Effect of blending coal with torrefied biomass for possible application in energy production

ABSTRACT

Emissions of greenhouse gases mostly from fossil fuels are responsible for global warming and climatic changes. This has led to research in bioenergy to reduce greenhouse emissions because bioenergy is part of the carbon cycle, and can only emit greenhouse gases that are part of the carbon cycle. The drawback is its low calorific value when it is in its raw form. Torrefaction improves its energy content to values that are comparable to coal.

In this study, marula seeds and blue gum wood, two of South Africa most abundant biomass, were blended with coal both raw and torrefied to see the impact of the torrefaction process on energy density. Blending was done at different ratios to see the optimum results. Results showed that highest calorific value was obtained at 100% marula seeds and 0 % coal, and it was recommended for further studies. Blue gum wood due to its high moisture had slightly higher heating value than the reference coal but from an economical point of view it was not attractive for further studies. This showed the significance of the torrefaction process in increasing heating value of selected biomass in the hope of reducing effects of greenhouse gas emissions.

Keywords: Coal, Biomass, Blending, Torrefaction

1. Introduction

Bioenergy is receiving wide spread attention as an alternative to fossil fuels and coal for the future. Some of the success stories from biomass are bioethanol and biodiesel which have vast applications and are able to reduce fossil fuel consumption thereby mitigating greenhouse gas emissions. The reason for an increase in the interest of biomass use is due to the fact that it is a renewable resource that is environmentally friendly as it releases less CO_2 into the atmosphere as compared to fossil fuels like coal i.e. CO_2 that is released is already part of the carbon cycle (Du *et al.*, 2014; Emami-Taba, *et al.*, 2013; Wannapeera, 2011). In addition there is an increase in carbon conversion when biomass is used or a larger proportion of biomass as compared to coal is used. However, there is an increase in CO concentration from biomass as compared to CO from coal, and the trend is the same when the two are blended giving higher concentrations of CO especially when biomass is ratio increases (Emami-Taba, *et al.*, 2013).

Research has shown that 14% of world's global energy demand is supplied by renewable energy with 13.4% of the primary energy being biomass. This share is mainly from traditional biomass. Renewable energy is mainly utilized for electricity generation, heat in industrial processes and transportation fuels (Dhillon & von Wuehlisch, 2013). Research has concluded that power plants that uses pulverized coal produces considerable greenhouse gases (GHG) emissions this has motivated research for alternative sources of fuels or co-firing of coal and biomass appears to be the solution. However, biomass as provided by nature has less energy density, higher moisture and volatiles levels when compared to coal (van der Stelt *et al.*, 2011; Wen *et al.*, 2014). Torrefaction is regarded as a simple and effective method to transform the biomass to become almost at par with coal in terms of energy density.

Torrefaction is a thermal pretreatment process, conducted at relatively low temperatures, between 200 and 300 ^{o}C, in an inert atmosphere with the aim of modifying biomass' chemical properties to:

(i) improve energy density (increase C/H and C/O ratio)
(ii) improve ignition properties
(iii) remove/reduce moisture and O_2 levels
(iv) improve gindability by partial disruptions of lignocellulosic structure thereby reducing energy required for grinding, and
(v) make biomass more homogenized i.e. torrefaction devolatilize, depolymerize and carbonize the biomass

This modification enhances the combustion performance particularly in a boiler and for gasification applications, and it changes biomass to being hydrophobic i.e. to have less affinity for water. This means that biomass can be used as an alternative to coal in the blast furnaces as coke (Du *et al.*, 2014). Bridgeman *et al.* (2008) studied raw and torrefied willow exposed to a methane-air flame and found that the latter was ignited more quickly than the former.

Wood biomass is currently the best alternative fuel because it is cheaper, is a renewable resource and it contains low amounts of sulphur and nitrogen meaning it results in low SO_x and NO_x emissions. That is why many researchers have investigated the co-firing characteristics of wood biomass and coal with respect to application in existing power plants with restricted modifications. Wood biomass fuels can cause flame instability because of their low heating values due to higher quantities of volatile matter in the biomass, low carbon content and low melting temperatures of ash, which leads to slagging and fouling (Ahn *et at.*, 2014). That is why the blending rate is controlled very carefully in power plants.

