ONLINE ISSN 2069-7430
ISSN-L 1841-4737

PRO LIGNO
www.proligno.ro

Vol. 12 N° 4 2016
pp. 21-29

COMBUSTION CHARACTERISTICS OF TORREFIED WOOD SAMPLES OF *PINUS CARREBEA* AND *LEUCAENA LEUCOCEPHALA* GROWN IN NIGERIA

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Abstract:
Torrefaction of selected wood samples of Pinus Carrebea and Leucaena Leucocephala were carried out at temperatures ranging from 200 to 300°C to improve the energy parameters of biomass and to determine the effect of torrefication temperature on the physical and combustion properties of wood selected from Pinus carrebea and Leuceanea leucocephala grown in Nigeria. In this process the biomass hemicellulose is degraded, maintaining its cellulose and lignin content. The samples were dried and heated to 225, 250, 275, and 300°C. Then the torrefied mass was subjected to basic property testing on proximate analysis and heating value was calculated in order to understand the differences between raw material and its torrefied products. Specifically, the wood blocks changed from light brown to black, stemming from the partial carbonization at the wood surface. When the temperature is 225°C, the color of the wood is between dark brown and once the torrefaction temperatures are 250 and 275°C, the colors of the wood become dark and darker respectively. The results of the proximate analysis also showed that increasing of torrefied temperature; volatile fraction was reduced while fixed carbon was increased with increase in temperature from 21.34 to 52.74 and 18.58 to 56.83 for Leucaena leucocephala and Pinus carreabeanus respectively at 225 to 300°C. The volatile content is decreased from 78.58% to 62.76% with increase in temperature. Ash content of were within 1.57-3.41% of torrefied wood. It could be observed that the High calorific value (HCV for pine ranged between 19.80 and 28.06MJ/Kg for the top, 19.93and 24.96MJ/kg for middle with 19.72and 25.96MJ/Kg for base. The values recorded for raw sample and at 275°C been the lowest and highest respectively. The High calorific value (HCV) were found to be on the increase and nose dive at 300°C for the tree parts used in this research. The result revealed that for Leuceana the value increased from raw up to 275°C and at 300°C, a drop in the HHC was experienced. The result also showed that between raw and 250°C the value were statistically not at variance though higher value was recorded at 250°C (22.04MJ/kg). Likewise, between 275°C and 300°C there was no variance statistically, but higher value was observed for 275°C (26.32). It could be observed that the HHC for pine ranged between 19.80 and 28.06MJ/Kg for the top, 19.93 and 24.96MJ/kg for middle with 19.72 and 25.96MJ/Kg for base. The result also showed that between raw and 250 the value were statistically not at variance though higher value was recorded at 250 (22.04MJ/Kg). Likewise, between 275°C and 300°C there was no variance statistically, but higher value was observed for 275°C (26.32MJ/Kg). The proximate analyses revealed that the species are a suitable biomass source for torrefaction process and calorific value increase compared to control raw sample.

Key words: *Pinus carrebea; Leucaena leucocephala; torrefaction; biofuel; energy; proximate analysis.*

INTRODUCTION

Biomass is a unique fuel and has the potential to play significant role in future energy mix in Nigeria. Unlike other renewable, biomass can provide continuous electricity generation, contribute to the reduction of CO_2 emissions and increase energy security. Hence, in the transition to a more sustainable energy supply, there is a clear need for better biofuels. Untreated woody biomass has a relatively low energy density, high moisture content and is difficult to transform into small particles. These properties make transportation of woody biomass relatively expensive. More so, after drying, it can retain moisture and may rot during storage.

Furthermore, enhancement of the energy density is advisable because a large amount of wood is required to replace an equivalent amount of coal in applications such as combustion and gasification. A technology that could help to overcome some of the technical problems associated with biomass utilization is a thermal processing step known as torrefaction.

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Torrefaction is a thermal treatment that occurs in an inert atmosphere between 225–300°C. It removes moisture and low weight organic volatile components (OVM) and depolymerises the long polysaccharide chains, producing hydrophobic solid product with an increased energy density (on a mass basis). As a result, significant lower energy is required to process the torrefied fuel and it no longer requires separate handling facilities when co-fired with coal in existing power stations. The advantages accompanied by torrefaction include: (1) the higher heating value or energy density (Prins *et al.* 2006, *Yan et al*. 2009), (2) the lower O/C ratio and moisture content (Felfri *et al*. 2005, Sadaka and Negri 2009) and (3) the easier storage, grindability, reactivity and delivery (Cohert *et al*. 2009, Repelin *et al*. 2010) of biomass. Besides, the properties of torrefied biomass are more uniform compared to those of raw biomass. Research on torrefied deciduous wood types, eucalyptus and a mixture of chestnut and oak, at 270–275°C increased the low calorific value of the wood from 18.6 to 22.7MJ/kg and from 17.9 to 21.5MJ/kg, respectively, while retaining over 90% of the energy. In recent times Pentanunt *et al.* (1990) compared combustion characteristics of torrefied wood produced after 2–3h of torrefaction and concluded that torrefied wood produces less smoke compared with untreated wood. Felfli *et al*. (1998) used a bench unit to determine the effect of raw material, temperature and residence time on the properties of torrefied wood.

