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Torrefaction of waste biomass for application in energy production in South Africa

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ABSTRACT

Power producing plants are major emitters of greenhouse gases that lead to global warming and climate changes. In the past two to three decades, attention has been drawn to organizations such as these reduce their dependence on coal reserves which are depleting and focus on producing clean energy i.e. for every ton of fuel produced, 100 kg or more should be made from clean energy. This has made torrefaction to gain interest as it improves energy content of biomass, a renewable and clean energy source, to levels equal to and sometimes above that of coal. The benefit of this is that, torrefied biomass could be co-fired with coal thereby reducing greenhouse gases and global warming.

In this study, the effect of different parameters were investigated on two abundant sources of biomass in South Africa. These parameters were temperature, oxygen content, heating rate and residence time. It was observed that a temperature range between 275 and 300 °C under inert conditions with a heating rate of 10 °C/min and residence time between 20 and 40 min were required to achieve the best biomass with properties comparable to those of coal. This made it possible to co-fire the biomass with coal for energy production at different proportions.

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1. Introduction

Majority of power used in household and industries in South Africa come from Eskom. Eskom power generating plants use energy from steam, combustion gases or expanding gas to convert heat energy into mechanical energy using rotary machines (Eskom website, 2016). However, a large amount of waste heat energy contained in the flue gases from combustion of fossil fuels mainly composed of CO₂, NO_x, SO_x and water vapour

are released into the atmosphere. These gases are hazardous to the environment and ways of limiting the emissions of such gases need to be implemented (Eskom website, 2016).

To reduce the amount of hazardous gases, biomass, that has undergone torrefaction, can be used to replace a small amount of coal. The gases emitted from torrefied biomass combustion are part of the carbon cycle as biomass is produced from CO₂ absorbed from the atmosphere during photosynthesis (Basu, 2010). Of late, Eskom has shown a

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strong interest in utilising torrefied biomass in existing large-scale combined heat and power (CHP) plants to co-fire with coal without having to change the design (Creamer, 2012; Rycroft, 2015; Stafford, 2014; Yende, 2017). Biomass is considered to be one of the most important renewable fuels. However, in its natural occurring form it has low energy density when compared to that of fossil fuels like coal and diesel. As a result, biomass has low utilization efficiency when it is directly consumed as a fuel. To overcome this disadvantage, studies have shown that the energy density of biomass can be enhanced by thermal/physical treatment processes. These treatments include compression, pelletization and torrefaction. Torrefaction occurs when thermal heat is carefully applied to biomass under controlled thermodynamic conditions causing chemical, physical and mechanical changes to the biomass. The temperature range required is between 200 and 300 °C and the process should occur under inert conditions, at low heating rates and low residence time (Basu, 2010; Chew and Doshi, 2011; Chen et al., 2013). Torrefied biomass can be co-fired with coal and the net CO₂, NO_x and SO_x emissions will be reduced thereby reducing environmental damage. The blending process results in negligible changes in synergistic effects between coal and torrefied biomass (Chen and Kuo, 2011). Currently, researchers are mostly focused on the compositional changes of solid biomass, along with the product distribution (Prins et al., 2006). The volatiles released during this process can be burned in a combustor, and the flue gases collected and used to preheat raw biomass.

Some research on biomass torrefaction parameters has led to the conclusion that slow heating rate has an effect on torrefaction, typically the heating rate should be significantly slow (<50 °C/min) to allow maximization of solid yield of the process (Batidzirai et al., 2013; Tran et al., 2013). Studies to evaluate the thermal behaviour of biomass in both oxidizing and inert atmospheres have been carried out by a number of authors. Most of these researchers have shown that in oxidative environment, the thermal reactivity of biomass is greatly enhanced. This is due to the acceleration of mass loss in the first stage of torrefaction (Chen and Kuo, 2011).

Biomass is mostly composed of cellulose, hemicellulose and lignin (Chen et al., 2015; Galletti and Antonetti, 2012). During torrefaction of biomass, the thermal decomposition of biomass happens through chemical reactions coupled with heat and mass transfer depending on the temperature range. Within the temperature range of 100–260 °C, hemicellulose is

chemically most active, but its major degradation starts from around 200 °C. Cellulose and lignin will start degrading at higher temperatures. Lignin starts degrading from around 275 °C, whilst cellulose starts degrading from 330 °C (Batidzirai et al., 2013). At 300 °C biomass begins to change colour to brown and give off additional moisture, CO₂ and large amounts of acetic acid with some phenols that have low energy values (Tran et al., 2013). In addition, torrefaction yield can vary between 24% and 95% of the original raw biomass weight. Usually, biomass with higher hemicellulose content will result in lower yield while biomass with lower hemicellulose gives higher yield (Chew and Doshi, 2011). This is due to the fact that during torrefaction, hemicellulose is mostly decomposed as it is active within the range 200–300 °C.

Due to large biomass requirements, the chosen raw biomass should be able to meet the demand and that is why different biomasses have been investigated. In South Africa, marula seeds and blue gum wood are some of the abundant raw biomasses that can be used to investigate the effect of the torrefaction process for application in power generation companies. In this study these biomasses abundant in South Africa and some parts of the world, were investigated for possible use in co-firing coal-fired boilers for electricity production. Different parameters were varied to determine their impact on the torrefaction process.

2. Experimental method

2.1. Biomass

The investigation was conducted on two South African biomasses, marula seeds and blue gum wood (Fig. 1).

2.1.1. Marula trees

Marula (*Sclerocarya birrea*) is a medium-sized tree, native to the following countries: South Africa, Malawi, Namibia, Niger, Botswana, Gambia, Zambia, Zimbabwe, Sudan, Swaziland, the Democratic Republic of Congo, Ethiopia, Kenya, Tanzania (including Zanzibar), Angola and Uganda. Marula is also present in Madagascar (possibly introduced) and has been introduced into Mauritius and Reunion. It has been grown as an experimental crop in Israel and has been introduced into Australia and India (Directorate Plant Production, 2010; Mng'omba et al., 2012; Neya, 2006).