However, the released volatile matter and the oxygen component in biomass lead to a low ignition temperatures, and activation energies, and also affect char combustion (Ahn *et at.*, 2014).

2. Torrefaction process

Several authors have described the process in detail (Basu *et al.*, 2014; Lu *et al.*, 2013; Peng *et al.*, 2013; Sabil *et al.*, 2014; Tumuluru *et al.*, 2012). Parameters that affect the process consists of:

(i) Reaction temperature in the range 200 to 300 ^{o}C
(ii) Heating rate up to 50 ^{o}C/min
(iii) Residence time up to 60 minutes
(iv) Some technologies uses elevated pressures but generally ambient pressures are used
(v) Variations of O_2 up to 20% (atmospheric O_2 content is about 21%)
(vi) Different biomass samples

Due to large biomass requirements, the chosen raw biomass should be able to meet the demand and that is why different biomass samples have been investigated. So far in South Africa, marula seeds and blue gum wood are some of the abundant raw biomass samples that can be used to investigate the effect of the torrefaction process and as such they were investigated for possible use as biomass to help in co-firing coal fired boilers for electricity production.

During torrefaction, biomass partially decomposes giving-off volatiles and producing an energy dense solid matrix. Loss of the tenacious nature of raw biomass is mainly coupled to the breakdown of the hemicellulose matrix which bonds the cellulose fibres in the raw biomass and decrease the length of the fibres during depolymerization process (Li *et al.*, 2012).

The co-firing of coal with biomass, particularly wood biomass, is a high efficiency technology and offers a potential solution to coal exhaustion and the GHG problem (Ahn *et at.*, 2014).

3. Experimental method

3.1. Materials and preparation

Two different South African biomass samples were investigated: marula seeds and blue gum wood. A reference coal sample was used for comparison and it was obtained locally.

3.2. Screening and size reduction

The preparation steps mainly involved size reduction and the reference coal also underwent similar steps before blending tests.

3.2.1. Screening

Screening was undertaken using different screen sizes due to the nature of the biomass samples. A 2 kg sample of raw marula seeds was screened with 14, 18 and 19 mm screen sizes to determine the top size and the most contained size fraction. 2 kg of a 4.5 cm diameter blue gum tree was cut to smaller pieces for ease of handling. The sample was also screened with 14, 18 and 19 mm screen sizes to determine the top size and the most contained size fraction. The size fractions obtained were weighed then mixed.

Marual seeds and blue gum wood samples were oven-dried overnight at 150 ^{o}C and milled to 100% passing 1.18mm. The biomass samples were screened using vibrating screens. The experimental procedure was analogous to Du *et al.* (2014) and Wannapeera *et al.* (2011).

3.2.2. Crushing

Crushing was done in two stages; primary and secondary. A jaw crusher was used for first stage of crushing to reduce the size fraction of biomass prior to cone crushing. A cone crusher that was used could crush to < 4 mm size fractions. The samples obtained after the second stage were screened with 1.18 mm screen size to remove the fines that were generated during the process. The screen oversize (> 1.18 mm) fraction was subjected to milling by means of a rod mill.

3.2.3. Milling

The screen over size of each biomass was milled separately for 45 minutes. The milled samples were screened with 1.18 mm screen and the screen oversize was subjected for pulverization.

3.2.4. Pulverization

The remainder of the sample >1.18 mm was pulverized for 6 minutes using a steel bowl to 100% passing through 1.18 mm. The screen undersize was composited with the fraction <1.18 mm obtained from milling.

3.3. Proximate analysis and Pretreatment of biomass

The proximate analysis was performed in accordance with the standard procedure of the American Society for Testing Materials (ASTM E870-82). The calorific value was determined according to BSI standard EN 14918 with a bomb calorimeter, in which 0.50 g of oven-dried biomass was completely combusted under a pressurized O_2 atmosphere (Chin *et al.*, 2013).

The biomass samples were pretreated by torrefaction process and the conditions used are summarised in Table 1. The conditions were investigated and optimised in two separate investigations (Mamvura and Muzenda, inpress 1a, 1b).