In torrefaction, the hemicelluloses fraction which is most reactive fraction of biomass is decomposed so that torrefied wood and volatiles are formed. Gaur and Reed (1998) summarized the hemicelluloses degradation as a two-step reaction where light volatiles (mono- and polysaccharide fractions and dehydrated sugar) are formed in the first step followed by their catalytic degradation (by mineral matter) resulting in the formation of CO and CO_2.

The objective of this research considering the effect of torrefaction from studies mentioned above, is to determine the effect of torrefication temperature on the physical and combustion properties of wood selected from *Pinus carrebea* and *Leuceanea leucocephala grown in Nigeria*.

MATERIALS AND METHODS

The wood samples in this study were Nigeria grown *Pinus carrebea* and *Leucaena leucocephala*. The tree species were harvested from the Plantation of Department of Forestry and Wood Technology, Federal University of Technology, Akure and Central Nursery of Department of Forest Resources Akure, Ondo State. The felled trees were sectioned into three major parts: top, middle and base. Samples were taken from each parts without separating the sap wood and heart wood, but care was taken not to include the bark of each species as part of projected samples. The samples were then processed into strips of dimension 1cm × 1cm × 6cm on a circular machine and oven dried at 103±2^{o}C until a constant weight was attained.

Fig. 1.
Cutting of felled Leucaena Leucocephala stems.

Torrefaction

Approximately 300g sample from the selected wood species were weighed and placed in an electric fired fixed bed reactor. The reactor was heated through an electrical circuit and thermocouples were used to read the temperature variation for both the reactor and the furnace. The torrefaction process was carried out at 225, 250, 275 and 300°C. A total number of 72 samples were torrefied accounting for 36 samples per species.

The volatile matters that were released during torrefaction were passed through a condensation unit and the condensate was collected inside a conical flask. The condensation unit was maintained at temperature between 12 to 15°C throughout the experiment. The non-condensable gas was left to escape (the condensate and the non condensable gas were regarded as torrefactaion volatiles in this project work); the char remaining in the reactor was measured immediately after torrefaction in order to determine the residual solid mass and later stored inside an air tight container for further analysis.

Table 1

Properties of woodchips

Wood Species	Classification	Specific gravity, g/cm^3	Average particles sizes (mm)			Moisture content (%)	Weight per batch (g)
			Thickness	Width	Length		
Pinus carrebea	Gynospermae	0.61	10	10	60	3.0-8.4	300
Leucaena leucocephala	Angiosperm	0.50-0.75					