It is a single stemmed tree with a wide spreading crown characterised by a grey mottled bark. The fruits are used to



Fig. 1 – Marula seeds (left) and Blue gum tree wood (right) used for torrefaction studies.

make Amarula, fruit pulp, essential oils and edible oils and the seeds are discarded. The fruits usually ripen between December and March and have a light yellow skin, with white flesh, rich in vitamin C. Marula trees have been estimated to take between 8 and 19 years to first fruiting, the big variance being that there are different answers from authors (Mng'omba et al., 2012). But once they reach first fruiting the trees become sources of marula seeds annually. The production rate is estimated up to one tonne per tree (Shackleton, 2002). This shows that the marula seeds production can match demand if implemented as biomass for co-firing boilers.

The nut can be eaten raw or roasted and is rich in protein (28%) and oil. The good-tasting oil is used for cooking and for products such as preservatives. Jelly, juice, salad dressing and jam can be made from the fruit. The skin can be processed into glue, soap, ointment, achar and vinegar. Cattle and wildlife eat the fruit and the leaves on the trees as well as on the ground. The leaves are nutritious and will contribute to a healthy diet for livestock (Directorate Plant Production, 2010).

Marula seeds can be recovered by being used as biomass in the torrefaction process to give an opportunity to clean the environment and reduce the quantities of coal being used in power generation stations. This gives an opportunity to reduce waste on the environment by making use of the seeds to help in co-firing power stations (Mng'omba et al., 2012).

2.1.2. Blue gum trees

Blue gum (Eucalyptus Species) are tall (25–50 m) evergreen trees with trunks that are shaft-like (*E. grandis*) or branched (*E. camaldulensis*) with high canopy. Their bark is generally smooth, mottled grey-white (or reddish for *E. camaldulensis*), but that of *E. grandis* usually peels in long thin strips to expose powdery pale undersurface. Their leaves are long narrow and green, are strongly aromatic when crushed; creamy white flowers; fruits are brown capsules (Oballa et al., 2010; Rejmánek and Richardson, 2011).

Blue gum trees were introduced from Australia and cultivated for timber, shelter and firewood, as windbreaks, as sources of honey; and to reduce marshland. Of over 700 species of Eucalyptus, (native to Australia and southern Asia), some 200 have been cultivated in Southern Africa (Rejmánek and Richardson, 2011). Eucalyptus are harvested for production of rails and fuelwood from 3 years; poles and pulp from 6 to 8 years; transmission poles from 10 to 12 years; timber from 15 to 20 years; and plywood from 20 to 25 years (Oballa et al., 2010). For use as biomass, the blue gum wood maybe available after 3 years.

Marula seeds contained 36.0 wt% hemicellulose, 48.3 wt% cellulose and 15.7 wt% lignin whilst blue gum generally contains about 18.1 wt% hemicellulose, 57.0 wt% cellulose and 25.0 wt% lignin (Neya, 2006; Wang et al., 2013). Biomass decomposition in torrefaction is highly dependent on temperature simply because cellulose normally decomposes at temperatures above 330 °C (Saadon et al., 2014; Lu et al., 2012) thus, it is anticipated that at the end of torrefaction the weight loss should not exceed 60%. The formation of fumes might be mostly due to the decomposition of hemicellulose (Bergman et al., 2005).

2.2. Sample drying and preparation

The seeds and the gum tree wood were oven dried (IncoTherm oven, model 389 from Labotec, South Africa), overnight, at a



Fig. 2 – Oven for drying biomass samples from Labotec.

temperature of 105 °C before any processing (Fig. 2). The oven-dried samples were weighed (Adam GW453I) to determine the amount of volatiles released. Experimental procedure was analogous to Wannapeera et al. (2011).

The properties of the biomass was determined using standard ASTM procedure. The moisture removed consisted of unbound moisture.

2.3. Torrefaction process

The torrefaction process took place in a tube furnace (Fig. 3) according to the procedure shown in Fig. 4.

The reactor operated batch-wise and an inert gas (N_2) was used to purge O_2 from the reactor during preheating, torrefaction process, and also when cooling down from torrefaction temperature to room temperature to avoid biomass ignition and causing a fire hazard. Four parameters were investigated as follows:

- Temperature was varied between 200 and 300 °C
- O_2 content was varied between 0 and 20%
- Heating rate was varied between 5 and 15 °C/min, and
- Residence time was varied between 20 and 60 min



Fig. 3 – Laboratory tube furnace used for torrefaction.

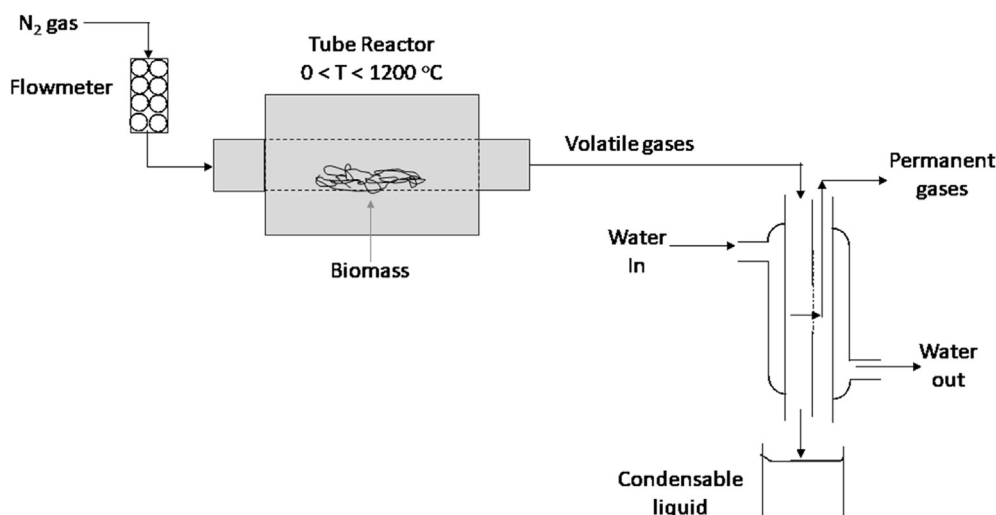


Fig. 4 – Schematic of torrefaction equipment used in the study.