Table 1: Optimum conditions used during torrefaction process

Biomass	Temp (°C)	Heating rate	Residence time	O_2 levels
Marula seeds	300 °C	15 °C/min	20 mins	0%
Blue gum wood	300 °C	15 °C/min	40 mins	0%

Nitrogen gas was continuously pumped into the horizontal tube furnace for the duration of the torrefaction process and cooling process to prevent auto-ignition of the biomass samples.

3.4. Energy density

Torrefaction is a thermal pretreatment process, conducted with the aim of modifying biomass' chemical properties to improve its energy density i.e. to increase the C/H and C/O ratios (Chen *et al.*, 2013). Energy density was calculated as follows:

$Energy\ Density = \frac{Energy\ Yield}{Mass\ Yield}$ (Lee & Lee, 2014)

where energy yield is calculated as: $Energy\ Yield = Mass\ yield \times \frac{HHV_t}{HHV_r}$ (Chin *et al.*, 2013

where HHV_t and HHV_r represent calorific values (heating values) of torrefied and raw biomass respectively

and mass yield is calculated as: $Mass\ Yield = \frac{M_t}{M_r} \times 100$ (Lee & Lee, 2014)

where M_r is mass of raw biomass and M_t is mass of torrefied biomass

3.5. Blending tests with reference coal

The blending tests were varied from 20 to 100% at 20% interval. The tests were done using raw biomass and torrefied biomass obtained at optimum conditions for the two biomass samples.

4. Results and discussions

4.1 Proximate analysis and Pretreatment

The proximate and calorific value analysis of the biomass samples and coal are provided in Table 2. The reference coal sample used had a lower moisture content as compared to the two biomass samples used even after drying to remove unbound water at 105 °C. However, the biomass samples had higher volatile matter and lower fixed carbon when compared to the reference coal. A study by Du *et al.* (2014) showed that torrefaction resulted in a linear decrease in volatile matter (VM) with an increase in temperature and there was an increase in fixed carbon (FC) as compared to coal.

Table 2: Proximate and calorific analysis for the biomass samples and reference coal

	Reference coal	Marula seeds	Blue gum wood
Moisture[a]	4.1	14.3*	50.5*
Proximate analysis (wt%)[b]			
Volatile Matter (VM)	28.2	79.1	82.1
Fixed Carbon (FC)	54.4	15.8	12.6
Ash	17.3	5.1	5.3
Higher heating value (HHV)			

Higher heating value (MJ/kg) – Torrefied	23.18	28.79	24.74

[a]Moisture analysis is for as received samples that were dried overnight at 105 °C.

[b]Proximate analysis is on a dry basis

Du *et al.* (2014) observed that up to 300 °C , VM for biomass was higher than for reference coal while FC for biomass was lower when compared to reference coal. These results were similar to the results obtained in the current study and in other studies (Doroodchi *et al.*, 2013; Idris *et al.*, 2012).

Ash content for reference coal was higher than for the two biomass samples which was to be expected as coal is fossil fuel formed from deposits of biomass over thousands of years i.e. there is accumulation of ash over the years (Idris *et al.*, 2012).

The heating value of the biomass samples was lower than that of the reference coal when raw (as expected) but it improved after torrefaction. Marula seeds had a 41% increase in heating value while blue gum wood had a 25% increase. The increases were based on HHV before and after torrefaction as presented in Figure 2 i.e. the formula used was $\frac{HHV_{after}-HHV_{before}}{HHV_{before}}$ and the answer presented as a percentage. The higher heating value for biomass samples as compared to reference coal was due to the inherent nature of the VM in biomass which has high reactivity and i.e. the VM ignite quickly (Ahn *et at.*, 2014). The biomass results in increased hydrocarbon contents as compared to coal giving higher heating values (Emami-Taba *et al.*, 2013). Even though the values were higher than for reference coal after torrefaction, the change for blue gum wood was not feasible from an economical point of view at it was only 6.7% higher than for reference coal after torrefaction process.