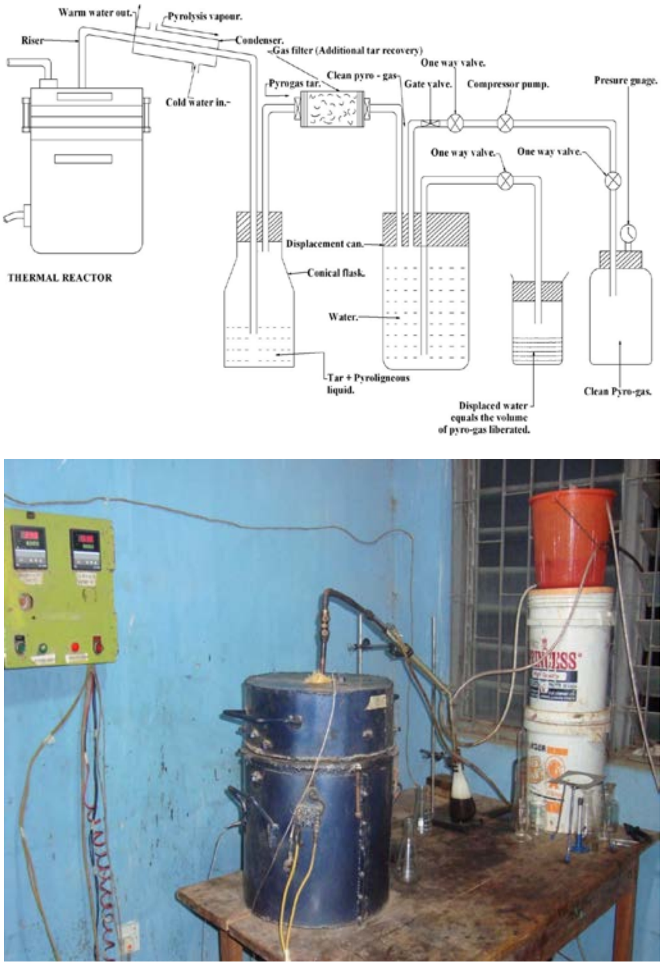

Fig. 2.
Torrefaction Schematic Experimental set-up.

Proximate analysis

The proximate analysis was carried on all the torrefied samples to determine the percentage of volatile matter content (PVM), percentage of ash content (PAC), percentage of fixed carbon (PFC) following ASTM E711-87 procedures. The calorific value was calculated applying formula (Eq.1):

$$HV = 2.326\,(147.6\,\mathbf{C} + 144\,\mathbf{V}), \qquad \text{KJ/Kg} \qquad (1)$$

where: C - percentage of fixed carbon (FC), in %;
V - percentage of volatiles, in %.

RESULT AND DISCUSSION

The result of analysis of variance for the mass balance for selected tree species which were toreffied at 225, 250, 275 and 300°C are presented in Table 2. The result showed that for *Leucaena Leucocephala,* there were significance differences at different temperature regimes while there were no significant differences recorded for the part of the wood species at P value ≤ 0.05.This implies that, at 5% probability level, the effect of temperature regimes used affected the mass of the samples used. Also, for *Pinus carrebeanus*, there were significance in the effects of temperature regimes and tree parts at P value ≤0.05. The follow up result as shown by DMRT in Table 3 revealed that, for *Leucaena Leucocephala* there was a clear distinction among the temperature regimes, while for pine, there was no significant difference between 250 and 275°C. Moreover, the mean mass value was found to decrease as the temperature increased from 225°C to 300°C for the two species considered for this work i.e. 231.54 to 121.67g for *Leucaena Leucocephala* and 247.20 to 115.02g for *Pinus carrebeanus*. Furthermore, the follow up test for tree parts as presented in Table 2, showed that there were no significant differences between the values recorded for middle and base for the selected tree species. Though, the values were found to increase from top to base for the two species. A similar finding reduction in biomass material with increase in temperature has been reported by Pentanunt (1990) and Prins *et al*. (2006). The differences recorded between the mean value of *Leucaena Leucocephala* and *Pinus carrebeanus* is also in agreement with other work as reported by Prins *et al*. (2006). This is due because the hemicelluloses fractions of coniferous wood have different chemical composition, i.e. the amount of the most reactive hemicelluloses is less than for the deciduous wood types (Wagenfuhr 1974). The hemicelluloses fraction of coniferous wood contains a high proportion of glucomannan, which is less reactive and has lower weight loss in this temperature range than xylan (Ramiah 1970).

Table 2

Analysis of variance (ANOVA´s) for mass variation between the two selected tree species at various torrefaction regimes and different parts

Species	Source	Type III Sum of Squares	df	Mean Square	F	Sig.
***Leucaena leucocephala* (Lam. deWit).**	**Temperature**	60871.841	3	20290.614	54.339	**.000**
	Parts	4578.651	2	2289.325	6.131	**.006**
	Error	11202.238	30	373.408		
	Total	76652.730	35			
Pinus carrebeanus	**Temperature**	79909.904	3	26636.635	36.671	**.000**
	Parts	12821.176	2	6410.588	8.826	**.001**
	Total	114521.822	35			

Table 3

DUNCAN multiple range test for the mass variation between the two selected tree species at various torrefaction regimes and different parts

Temperature	***Leucaena Leucocephala* (Lam. deWit).**	**Pinus carrebeanus**
225	231.54[a]	247.20[a]
250	179.31[b]	179.46[b]
275	146.46[c]	163.63[b]
300	121.67[d]	115.62[c]
TREE PARTS		
TOP	153.8[b]	149.93[b]
MIDDLE	177.52[a]	187.35[a]
BASE	177.93[a]	192.15[a]

[*]Mean Values with the same alphabet are not significantly different from each other (at 95% of test).