The procedure was done to determine the optimum conditions for the two different biomasses i.e. the conditions that yield energy densities of biomass that are greater than those of reference coal. During optimization of one parameter, the other parameters were kept constant.

2.4. Higher heating value

The higher heating value (HHV) was determined according to BSI standard EN 14918 with a bomb calorimeter (DDS CAL2K oxygen bomb calorimeter, Fig. 5), in which 0.50 g of oven-dried biomass was completely combusted under a pressurized O_2 atmosphere (Chen et al., 2013).

2.5. Process efficiency parameters

Four critical parameters were used to determine the optimum parameters were conducted and concluded using four critical parameters. The parameters were weight loss, mass yield, energy yield and energy density. Energy yield is defined as the ratio of an increase of calorific value (heating value) to a decrease in weight of biomass i.e. for a higher energy yield; the biomass weight loss should be overcome by an increase in the calorific value (Lee and Lee, 2014). Optimizing torrefaction parameters leads to an improvement in both the quantity and quality of the torrefied biomass that is of benefit to power generation companies in South Africa. With that in mind, it

means that maximising biomass higher heating value whilst minimising biomass weight loss from its raw state results in optimised torrefaction parameters. Thus, the focus was on finding the optimised torrefaction parameters by minimising biomass weight loss and maximising biomass higher heating value.

(a) Weight loss was calculated using the equation;

$$\text{Weight loss (WL)} = \left(\frac{M_r - M_t}{M_r} \right) \times 100\% \quad (\text{Chen et al., 2013})$$

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

(b) Mass yield was computed as:

$$\text{Mass Yield} = \frac{M_t}{M_r} \times 100 \quad (\text{Lee and Lee, 2014})$$

A conventional method of comparison for torrefaction conditions is to examine the energy yield of the product (Lee and Lee, 2014) and this method was used to optimize the parameters in this study.

(c) Energy yield was calculated as follows:

$$\text{Energy Yield} = \text{Mass yield} \times \frac{CV_t}{CV_r} \quad (\text{Chen et al., 2013; Lee and Lee, 2014})$$

where CV_t and CV_r represent calorific values (heating values) of torrefied and raw biomass respectively.

(d) Energy density was calculated as follows:

$$\text{Energy Density} = \frac{\text{Energy Yield}}{\text{Mass Yield}} \quad (\text{Lee and Lee, 2014})$$

However, a weight loss of 30% of the original weight, i.e. torrefied biomass weight should be 70% of original weight, was considered to be the maximum as in literature (Basu, 2010).



Fig. 5 – Bomb calorimeter to determine biomass HHV.

Table 1 – Biomass properties on a dry basis (Proximate analysis from Mamvura and Muzenda, 2015).

	Marula seeds	Blue gum wood
Moisture (as received)	17.1	56.7
Proximate analysis		
Volatile matter (VM)	79.10	80.65
Ash	5.10	5.85
Fixed carbon (FC)	15.80	13.50
Ultimate analysis		
Carbon	47.38	50.13
Hydrogen	6.33	5.96
Nitrogen	1.46	0.53
Sulphur	0.37	0.22
Oxygen	44.46	43.16
Higher heating value (HHV), MJ/kg	20.40	19.74

3. Results and discussions

The proximate and ultimate analysis for the biomass used for torrefaction is presented in Table 1.

The proximate and ultimate analysis shows that less volatile matter but more ash and fixed carbon as compared to blue gum wood. However, their composition was almost similar and during torrefaction, it was expected that they would behaviour in a similar way.

3.1. Effect of temperature on torrefaction

Experiments were done at a constant heating rate, constant holding time under inert conditions whilst varying only torrefaction temperature between 200 and 300 °C. The results are shown in Fig. 6.

Weight loss at 200 °C was attributed to loss of remaining bound and unbound moisture (Asadullah et al., 2014). At this temperature blue gum wood lost 12% weight as compared to 5% for marula seeds. As temperature was increased, there was a significant weight loss for blue gum wood than marula seeds. This was due to devolatilization of organics that starts at 210 °C when the hemicellulose starts to breakdown by bond breakage (Kim et al., 2012). As hemicellulose breaks down, H₂O

is produced from its –C–O–H bonds, leading also to production of non-condensable gases like CO and CO₂ (Chen et al., 2012). However, of these three, H₂O was the most abundant at 250 °C. Blue gum wood lost more weight at 250 °C as it had more hemicellulose than marula seeds. This was expected, as it is softwood (eucalyptus) as compared to marula seeds that are considered as hardwood due to the outer shells. Higher weight loss in marula seeds than blue gum wood was observed at 300 °C. This was due to marula seeds having more cellulose content than blue gum. At this temperature, the less reactive marula seeds became more reactive resulting in non-condensable gases. Previous studies done on woody biomass and peaken nut shells found out that the amount of H₂O, CO and CO₂ produced at 200, 250 and 300 °C followed a similar trend as observed in our study (Asadullah et al., 2014). The main product at this stage is acetic acid (Tsai and Liu, 2013).

With an increase in temperature, it was also observed that the torrefied product turned darker from the raw brown colour, to dark brown at 200 °C, blackish brown at 250 °C and black at 300 °C. This was observed on marula seeds sample before and after torrefaction (Fig. 7). The change in colour was because of increased hemicellulose breakdown leaving higher content of carbon black. The marula seeds formed a solid pellet after torrefaction at 300 °C (Fig. 7); this is of great essence as it enables easy pelletization for application in energy production.

An average higher heating value (HHV) for raw and torrefied biomass was calculated for accuracy. The change in energy yield and energy density for the biomass is shown in Fig. 8 and for HHV is shown in Fig. 9.

