academicJournals

Vol. 4(4), pp. 64-71, April, 2013
DOI 10.5897/JPTAF12.028

http://www.academicjournals.org/JPTAF

Journal of Petroleum Technology and Alternative Fuels

Full Length Research Paper

Influence of wood humidity of three species (*Prosopis africana*, *Anogeissus leiocarpa* and *Tectona grandis*) on the production of charcoal by the traditional wheel

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Accepted 4 March, 2013

Charcoal production is an increasing practice which however, remains traditional in Benin despite the introduction of new techniques of carbonization. The objective of this study is to evaluate the effect of species humidity on the production process, in the perspective of improving the yield in relation to farming practices. To achieve this, three wood species appearing in four humidity conditions were used in randomized complete block design with two replications. The humidity of wood negatively affects the process; while an increased density had a positive effect on the process. The mixture of species and mixture of wood at different state of humidity gave good results compared to the use of a single species in the dry state. The yield of dry wood was estimated to an average of 31.38% for *Prosopis africana*, 21.5% for *Anogeissus leiocarpa*, 15.25% in wet or mixture of wood of different humidity and 21.5% in semi-wet or dry for *Tectona grandis* and 22% for the mixture of species.

Key words: Carbonization, charcoal, wood humidity, mass yield, Benin.

INTRODUCTION

Biomass which is the fourth largest energy source in the world, provides about 13% of world's energy consumption (Hall et al., 2000). In general, wood represents about 86% of household energy consumption (Broadhead et al., 2001) and the demand is expected to rise to 45% over the next 30 years due to the population growth and the increasing needs in sub-Saharan Africa (De Montalembert and Clement, 1983). For many urban areas in developing countries, charcoal provides a reliable, convenient and accessible source of energy in meeting household requirements as well as a variety of other needs (Goldstein, 1981; Demirbas, 2001). Charcoal also has unique cooking properties that make households go for it even when other fuels are also available (Seidel, 2008).

Wood constitutes the main fuel for Beninese households and provides 89% of domestic energy. Ninety three percent (93%) of the Beninese population use wood energy in rural areas, against 80% in urban areas (Dossou, 1992, 1996). Daily consumption of charcoal is estimated at 0.35 kg per person in urban areas as against 0.15 kg per person in rural areas (Agbo and Mama, 2001). About 3 million tons of fuelwood are consumed each year in Benin; and due to demographic growth, the need for fuel wood is expected to increase. Faced with growing demand for fuelwood and its lack,

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solutions differ from one author to another. According to Malty (1999), wood transportation is the main factor in the increasing cost of wood during periods of scarcity, as consumers have to travel long distances in search for them; logically its price increases. Wood as energy source is no longer competitive with other sources of energy such as oil, gas, etc. The pressure on forest resources is naturally regulated by the law of supply and demand, without any particular action. But the author recognizes that the law of supply and demand cannot effectively regulate the pressure on forest resources, so producers should be able to influence it by imposing the prices. However, this is often not the case.

De Gier (1989) has proposed three alternatives to fuel wood crisis such as: the identification of other sources of energy; increasing the supply of wood and adoption of energy conservation methods. To prove the ineffectiveness of the first solution in developing countries, Anderson and Firhwick (1984), reported that as long as wooded areas and forests have not disappeared, the costs of cooking with wood fire or coal are lower than those of other commercial fuels as oil and gas. Compared to the second solution, efforts to promote community and private plantations for the production of wood as source of energy (coal, firewood) marketed in Benin, comes exclusively from the natural fallow or wastelands (Ogouvidé et al., 2006).

In addition, the requirements in quality (heavy and slow burning coal) are actualized by species characterized by great density, slow growing and therefore particularly vulnerable to exploitation, this being a serious constraint for producers (Girard, 2002). The most used species in Benin are among others *Anogeissus leiocarpa*, *Pterocarpus erinaceus*, *Prosopis africana*, *Vitellaria paradoxa* and *Pseudocedrela kotschyi* (Idjigbérou, 2007). The same species are considered the most exploited in the Sudanian savanna and dry forest areas of Togo (Kokou et al., 2009). Adam (1990) and Schenkel et al. (1997) reported that “The Wheel” is still the most prevalent traditional method for charcoal production in developing countries despite the introduction of new techniques of carbonization through development projects.

