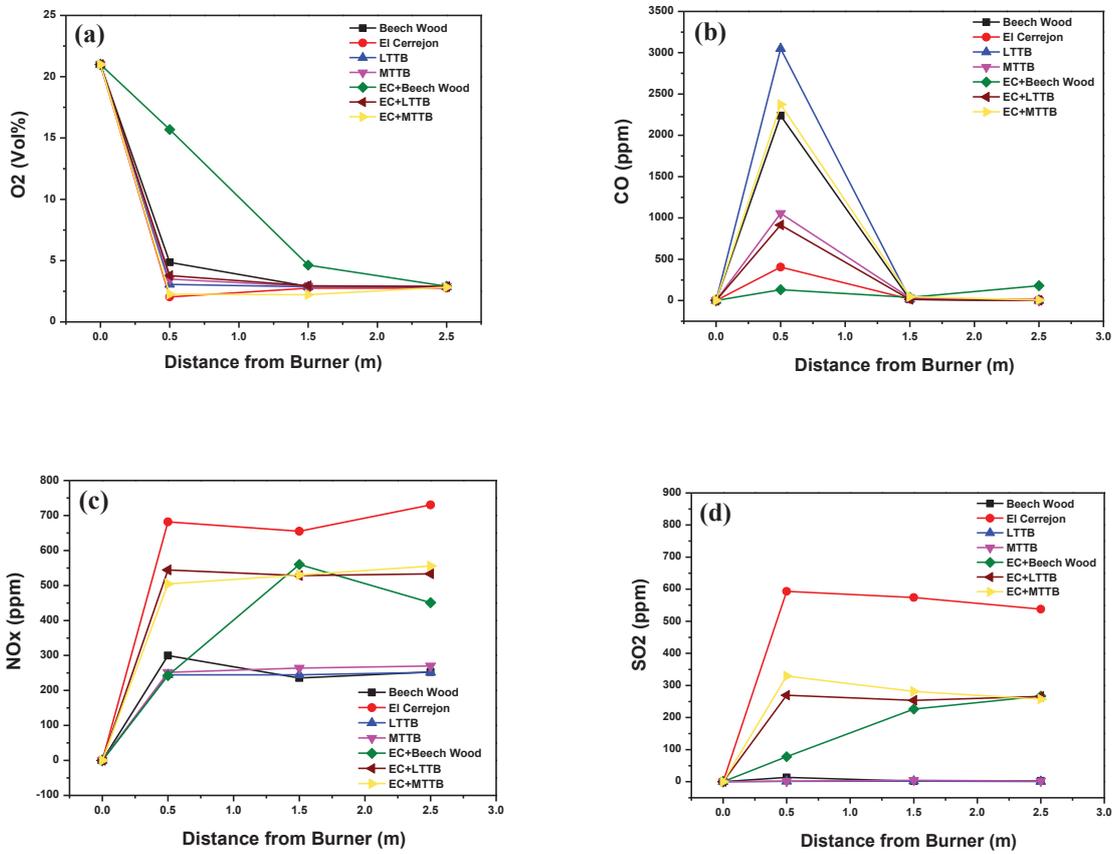
Fig. 4. FTIR spectra of raw and torrefied beech wood biomass (LTTB and MTTB).