Generally, energy yield decrease with an increase in temperature for both biomass. Energy yield above 100% is desirable for bio-coal as it shows more energy gained after torrefaction as compared to raw biomass i.e. energy yield is the net usable energy retained in the biomass after torrefaction, so a value of 105% means the net usable energy was increased by torrefaction. Both trends might seem strange because the HHV is expected to increase with increase in temperature as more volatiles are emitted at higher temperatures leaving bio coal with high carbon content. However, as the HHV increased, weight loss also increased thereby

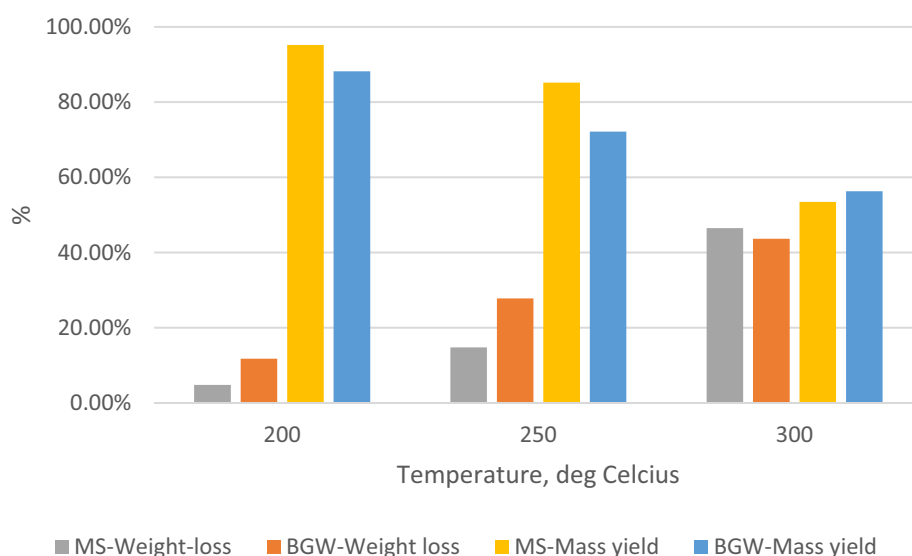


Fig. 6 – Weight loss and mass yield for marula seeds (MS) and blue gum wood (BGW).



Fig. 7 – Change in colour of biomass before (left) and after (right) torrefaction.

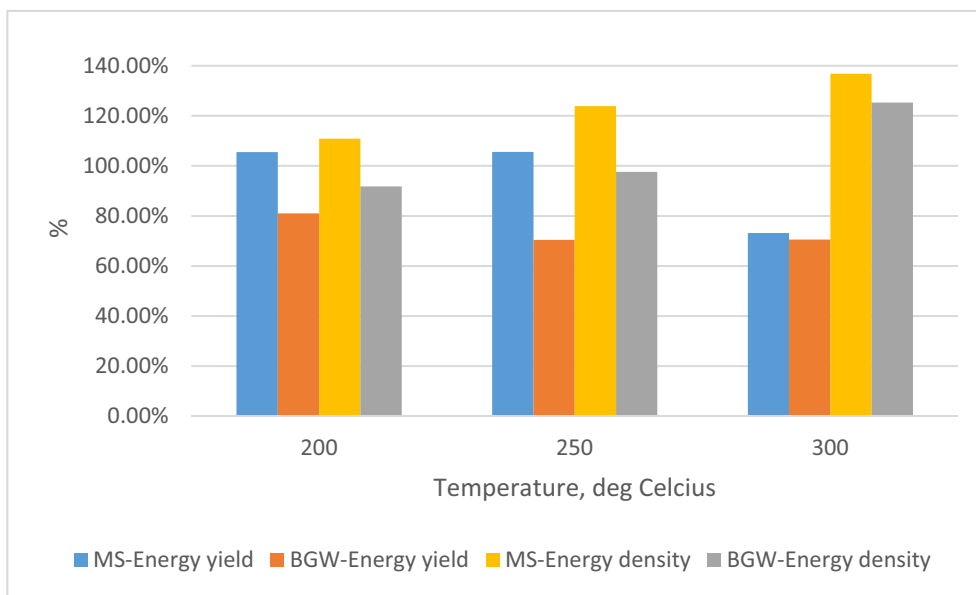


Fig. 8 – Energy yield and energy density for marula seeds (MS) and blue gum wood (BGW).

affecting the energy yield. The black line in Fig. 9 shows the HHV for the reference coal used for comparisons.

The optimum torrefaction temperature at a constant holding time would ideally be the trade-off between an increase in weight loss against an increase in HHV. This can be

seen for marula seeds as the intersection of the two curves in Fig. 10 and for blue gum wood in Fig. 11. There was no intersection of the two curves for blue gum wood.

The graph shows that a weight loss of 28% coupled with HHV increment of 28% will produce the best quality bio-coal

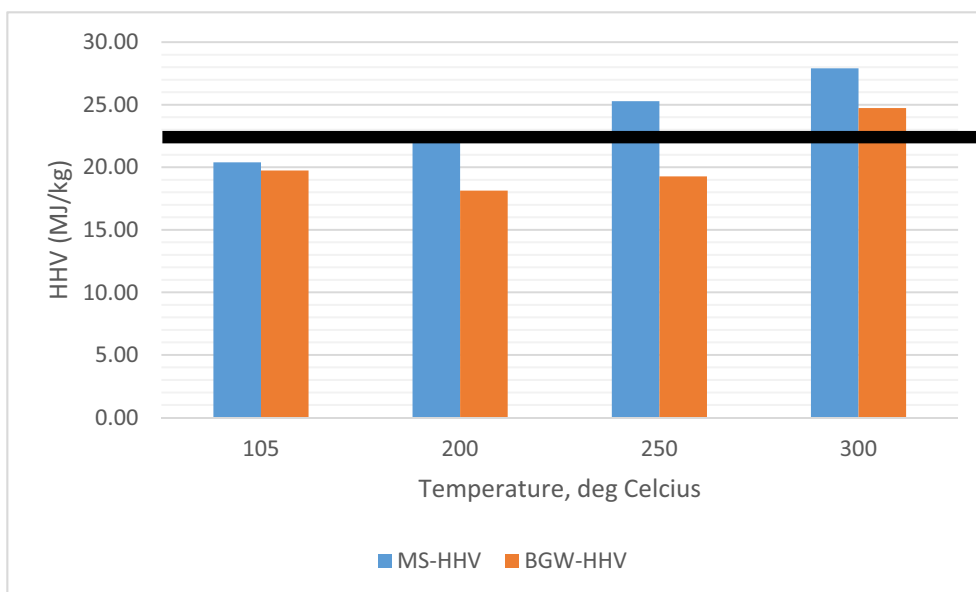


Fig. 9 – HHV for marula seeds (MS) and blue gum wood (BGW).