In Africa, a limited number of people consider charcoal production to be their main economic activity, while a majority engage only occasionally as a means to generate income, particularly in times of financial stress, such as when making large payments for medical bills; funeral expenses; food supplies in the event of poor harvests; marriage ceremonies or school fees (BTG, 2010). Other reasons for non-adoption of new production techniques are the cost of investment, difficulties of installation and availability of equipments. Therefore, practices and current production of charcoal are characterized by a low yield estimated at 15 and 20% (150 to 200 kg of charcoal per ton of wood) (Girard, 2002). However, the yields obtained during the carbonization of wood are the best possible, as the producer must work with rigor and professionalism.

According to FAO (1983), it is possible to save nearly 2 million cubic meters of wood, thereby increasing efficiency in the production of charcoal with the use of improved wheel. With improvements to the traditional wheel on the number of vents reduced to 4 instead of 7, the stacking of wood, the choice of species with high calorific value and the tightness of the wheel, brought the coal mass yield from 11 to 20% (Mama, 2006). By entering this logic to improve yields of charcoal produced by the traditional wheel to allow producers to generate more income and reduce pressure on forest resources, this paper aims to assess the effect of the wood humidity content of three species based on the endogenous production practices.

MATERIALS AND METHODS

Experimental site

The experiment was carried out on a site located in the district of Savè in central Benin. The district of Savè is a transition zone between the Guinean climate with four seasons and the Sudanian climate with two seasons. It enjoys a climate with contrasting seasons characterized by noticeable fluctuations in temperature and an average annual rainfall of 1200 mm. The average annual temperature is 27°C; the average relative humidity is 31% for the minimum and 98% for the maximum. The soil type is tropical ferruginous concretions of crystalline basement or hydromorphic along the river.

Experimental design

The experimental design used was a randomized complete block design with two replications. Controlled factors are:

(i) The species of wood with four levels, these species are among the species most used in the carbonization process in Benin (*A. leiocarpa*, *P. africana*, *T. grandis* and their mixture in proportions of 1/3);
(ii) Four moisture conditions, wet wood (humidity approaching 45%), semi-dry wood (humidity around 30%), dry wood (humidity approaching 15%) and a mixture of wood at different humidity levels.

The combination of the levels of two factors (humidity and species) gives a total of 4 × 4 = 16 objects. Each object was repeated twice. Thus, the implementation of this experimental design required 32 outbreaks of carbonization. For each outbreak of carbonization, the load volume is a stere of wood. In this context, the wood was cut in pieces of one meter long. Characteristics of wood used in the experiment are presented in Table 1. The carbonization was carried out according to the method of the traditional wheel.

Data collected

The data collected include the duration of carbonization, the total weight of the charcoal obtained, the weight of unburnt wood remaining; the mass yield calculated from the mass of a stere of green wood and mass of charcoal obtained on one hand; the mass of the stere of anhydrous wood and mass of charcoal obtained on

Table 1. Mean values and standard errors (in parentheses) of humidity, diameter of the logs, and mass (kg) of a stere of wet wood and anhydrous wood for different levels considered.