The reason for lower calorific values after torrefaction for blue gum wood and for raw biomass samples before torrefaction could be due to higher moisture content and VM in biomass samples. Coal usually has a moisture content of approximately 5%. Higher moisture content affects the combustion properties of biomass by reducing heat of combustion given out and increases the residence time required to achieve complete combustion (Du *et al.*, 2014). These effects may have led to incomplete combustion and subsequently an increase in the emissions of the flue gases. Calorific values of biomass samples are affected by, amongst other factors, moisture content and density (Du *et al.*, 2014). Studies on wood calorific value showed that higher moisture content led to lower calorific values of the biomass (Figure 1).

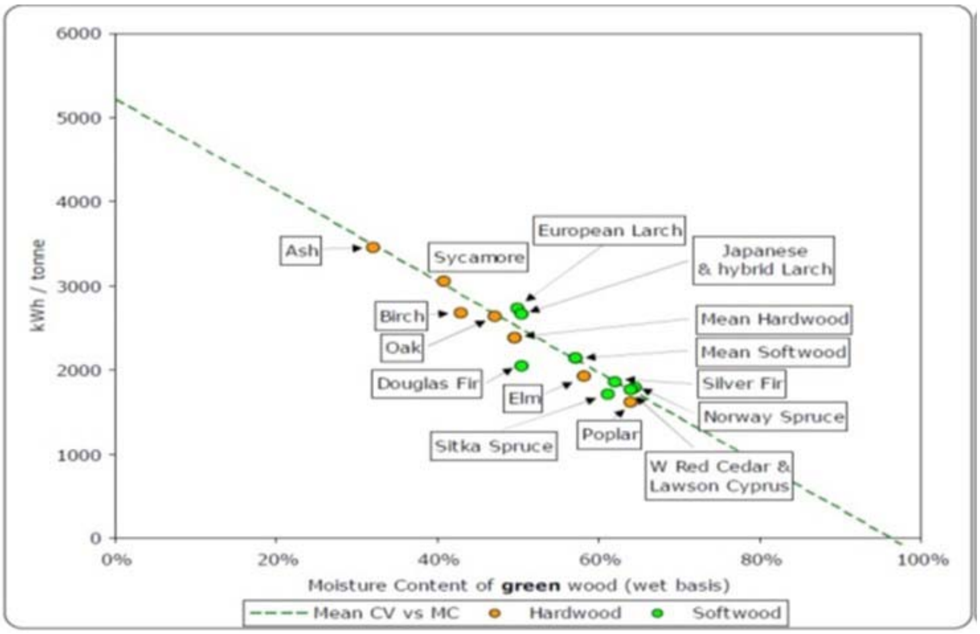

Figure 1: Effect of moisture content on calorific value of different biomass (Data obtained from Biomass Energy Centre website)

NB: Data at 0% moisture is through extrapolation but it is an idealised state which we are not interested in this study.

This was explained based on the burning process. It was noted that materials with high moisture content required a longer burning process because the rate of evaporation of water is low. Figure 1 showed that with an increase in moisture content, there is a decrease in energy content for the fuel as some of the energy is used to heat the water to boiling point and changing its phase.

After torrefaction at the optimum conditions, comparison showed that marula seeds had a higher calorific value than blue gum wood and reference coal (Table 2 and Figure 2).