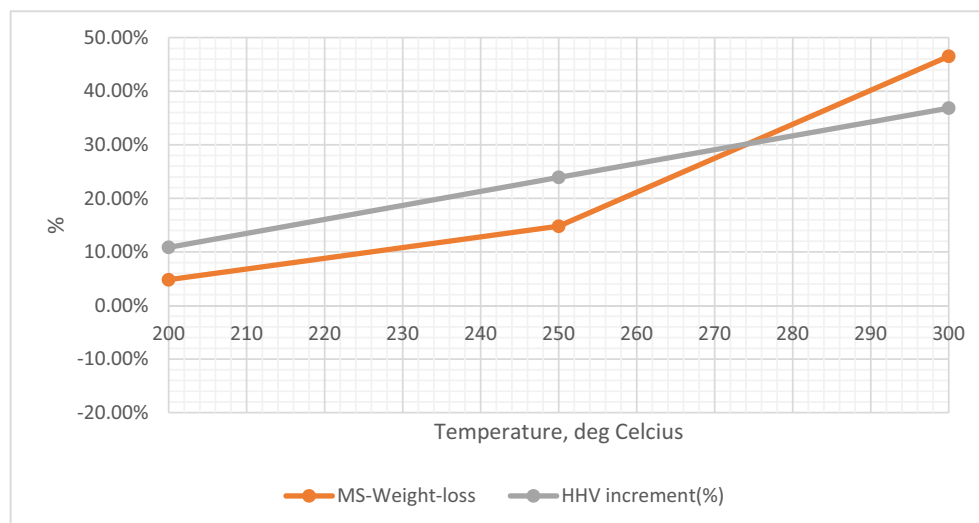


Fig. 10 – Comparison of weight loss and HHV increment for marula seeds.

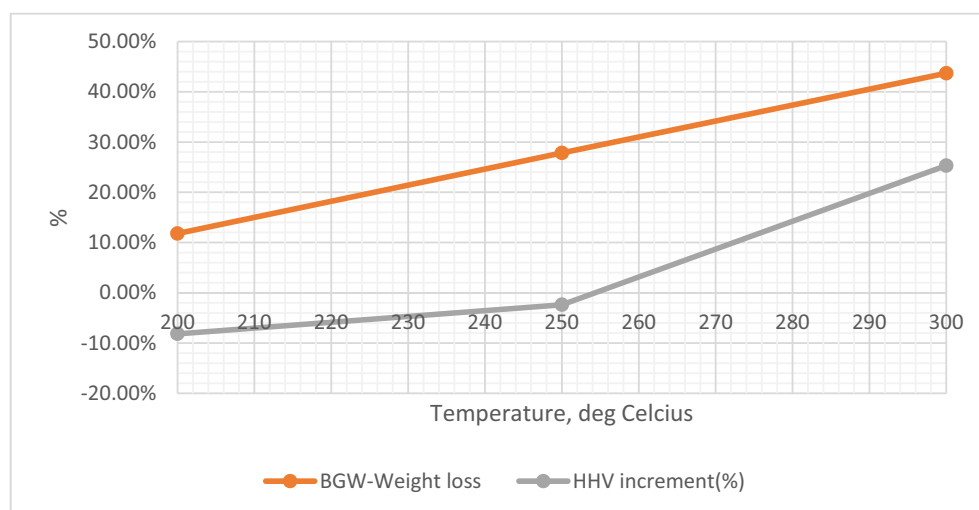


Fig. 11 – Comparison of weight loss and HHV increment for blue gum wood.

for marula seeds at these investigated conditions. This point to a temperature of 275 °C at intersection of the two graphs. Blue gum wood did not present an optimum temperature (Fig. 11), so the optimum was chosen as 300 °C due to highest value of HHV over the temperature range. It was observed that marula seeds torrefied at 300 °C lost 27% of its original energy and this could be compared to peaked nut shells that lost 36% (Asadullah et al., 2014).

The mass and energy yields for the two biomasses were compared to a study on peaked nuts done by Asadulla et al. (2014). Marula seeds had results that were comparable to peaked nuts but blue gum wood showed lower mass and energy yield values. The general range for agricultural waste at the same conditions is between 20 and 50% (Kim et al., 2012). This shows that marula seeds are a good torrefaction raw material. Blue gum wood torrefied at 300 °C lost 30% of its original energy, which is still in the acceptable range. The blue gum energy yield at 300 °C was the lowest compared to the ones produced at lower temperatures, giving another reason why this temperature was chosen as the optimum.

In essence, there are three important phases involved in the torrefaction process. The first phase consists of free and bound water extraction from biomass at the normal boiling point of water 105 °C. The second phase is irreversible biomass degradation that occurs at temperatures ranging from 100 to 250 °C. The third phase, which occurs between about 250 and 330 °C, usually involves the total destruction of most reactive component of lignocellulose biomass, hemicelluloses. The destruction of cellulose occurs during the fourth phase is outside torrefaction and it occurs between about 330 and 370 °C.

3.2. Effect of O₂ content on torrefaction

Different results are presented for both biomass: Fig. 12 shows mass yield and energy yield change due to change in O₂ content, Fig. 13 shows HHV change.