Species	Humidity (%)		Diameter (cm)	Total mass load / stere (kg)	Mass of dry wood / stere (kg)
	State	Value			
A. leiocarpa	Wet	40.26 (0. 52)	15.98 (0.16)	757.73 (73.02)	453.10 (47.54)
	Semi-humid	24.00 (0.06)	17.76 (0. 59)	759.13 (35.85)	576.97 (26.86)
	Dry	12.63 (0.32)	15.86 (0.30)	575.36 (9.85)	502.77 (10.42)
	Mixed	27.61 (0.57)	16.02 (0.01)	708.94 (9.28)	513.32 (10.72)
P. africana	Wet	38.59 (0.16)	15.98 (0.30)	913.40 (5.06)	560.96 (1.72)
	Semi-humid	24.52 (0.68)	16.02 (0.00)	864.02 (35.77)	652.43 (32.84)
	Dry	13.07 (0.21)	16.46 (0.10)	633.41 (11.26)	550.61 (8.47)
	Mixed	24.70 (0.11)	15.82 (0.22)	784.55 (9.55)	590.79 (6.34)
Tectona grandis	Wet	41.14 (0.80)	14.86 (0.78)	625.08 (5.77)	367.91 (1.58)
	Semi-humid	24.12 (0.26)	14.32 (0.78)	547.22 (14.24)	415.31 (12.20)
	Dry	12.55 (0.32)	15.68 (0.53)	478.09 (0.36)	418.11 (1.83)
	Mixed	26.08 (0.96)	15.80 (0.15)	531.63 (21.70)	392.79 (10.96)
A. leiocarpa + T. grandis + P. africana	Wet	37.99 (1.82)	15.38 (0.01)	836.39 (15.09)	518.98 (24.55)
	Semi-humid	23.69 (0.26)	15.50 (0.36)	698.68 (1.13)	533.16 (0.98)
	Dry	12.53 (0.17)	13.93 (0.30)	682.16 (190.60)	596.36 (165.56)
	Mixed	25.60 (0.70)	14.42 (0.20)	719.02 (20.60)	534.95 (9.80)

the other hand. Yields are given by the following formulas:

$RM_{bh} = M_{ca} / M_{bh}$ and $RM_{ba} = M_{ca} / M_{ba}$

with

RM_{bh} = Wet mass yield

RM_{ba} = Dry mass yield

M_{ca} = Mass of dry coal

M_{bh} = Mass of wet wood

M_{ba} = Mass of dry wood

The mass yield also known as yield or yield weight on dry wood is only valid for a rigorous comparison (Girard, 1992), because from a stere of green wood of the same weight and different humidity, the quantities of charcoal they produce will be different, only dry wood being transformed into charcoal (Mundhenk et al., 2010).

Statistical analysis

Data analyses were performed using SAS software. Factors (species and moisture) were subjected to analysis of variance with two factors of classification, as response variables were the duration of carbonization, the weight of charcoal obtained, unburnt weight and yield. Duncan's tests comparing mean was used to detect possible differences between the levels of a factor.

RESULTS

Quantity of charcoal

Quantities of charcoal obtained per a stere of wood vary from one humidity state to another according to the species. The highest values of quantities of charcoal were observed with wood in the semi-wet of species *A. leiocarpa*, *P. africana*, *T. grandis*, and with wet wood for the mixture of species. The lowest values were obtained with dry wood for the species *A. leiocarpa* and wet wood for species *P. africana*, *T. grandis* and mixture of species. However, comparing the values revealed no difference in the degree of wood humidity regardless of the species, except *T. grandis* which had a higher quantity of charcoal at semi-wet state of 98.15 kg/stere.

Whatever the state of humidity, the quantity of charcoal obtained by stere can be estimated to 109.11 kg/stere for *A. leiocarpa*, to 182.9 kg/stere for *P. africana* and 116.89 kg/stere for the mixture of the three species. After carbonization of a stere of wood, *P. africana* presented the highest value in the quantity of charcoal. The mixture of species provided an intermediate value. *T. grandis* had the lowest values (Table 2). For a given species or a given state of humidity, the values associated with the same letter were not statistically different from each other

Table 2. Mean values and standard deviations (in parentheses) of mass (in kg) of charcoal produced per stere of wood with different considered level of humidity.

Species	Humidity			
	Wet	Semi - wet	Dry	Mixture of humidity
A. leiocarpa	108.70^{aA} (8.9)	118.00^{aA} (9.9)	104.25^{aAB} (2.47)	105.50^{aA} (3.50)
P. africana	165.75^{aB} (6.01)	191.85^{Ab} (13.22)	190.20^{aC} (9.48)	183.80^{aB} (1.13)
T. grandis	52.55^{aC} (3.75)	98.75^{bA} (3.89)	80.00^{aB} (5.66)	62.50^{aC} (3.54)
A. leiocarpa + *T. grandis* + *P. africana*	108.05^{aA} (8.13)	114.00^{aA} (4.24)	125.00 ^{aA} (8.49)	120.50^{aA} (0)

Table 3. Mean values and standard deviations (in parentheses) of mass (in kg) of unburnt wood per stere of wood for different levels considered.