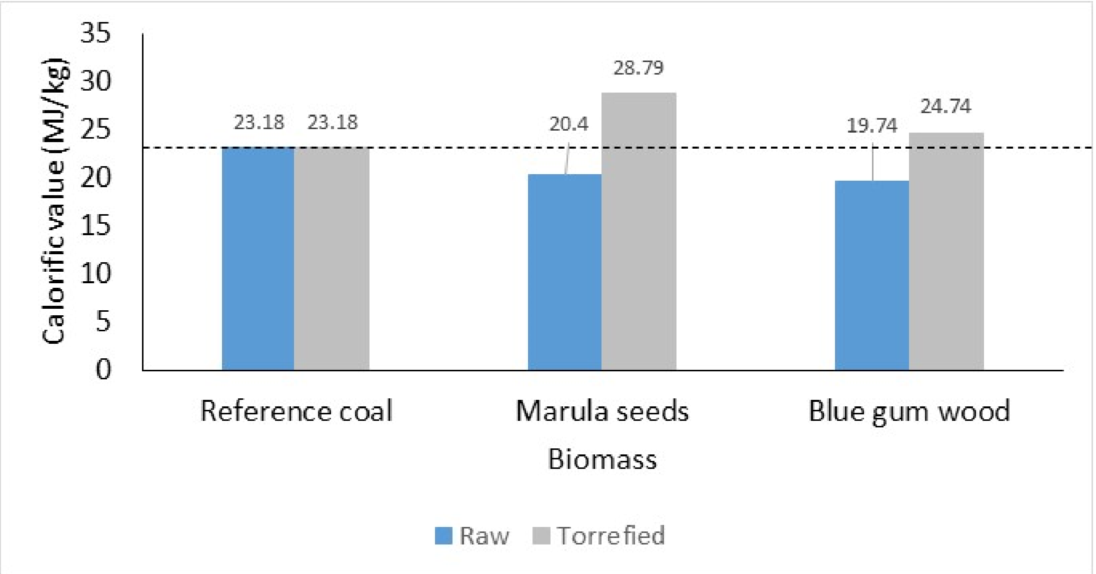

Figure 2: Effect torrefaction on biomass

Torrefaction produced biomass with least moisture content, with less fibre and increased energy density as shown in Figure 2. Marula seeds released about 54% of volatiles during torrefaction process and the calorific value increased from 20.40 to 28.79 MJ/kg while blue gum wood increased from 19.74 to 24.74 MJ/kg after torrefaction. This gave encouraging results for blending the biomass samples with coal and to compare the effect on calorific value. Co-firing of coal with about 10% biomass in a pilot plant has shown promising results.

4.2. Fuel ratio, Replacement ratio and Energy density

Comparison of fuel ratio, replacement ratio and energy density are shown in Tables 3 and 4. The fuel ratios for the two biomass samples were lower than for reference coal both before and after torrefaction. However, marula seed samples were closer to reference coal after torrefaction, and this trend was similar to results obtained by Du *et al.* (2014). The higher the fuel ratio, the higher the calorific value and this showed for the biomass samples under investigation. The results were also similar to work done by (Couhert *et al.*, 2014; Lu *et al.*, 2012 and Parikh *et al.*, 2005).

Table 3: Comparison of fuel ratios for reference coal and biomass samples

	Reference coal	Marula seeds	Blue gum wood
Proximate analysis (wt%)			
◊Fuel ratio before torrefaction	1.93	0.20	0.15
*Fuel ratio after torrefaction	1.91	1.61	0.67

◊Fuel ratio $= \frac{FC}{VM}$

*Fuel ratio after torrefaction was based on proximate analysis after torrefaction. Data for proximate analysis after torrefaction not provided in paper.

Table 4: Comparison of replacement ratios and energy density for reference coal and biomass samples

	Reference coal	Marula seeds	Blue gum wood
Proximate analysis (wt%)			

*Replacement ratio – Raw	1.00	0.88	0.85
*Replacement ratio – Torrefied	1.00	1.24	1.01
Energy density	1.00	1.41	1.25

*Replacement ratio $= \frac{HHV_{torrefied}}{HHV_{coal}}$

There was an increase in the replacement ratio for both biomass samples after torrefaction showing that the HHV of the torrefied biomass samples increased during torrefaction as compared to reference coal. This trend was similar in terms of energy density which also increased after torrefaction. This showed that torrefied biomass had the potential to replace or blend (co-fire) with coal in coal-fired boilers.

4.3 Blending coal with biomass

For blending tests to be comparable, coal was subjected to the same size reduction procedure as the two biomass samples and then it was blended at different proportions with the two biomass samples under investigation. The calorific value and replacement ratio were determined afterwards. The results for marula seeds are presented in Figure 3.