Blue gum wood had higher weight loss and lower mass yield than marula seeds with an increase in O₂ content. This was attributed to higher moisture content leading to lower O/

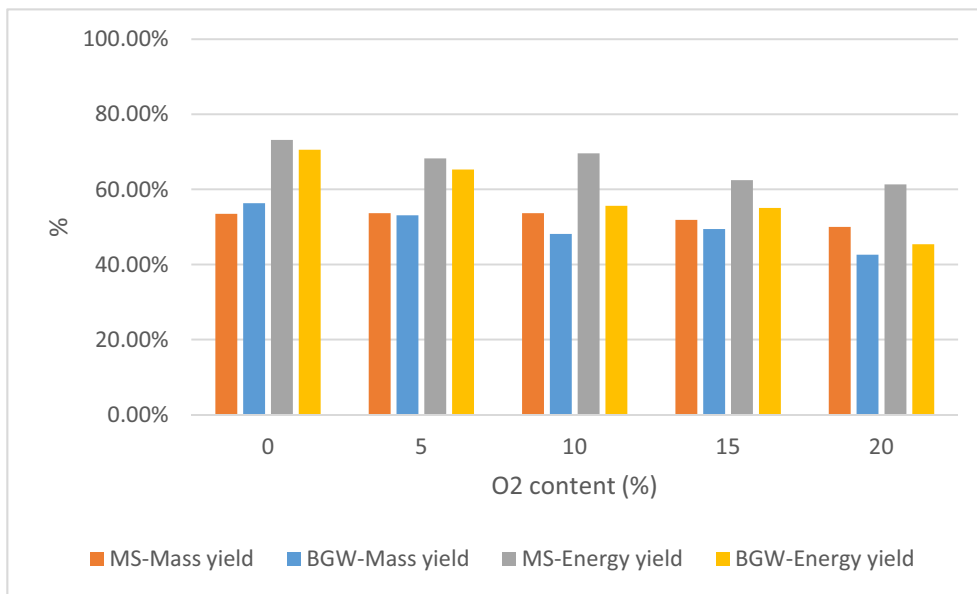


Fig. 12 – Mass yield and Energy yield for marula seeds (MS) and blue gum wood (BGW).

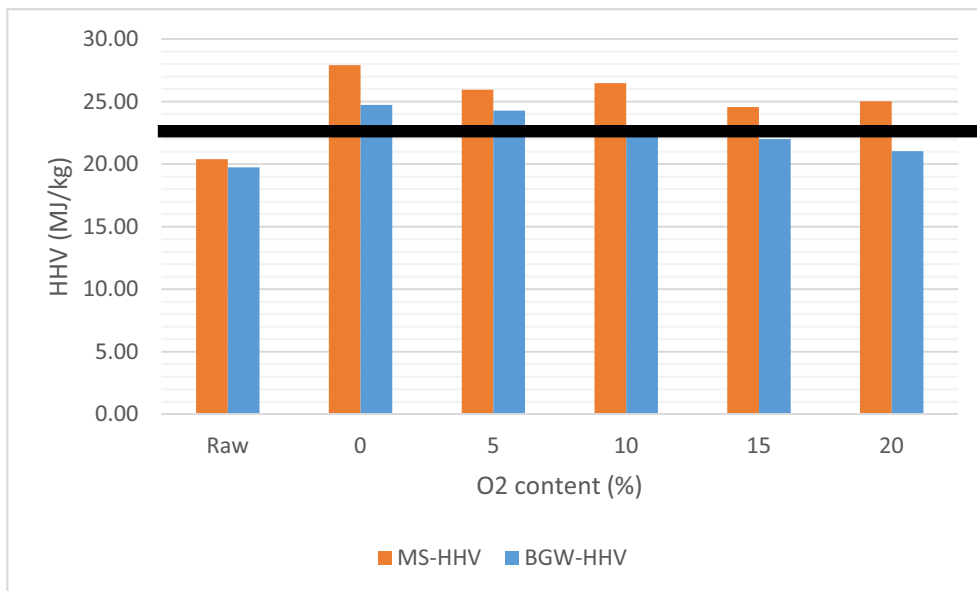


Fig. 13 – HHV for marula seeds (MS) and blue gum wood (BGW).

C and H/C ratios i.e. bound and unbound moisture was higher in blue gum wood and as it was lost, it led to a higher weight loss.

In general, it can be seen that there was a decrease in energy yield and energy density with an increase in O₂ content for both marula seeds and blue gum wood. This showed that inert conditions had the best desired effect.

HHV decreased with an increase in O₂ levels for both of the two biomasses used. Maximum HHV was also determined at 0% O₂ content i.e. inert conditions for both biomass. This was attributed to the fact that the total energy increased significantly while the energy density of torrefied biomass decreased after torrefaction. HHV values obtained at 0% O₂ levels for marula seeds and blue gum wood were higher

when compared against the reference coal (shown with black line).

3.3. Effect of heating rate on torrefaction

The effect of heating rate on torrefaction of both biomass is presented in Fig. 14 for mass yield and energy yield change and Fig. 15 for HHV change.

It was observed that weight loss became more pronounced as the heating rate increased with small loss observed at 10 °C/min for marula seeds and 5 °C/min for blue gum wood. At heating rate of 5 and 10 °C/min, devolatilisation of marula seeds hemicellulose was limited, as the heating rate was increased to 15 °C/min, devolatilisation of hemicellulose was

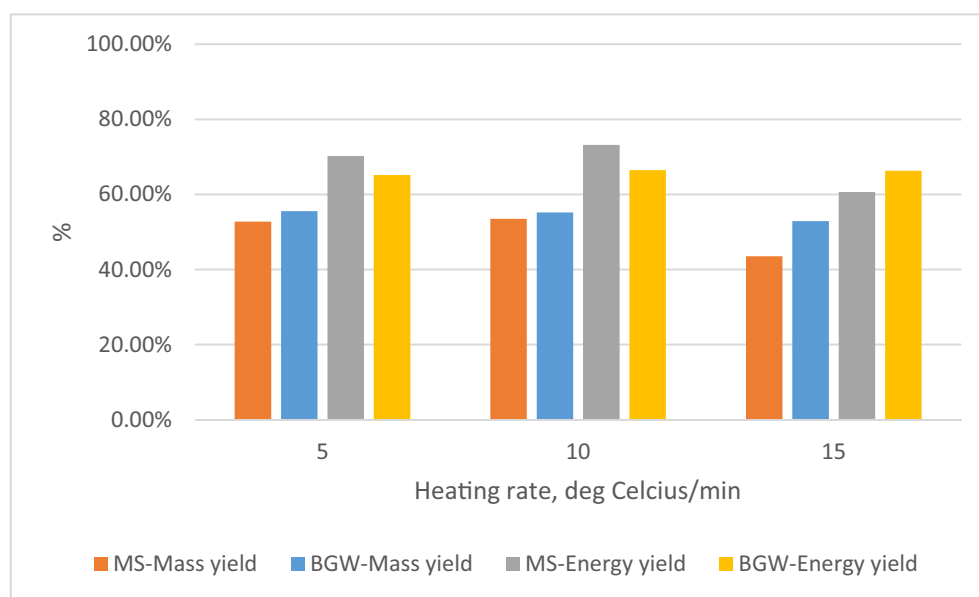


Fig. 14 – Mass yield and Energy yield for marula seeds (MS) and blue gum wood (BGW).