As shown in Fig. 3., the visual observations of the raw and torrefied wood blocks at the four torrefaction temperatures (i.e. 225, 250, 275and 300°C) were presented. As can be seen in the Fig. 3. following the torrefaction for wood, the torrefaction temperature has a pronounced effect on the color of wood. Specifically, the wood blocks changed color from light brown to black, stemming from the partial carbonization at the wood surface. When the temperature is 225°C, the color of the wood is between dark brown and once the torrefaction temperatures are 250 and 275C, the colors of the wood become dark and darker respectively. This may be explained by the sensitive behavior of volatiles released from the torrefaction processes at various temperatures. This result is similar to the work of Chen *et al*. (2011).

a - Leuceanna Leucocephala

b - Pinus Carrebea

Fig. 3.
Colour variation as affected by temperature.

Proximate analysis

The results of proximate analysis for the raw and torrefied samples were presented in Tables 4 and 5. As shown in Table 4, the ANOVAs for ash content of *Leucaena leucocephala* and *Pinus carrebeanus* revealed that, there were no significant differences recorded for the different temperatures and different parts of the tree at P value ≤ 0.05. Though there were no significant differences recorded, the result of mean separation for *Leucaena* showed that the mean value within the temperature 250 and 275 were not statistically different from each other, but they were different from 225 and 300. The mean values also revealed that the value increased with increase in temperature for the two selected species i.e. for *Leucaena*, the value ranged from 1.57 to 2.71 and for pine 2.57 to 3.41 for 225 and 300 respectively as shown in Table 4.

Also, as shown in Table the result of Anova's for *Leucaena leucocephala* and *Pinus carreabeanus* showed that there is a significant difference in the effect temperature on volatiles, but the volatiles is not significantly affected by different parts of the tree. The volatiles value for *Leucaena leucocephala* varied between 44.70 and 77.09 and *Pinus carreabeanus* 39.76 and 78.85 for 300 and 225 respectively. The result also revealed that for *Leucaena leucocephala,* the mean were not statistically different between 225 and 250 as well as 275 and 300; also similar trend were recorded for *Pinus carreabeanus.*

The result of fixed carbon (FC) also showed Temperature had significant effect on FC but different parts did not show any significant effect on the value of FC for both *Leucaena leucocephala* and *Pinus carreabeanus*. The mean value as shown in Table showed that the value increased with increase in temperature from 21.34 to 52.74 and 18.58 to 56.83 for *Leucaena leucocephala* and *Pinus carreabeanus* respectively at 225 to 300°C. It is evident from this study that as the torrefy temperature increases, the volatiles reduces while the fixed carbon is increased. The result from this study showed similar trend with the study conducted by Chun-Te Wu and Far-Ching Lin (2012). The result of is work also show a similar trend with the work of Ho Seong *et al*. (2014) where they reported that, in proximate analysis for Larch wood, fixed carbon content increased from 17.09% to 34.79% with

ONLINE ISSN 2069-7430
ISSN-L 1841-4737
PRO LIGNO
www.proligno.ro
Vol. 12 N° 4 2016
pp. 21-29

increasing the reaction temperature. Hence, the color of samples becomes black. Also, the volatile content is decreased from 78.58% to 62.76% and ash are very low compared with other contents and very slowly decreased. Therefore, the proximate analysis provides deep insight on how biomass is expected to behave during torrefaction and pyrolysis. The volatile matter content is related to the amount of biomass, excluding water, which can be volatilized by the application of heat. During torrefaction, these volatiles end-up in either gaseous products or bio-oils. However, proximate analysis provides no information as to where the volatile matter of biomass will end-up, *i.e.*, in the bio-oil or gases (Wenja *et al.* 2013). In addition, the fixed carbon represents the ash-free carbon residue left after torrefaction. In the absence of mass transfer limitations in large batch pyrolysis experiments, quantities of bio-char produced from pyrolysis should be theoretically equal to the sum of fixed carbon content and ash content measured from proximate analysis Ho Seong *et al*. (2014). However, in practical situations, actual maximum bio-char yields on an ash-free basis were reported to be 57% (chestnut wood) and 80% (oak wood) of their respective fixed carbon contents by Antal and Gronil (2003).

The HVC of the raw wood and the torrefied materials are provided in Table 7. The HHV of the raw wood ranges between 17.56-19.93MJ/Kg for *Leuceana* and Pine. Once the wood undergoes torrefaction at 225°C, the HHV is lifted to around 19.41-21.90MJ/ kg revealing that the HHV value of the wood is amplified by a factor of 1.12-1.15. With the torrefaction temperature of 250°C, the heating value is in the range of 19.72-25.36MJ/kg. It follows that the energy contained in the torrefied wood is enlarged by 30-36%. Once the torrefaction temperature is further increased to 275°C, the HCV is between 22.60 and 28.05MJ/kg that is, the increment in HHV value is between 36 and 40%. Even though the HCV is increased markedly at 275°C and 300°C, the weight loss of the wood is also pronounced, as shown in Fig. 3 and 4. It is thus pointed out that the torrefaction temperature of 275 and 300°C is inadequate to pretreated biomass. The trend observed in this work is further corroborated by the work of Chen (2011) and it could be affirmed that the energy contained in torrefied samples increases with temperature and reaction time (Prins *et al*. 2006b).