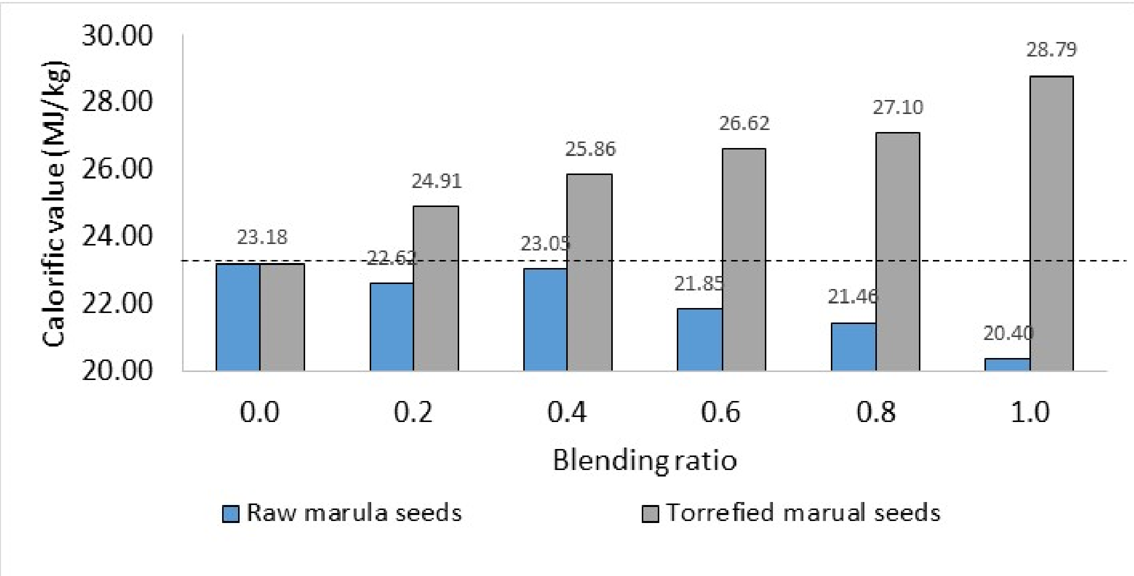

Figure 3: Effect of blending coal and with raw and torrefied marula seeds

The two columns in Figure 3 at each blending ratio indicate raw (blue) and torrefied (grey) marula seeds. The values for 0.0 are for coal without any marula seeds i.e. this is the calorific value of coal alone. As the blending ratio increases, the calorific value of mixed coal and torrefied biomass increases until there is only biomass only. The trend for coal and raw marula seeds is in reverse i.e. as raw biomass ratio increased, the calorific value of the mixture decreased.

When reference coal was blended with marula seeds, it was observed that the calorific value of the blend increased with an increase in biomass proportion. The highest calorific value was obtained at 100% torrefied seeds at 28.79 MJ/kg. When the biomass was blended with reference coal, the VM of the biomass dominated the ignition temperature, whereas the burnout temperature was governed by the FC in the coal, because of the relatively low FC in the biomass (Ahn *et at.*, 2014). The increase in HHV during blending with reference coal when the ratio of biomass was increasing can be further attributed to the enhanced hydrocarbon formation when they is combustion i.e. biomass results in higher hydrocarbon formation as compared to reference coal so a higher proportion of biomass leads to higher heating value (Emami-Taba *et al.*, 2013). The trend for blending of raw marula seeds with reference coal was opposite to the one for torrefied marula seeds i.e. the increase in composition of raw seeds to coal mixture decreased the heating value of the mixture. This gave further evidence to the importance of the torrefaction process. The change in the replacement ratio was monitored and is represented in Figure 4.