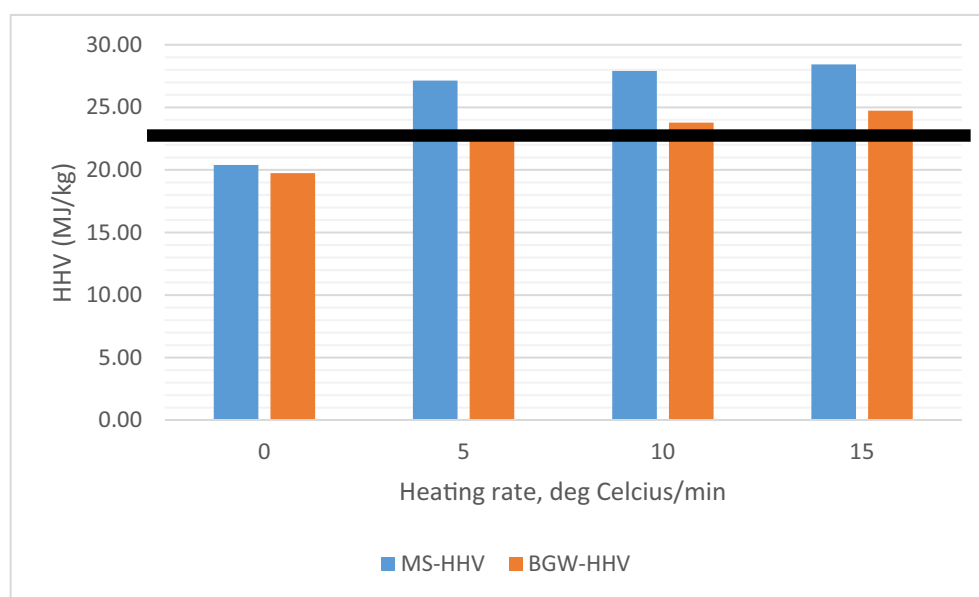


Fig. 15 – HHV for marula seeds (MS) and blue gum wood (BGW).

more pronounced resulting in greater weight loss. Change in heating rate had little effect on devolatilisation of blue gum wood hemicellulose.

HHV, weight loss and energy density for both biomasses were observed to increase with an increase in heating rate. This is in agreement with [Tran et al. \(2013\)](#) who discovered that slower heating rate is good for torrefaction as it resulted in higher solid yields. Optimum heating rate was observed to be 10 °C/min which resulted in biomass with higher mass yield, HHV, energy yield and energy density; and lower weight loss. The values for HHV, energy density and energy yield were close to those at 15 °C/min but operating at 10 °C/min meant less energy was used to achieve the same results as at 15 °C/min. Higher heating rates promote dehydration and decarboxylation reactions which results in volatiles being

removed rapidly in a short period of time thereby densifying the biomass energy ([Ohliger et al., 2013](#)).

3.4. Effect of residence time on torrefaction

Results for mass yield and energy yield due to change in residence time are presented in [Fig. 16](#) for both biomass and [Fig. 17](#) for change in HHV.

It was observed that weight loss became more pronounced as the residence time increased for blue gum wood while for marula seeds, weight loss increased from a residence time of 20–40 min and then decreased at 60 min. In the context of residence time, smaller weight loss at short residence time are attributed to limited devolatilisation ([Shankar et al., 2011](#)). The period the sample is subjected to heat in the furnace has an

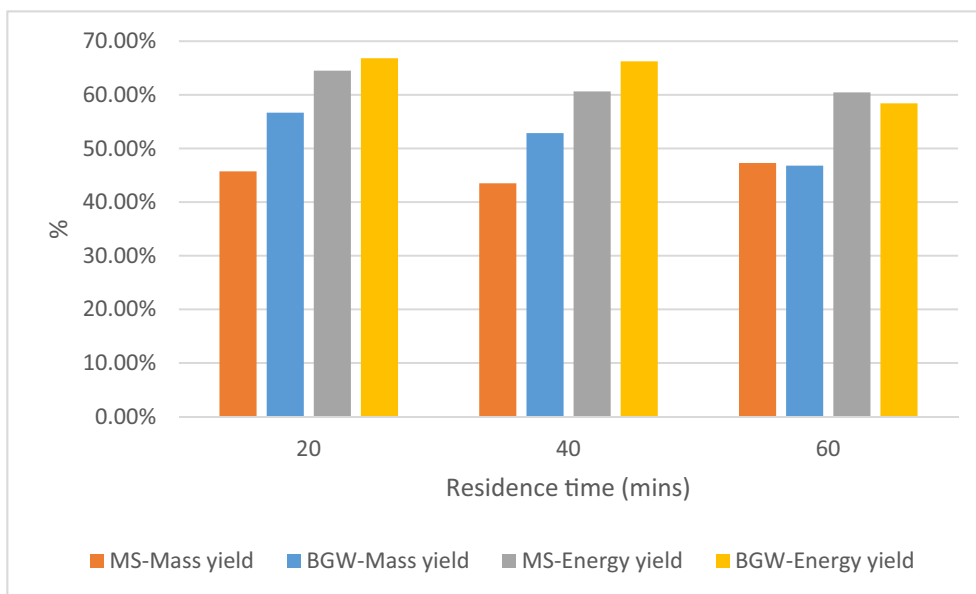


Fig. 16 – Mass yield and Energy yield for marula seeds (MS) and blue gum wood (BGW).