It is observed that the calorific values increase with either torrefaction temperature or part of the tree. However, the effect of temperature is more pronounced than the effect of part. Moreover, the effect of torrefaction temperature for Pine wood is also more pronounced than for Pine. Consequently, the HCV of Leuceana wood torrefied at 225°C is close to Pine wood treated in the same condition, although the of raw Leuceana is higher than that of Pine wood due to different chemical composition. Trends in HCV in this work were also reported by Prins *et al*. 2006b, for spruce and birch, (Dorde 2012) for Stalk pith, cob shell and Edward *et al.* (2002) for maritime pine at torrefaction temperatures of 200-300°C

Table 4

The ANOVA's for proximate values of torrefied Leucaena leucocephala and Pinus carrebeanus

		Source	Sum of Squares	Df	Mean Square	F	Sig.
ASH	Leu	Temp	6.918	3	2.306	1.94	.0144
		Part	.891	2	.445	.375	0.690
		Error	35.618	30	1.187		
		Total	43.426	35			
	Pine	Temp	3.811	3	1.270	.962	0.423
		Part	1.350	2	.675	.511	0.605
		Error	39.604	30	1.320		
		Corrected Total	44.765	35			
Volatiles	Leu	Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
		Temp	6793.861	3	2264.620	16.457	0.000
		Part	94.147	2	47.073	.342	0.713
		Error	4128.240	30	137.608		
		Total	11016.248	35			

	Pine	Source(pine	Type III Sum of Squares	Df	Mean Square	F	Sig.
		Temp	7266.068	3	2422.023	9.729	0.000
		Part	402.957	2	201.478	.809	0.455
		Error	7468.749	30	248.958		
		Total	15137.774	35			
FIXED CARBON	LUE	Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
		Temp	6417.831	3	2139.277	16.033	0.000
		Part	80.091	2	40.046	.300	0.743
		Error	4002.961	30	133.432		
		Total	10500.884	35			
	PINE	Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
		Temp	6945.058	3	2315.019	9.081	0.000
		Part	450.624	2	225.312	.884	0.424
		Error	7647.906	30	254.930		
		Corrected	15043.588	35			

Table 5

Mean Values of Proximate Analysis At Different Temperature

	ASH		**VOLATILES**		**FC**		**Calorific Value (KJ/Kg)**	
Temp	Leu	Pine	Leu	Pine	Leu	Pine	Leu	Pine
control	1.44	2.20	82.31	80.03	16.25	17.76	19.82^{b}	18.13^{b}
225	1.57^{c}	2.57^{a}	77.09^{a}	78.85^{a}	21.34^{b}	18.58^{c}	20.73^{b}	20.05^{b}
250	2.33^{ab}	2.87^{a}	68.44^{a}	59.29^{b}	29.22^{b}	37.83^{b}	22.04^{b}	23.53^{a}
275	2.55^{ab}	3.23^{a}	47.40^{b}	51.71^{bc}	49.90^{a}	45.06^{ab}	26.32^{a}	24.80^{a}
300	2.70^{a}	3.41^{a}	44.70^{b}	39.76^{c}	52.74^{a}	56.83^{a}	25.77^{a}	26.92^{a}

*Values are mean of Proximate and Heating value of Toreffied and untoreffied selected wood sample ---- replicates

CONCLUSION

In this research, torrefaction was applied to improve the biomass properties of biomass materials selected from Pine and Leucocephalla. The results of the proximate analysis showed that increasing of torrified temperature; volatile fraction was reduced while fixed carbon was increased. Ash content of were within 1.57-3.41% of torrefied wood. This indicates that the selected species were suitable biomass source for torrefaction process. At 300 the species lost many volatile contents and has the lowest mass yield. The mass yield is closely related to volatile matter. It was observed that deciduous xylan-containing wood (*Leucaena leucocephala*) is more reactive in the torrefaction process than coniferous wood (*Pinus carreabeanus*). In the first case, the mass conserved in the torrefied wood is lower likewise the value of volatile was much for *Leucaena leucocephala* than *Pinus carreabeanus* and this translate directly into mass loss.

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