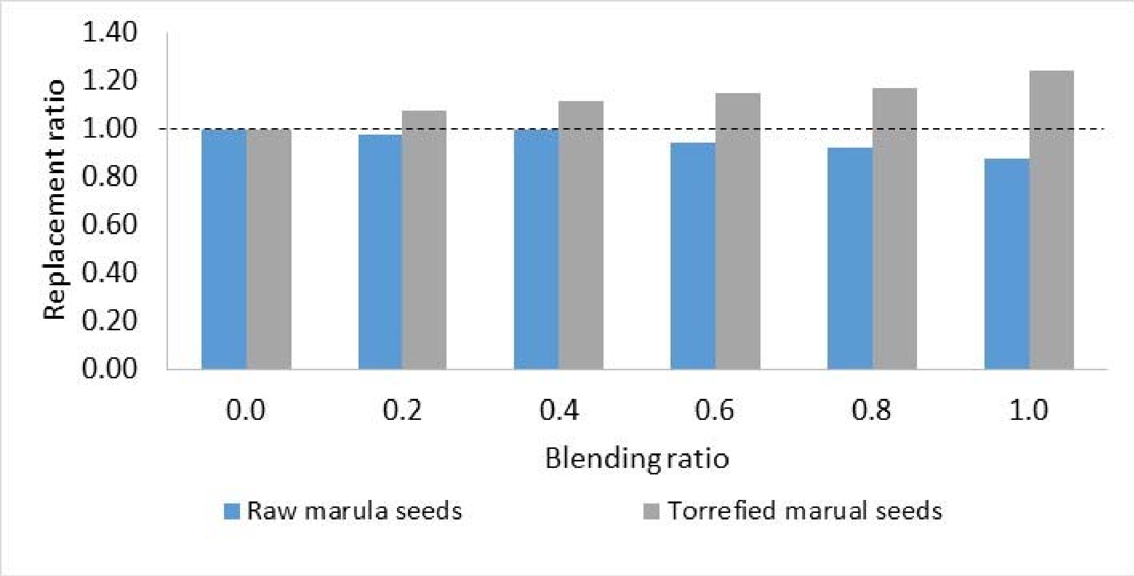

Figure 4: Effect of blending coal with raw and torrefied marula seeds on replacement ratio

The two columns in Figure 4 indicate raw (blue) and torrefied (grey) marula seeds. The values for 0.0 are for coal without any marula seeds i.e. this is the replacement ratio of coal alone with no biomass. As the blending ratio increases for both raw and torrefied marula seeds, a trend is observed same as in Figure 3.

The results showed that with an increase in torrefied marula seeds, the HHV of the blend improved up to 100% marula seeds. Blue gum wood was also blended with coal and the results are presented in Figure 5 for calorific value and Figure 6 for replacement ratio.

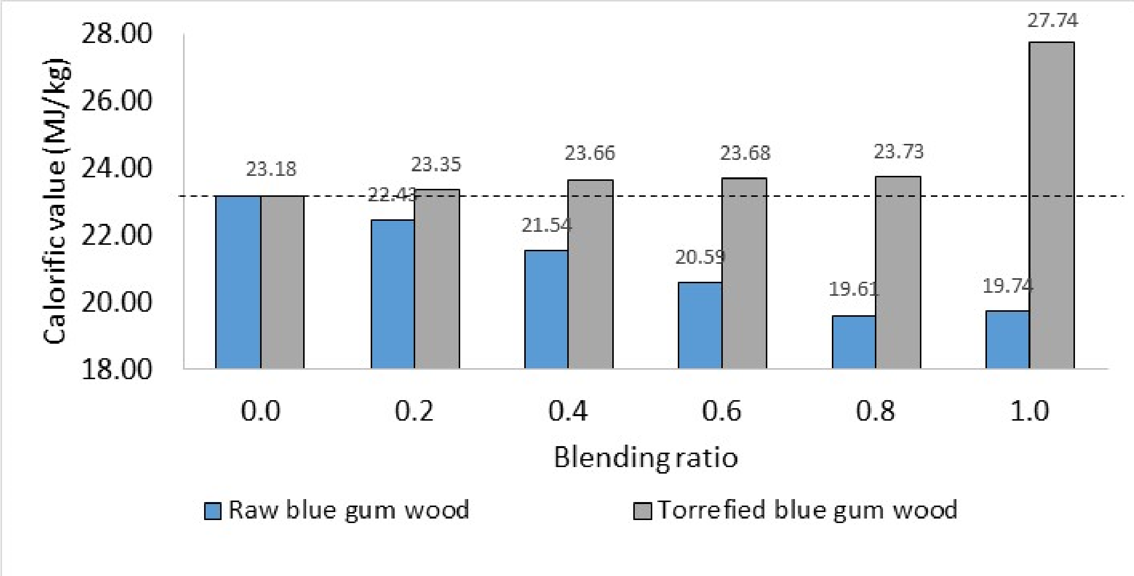

Figure 5: Effect of blending coal and with raw and torrefied blue gum wood

The two columns in Figure 5 indicate raw (blue) and torrefied (grey) blue gum wood biomass. The values for 0.0 are for coal without any blue gum wood i.e. this is the calorific value of coal alone. As the blending ratio increases, the calorific value of mixed coal and torrefied biomass increases until there is only biomass only. The trend for coal and raw blue gum wood is in reverse i.e. as raw biomass ratio increased, the calorific value of the mixture decreased.