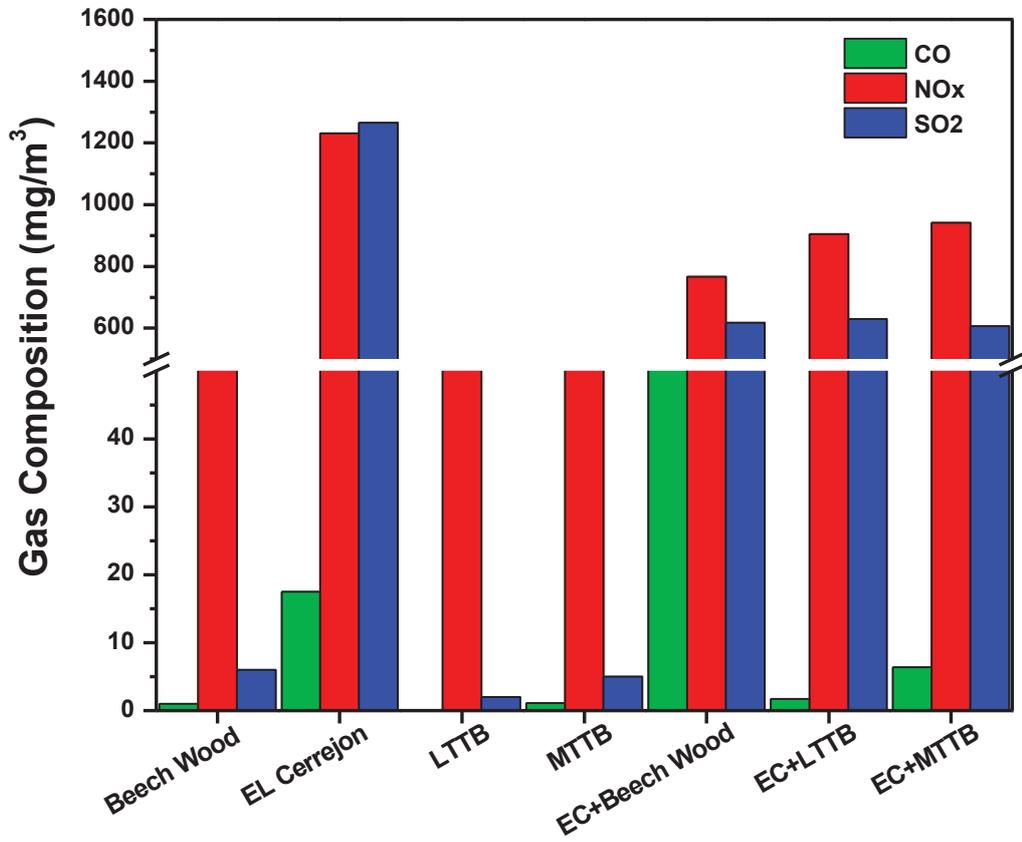
**Fig. 5.** Comparison of HGI values of different fuels found by DIN 51742 IFK, and IS calibration methods.



**Fig. 6.** The particle size distribution of coal, raw biomass and torrefied biomasses (LTTB and MTTB) after grinding.



**Fig. 7.** Flue gas emission profiles at various distances from the burner during combustion and co-combustion of raw biomass, coal and torrefied biomasses (LTTB and MTTB); (a) O<sub>2</sub>, (b) CO, (c) NO<sub>x</sub> and (d) SO<sub>2</sub>.



**Fig. 8.** CO, NO<sub>x</sub> and SO<sub>2</sub> concentrations in flue gas at the furnace outlet for various combustion settings, corrected at 6% O<sub>2</sub> in the flue gas.