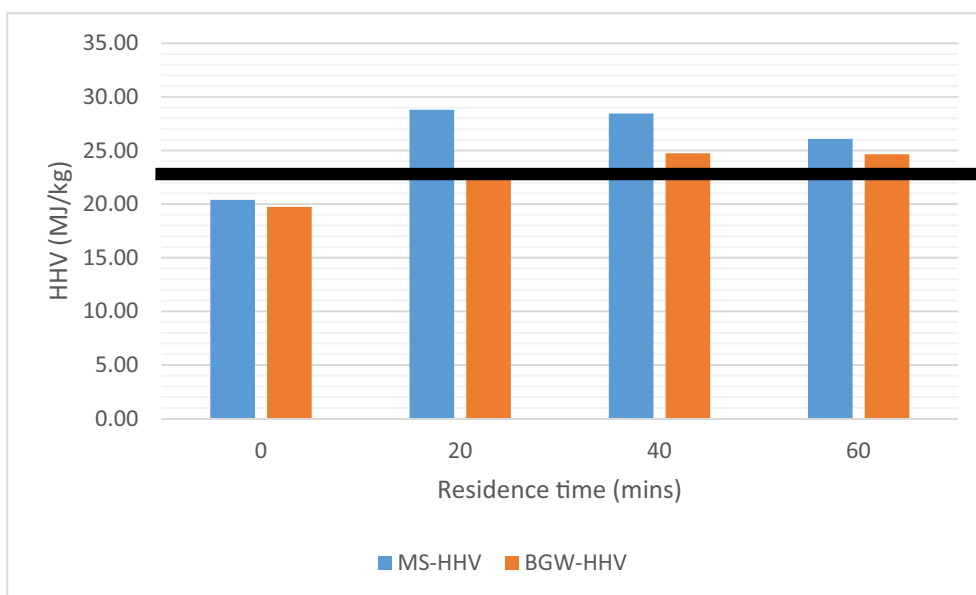


Fig. 17 – HHV for marula seeds (MS) and blue gum wood (BGW).

influence on devolatilisation of hemicellulose of the biomass. Marula seeds had the highest weight loss at 40 min and this was even higher than for blue gum wood that had a higher moisture content. This was attributed to degradation of the biomass at a higher residence time.

During torrefaction principle gases produced from biomass include CO_2 , CO and CH_4 with CO_2 produced in higher proportions as compared to other gases (Chen and Kuo, 2010). The CO_2 is formed as a result of decarboxylation and depolymerisation of acid groups in biomass (Chen and Kuo, 2010). The first 10–20 min of torrefaction consist mainly of a heating stage of biomass to the desired temperature of 300 °C with a small amount of CO_2 produced. The torrefaction reaction then starts to take place and the production of CO_2 increases exponentially along this stage (Chen and Kuo, 2010).

Results showed that the energy density increased with an increase in residence time for both biomass. As residence time increases, O_2 and H_2 will be used up to form water vapour, CO and CO_2 that are then released into the atmosphere. This results in high C/O and C/H ratios giving higher calorific values. At a residence time of 60 min, the calorific value declined for both biomasses. This can be attributed to high conversion rates of C to CO and CO_2 giving low calorific value of biomass.

Energy yield for blue gum wood and marula seeds decreased as the residence time increased. This was attributed to decomposition of hemicellulose that happened at a lower rate at the beginning before increasing residence time to 60 min. This decomposition mostly produced water and the energy content was preserved in the lipids and organics while some was lost with non-condensable gases (CO , CO_2). This

was similar to findings from Chen et al. (2014) and Asadullah et al. (2014).

3.5. Summary of results

Four parameters were investigated against two biomass to determine optimum conditions for torrefaction. It was observed that marula seeds required a temperature of 275 °C, under inert conditions at a heating rate of 10 °C/min and a residence time of 20 min achieve the best torrefied biomass that has properties comparable to those of coal. For blue gum wood a temperature of 300 °C, under inert conditions at a heating rate of 10 °C/min and a residence time of 40 min gave optimum torrefied biomass that could be co-fired with coal at different proportions for energy production.

4. Conclusions

Torrefaction of marula seeds and blue gum improved the higher heating value of the biomass. The physical appearance and the energy content of torrefied product were almost similar to our reference coal and even surpassed, the HHV of coal in some instances. Weight loss increased when torrefaction temperature increased due to moisture removal and hemicellulose breakdown which produced H₂O, CO, CO₂, and other hydrocarbons. Energy yield decreased with increasing torrefaction temperature because of the increase in weight loss.

From the standpoint of energy use of torrefied biomass for co-firing with coal in boilers, its HHV is the most important thermochemical property. It can be seen that marula seeds had an HHV of 27.9 MJ/kg, which is higher than that of bituminous coal that averages between 23 and 26 MJ/kg (Asadullah et al., 2014). Since bituminous coal is the most used in thermal power stations, marula seeds can actually increase the energy output when co-fired with bituminous coal for energy production. In general, HHV of raw wastes is in the range between 16 and 21 MJ/kg and it goes up to between 18 and 28 MJ/kg after torrefaction (Arnsfeldt et al., 2014). This corresponds with results from marula within our investigated temperature range, as well as blue gum wood at 300 °C.

It can be concluded that non-oxidative conditions with low heating rates and shorter residence time resulted in the best torrefied biomass. The increase in HHV coupled with increase in energy density for torrefied marula seeds during experimentation meant that it is possible to co-fire with coal making it a promising biomass source. Chen et al. (2014), Shankar et al. (2011), and Xue et al. (2014) reported that biomass energy density usually increases to 1.3 and marula seeds are comparable to these findings. On the other hand, blue gum wood, energy densities were below 1.3 and this was largely attributed to higher moisture and volatile content (it is softwood) and it will require pretreatment or blending with biomass with higher HHV to make an impact in energy production. If blue gum wood is combined with coal, it will result in lower HHV, thereby resulting in lower energy being produced. Marula seeds gave promising properties; however, further studies should be done to maximize the energy yield of the biomass so it could be a substitute for coal in power generation plants.

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