Blue gum wood behaved in the same manner as marula seeds: the calorific value of the mixture increased with an increase in blending ratio of torrefied blue gum wood while the calorific value decreased with an increase in blending ratio of raw blue gum wood mass. However, the change was smaller when blue gum wood was blended with coal as compared with coal. The results for replacement ratio also showed the same trend.

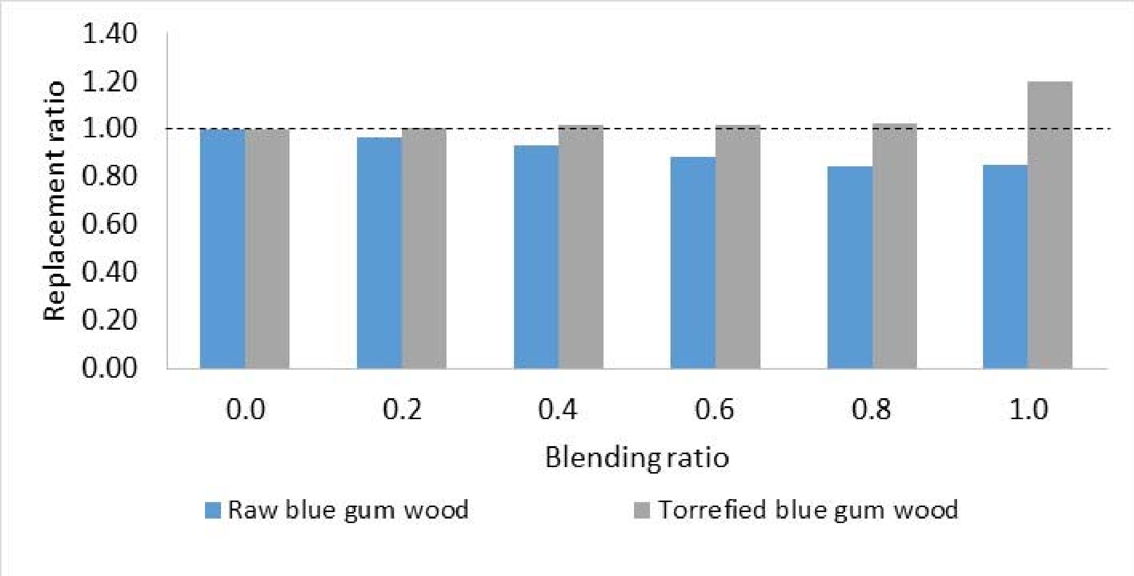

Figure 6: Effect of blending coal and with raw and torrefied blue gum wood on replacement ratio

However, industries to date are just blending coal with torrefied biomass up to 10% due to economic reasons i.e. the torrefaction process makes the biomass more expensive than coal and in terms of sustainable burning in the coal fired boilers, coal is still better. The results in the study showed that using the right torrefied biomass alone can give you better results.

5. Conclusions

Calorific value of raw marula seeds and blue gum wood were low at 20.40 and 19.74 MJ/kg respectively as compared to reference coal that has a calorific value of 23.18 MJ/kg. High moisture content of the raw biomass samples was the major factor that contributed to these results.

Blending torrefied biomass and coal led to an increase in calorific value particularly at high composition ratio of biomass. This means that biomass that was investigated may be used alone in co-firing plant as torrefied biomass has higher heating value than reference coal, however, from an economical point of view, blending at 20% for marula seeds is of economic benefit. Calorific values for blue gum wood were closer to those of reference coal and it does not seem beneficial to do torrefaction and blending steps. Marula seeds are recommended for further studies like grinding tests, hydrophobicity and also further blending tests.

In conclusion torrefaction of marula seeds and blue gum wood increased the energy content of each biomass by 41 and 25% respectively. These increments enhanced the energy content of the reference coal by increasing its calorific value.

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