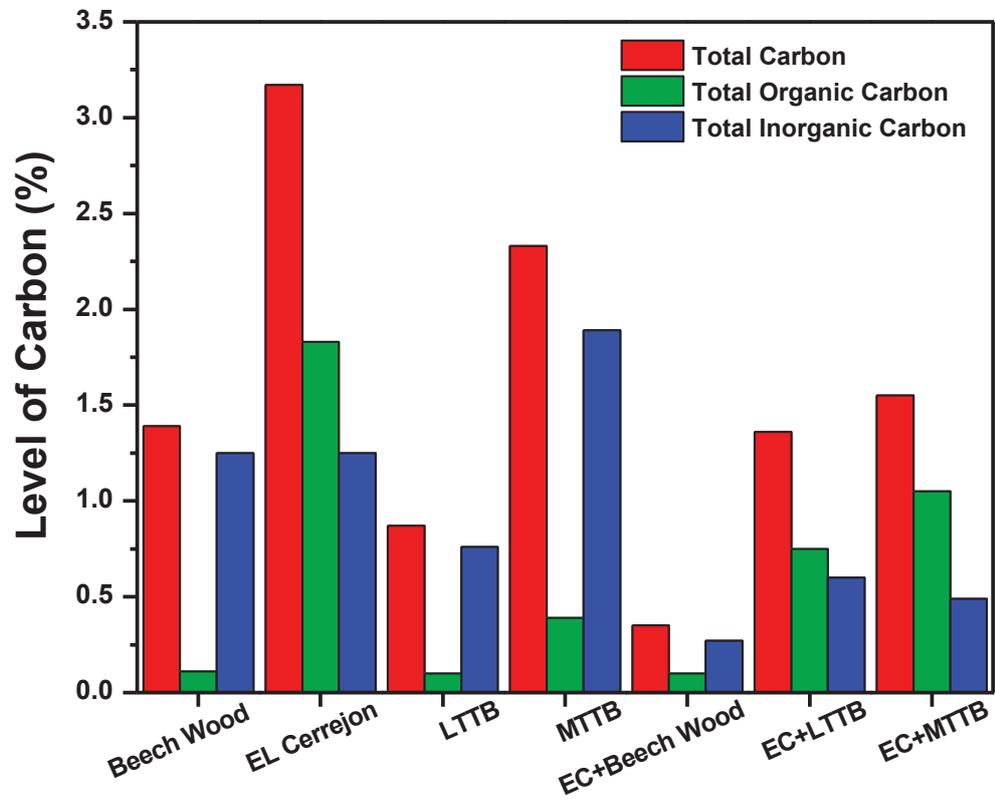


Fig. 9. Multiphase carbon analysis of fly ash taken from furnace exit.

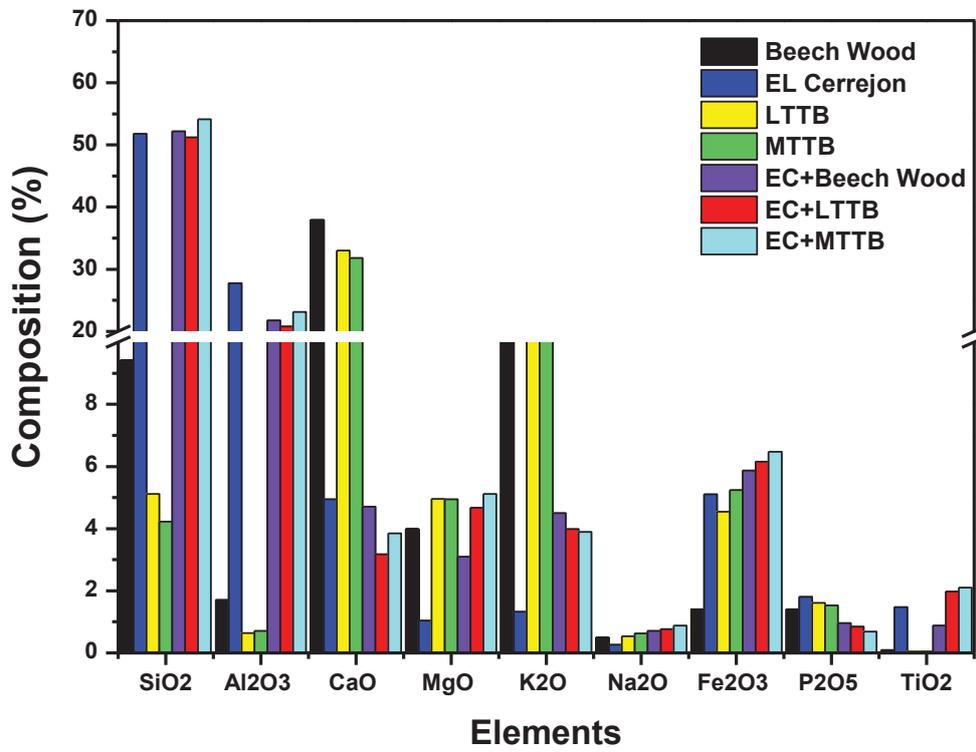


Fig. 10. Fly ash composition of different fuels in terms of elemental oxides.