Species	Humidity			
	Wet	Semi - wet	Dry	Mixture of humidity
A. leiocarpa	11.00^{aA} (2.12)	6.90^{aA} (1.27)	1.25^{aA} (1.77)	6.75^{aA} (3.18)
P. africana	3.50 ^{aA} (4.24)	10.00^{aA} (4.24)	10.50^{aA} (3.54)	15.25^{bA} (3.89)
T. grandis	10.35^{aA} (1.67)	4.55^{aA} (2.05)	6.00^{aA} (2.83)	13.75^{aA} (3.89)
A. leiocarpa + *T. grandis* + *P. africana*	12.50^{aA} (2.12)	6.50^{aA} (0.71)	6.75^{aA} (1.48)	8.50^{aA} (1.43)

at the level α = 5%. Lowercase letters denote the comparisons between humidity state for a given species, and the capital letters indicate the comparisons between species of a given humidity level.

Quantity of unburnt wood

For the same humidity, the quantities of unburnt wood did not differ from one specie to another. Similarly, for the same species, the humidity of wood had no influence on the mass of unburnt wood species except *P. africana*, whose blend of wood with varying degrees of humidity of wood had a value higher than the other degrees of humidity (15.25 kg/stere) (Table 3).

For a given species or a given state of humidity, the values associated with the same letter were not statistically different from each other at the level α = 5%. Lowercase letters denote the comparisons between humidity state for a given species, and the capital letters indicate the comparisons between species of a given humidity level.

Duration of carbonization

The species of wood had basically no effect on the duration of carbonization. On the contrary, humidity influenced this duration. It was estimated at about four days for wet wood, semi wet and mixture of humidity and three days for dry wood shown in Figure 1. In the dry state, the species *P. africana* had duration of carbonization relatively higher than other species (about four days).

Yield of charcoal

The analysis of results showed that there was no interaction between the factors of humidity and species regardless of the yield considered (p = 0.09, p = 0.07, p = 0.08 respectively of yields of wood put in the oven, dry wood and dry wood minus wood unfired). The evaluation of the influence of the species reveals that *P. africana* presented highest yield of dry wood. It was estimated at 31.38%.

The yield of dry wood of *A. leiocarpa* was estimated at 21.50%; for *T. grandis*, it was estimated at 18.50% and for the mixture of the three species, it was estimated at 21.86%. The assessment of the effect of humidity in each species showed that the efficiency increased when the wood humidity decreased. The highest yield of hydra wood was obtained in the dry state (Table 4).

DISCUSSION

The efficiency of a wheel is determined by a number of factors, including wood humidity, the dimensions of pieces of wood, the size of the wheel, the species of

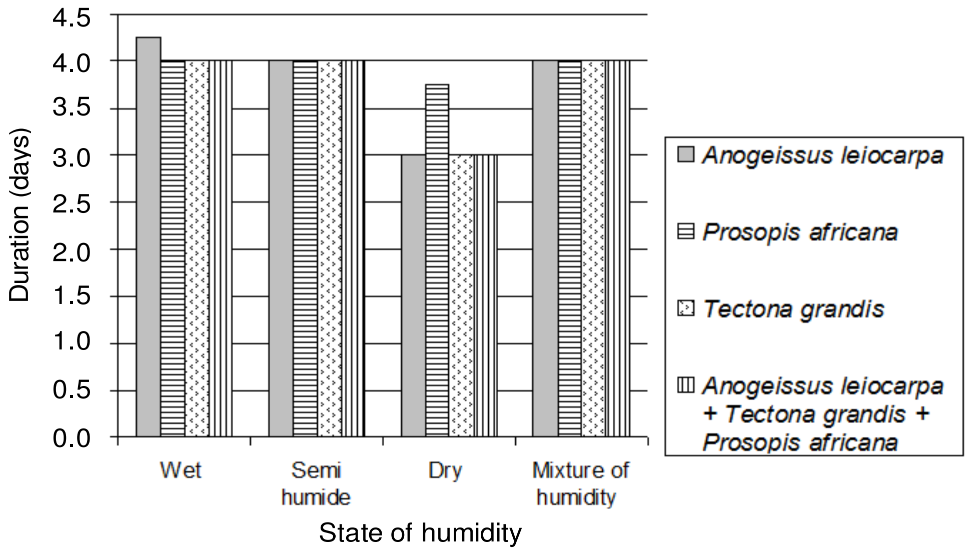

Figure 1. Duration of carbonization of each species according to the state of humidity.

Table 4. Mean values of yields of wet wood, dry wood and dry wood minus unburnt wood for different combinations levels considered.

Species	Humidity		Yield (%)		
	State	Value (%)	Wood put in the oven	Dry wood	Dry wood minus unburnt wood
A. leiocarpa	Wet	40.26 (0.52)	14.50[b]	24.00[a]	24.50[a]
	Semi-wet	24.00 (0.06)	15.50[b]	20.50[a]	20.50[a]
	Dry	12.63 (0.32)	18.50[a]	21.00[a]	21.00[a]
	Mixture of humidity	27.61 (0.57)	15.00[b]	20.50[a]	21.00[a]
P. africana	Wet	38.59 (0.16)	18.50[b]	30.00[a]	30.00[a]
	Semi-wet	24.52 (0.68)	22.00[b]	29.50[a]	30.00[a]
	Dry	13.07 (0.21)	30.00[a]	34.50[a]	35.50[a]
	Mixture of humidity	24.70 (0.11)	23.50[a]	31.50[a]	32.00[a]
T. grandis	Wet	41.14 (0.80)	8.50[c]	14.50[b]	14.50[b]
	Semi-wet	24.12 (0.26)	18.00[a]	24.00[a]	24.00[a]
	Dry	12.55 (0.32)	17.00[a]	19.00[a]	19.00[a]
	Mixture of humidity	26.08 (0.96)	12.00[b]	16.00[b]	16.50[ab]
A. leiocarpa + T. grandis + P. africana	Wet	37.99 (1.82)	13.00[a]	21.00[a]	21.50[a]
	Semi-wet	23.69 (0.26)	16.50[a]	21.50[a]	21.50[a]
	Dry	12.53 (0.17)	19.50[a]	22.50[a]	22.50[a]
	Mixture of humidity	25.60 (0.70)	17.00[a]	23.00[a]	23.00[a]

For a given species, the yield values associated with the same letter were not statistically different from each other at the level $\alpha = 5\%$.

wood used in the wheel, climatic conditions as humidity of the air, wind, etc. (Schenkel et al., 1997). In this study, the wood humidity and species were considered. Climatic conditions were considered using an average climatic condition of the subject area, because the study site is located in the transition zone of Benin, between the Sudano-Guinean and Sudanian zone.

The influence of physicochemical characteristics of wood on the process of charcoal production has been reported by several authors including Larzilliere (1978), FAO (1983) and Bugnicourt and Mhlanga (1985). The quantity of charcoal obtained depends on physico-chemical characteristics of wood used as raw material. Thus, the quantity of charcoal obtained with *P. africana*, the heavier wood between the species investigated in this study, was different from other species. *P. africana* presented the quantities of charcoal ranging from 165 to 191 kg/stere. *A. leiocarpa* (heavyweight wood) presented an intermediate situation with quantities of charcoal per stere ranging from 104.25 to 118 kg/stere. *T. grandis*, the lighter species had the lowest quantities of charcoal per stere with values ranging from 52.55 to 98.75 kg/stere.

As a result of the lack of availability of raw material, producers in their practice often mixed species in the outbreaks of carbonization. The mixture of species of different densities can increase to some extent the quantity of charcoal produced. The quantities of charcoal obtained per stere (108 to 125 kg) are greater than those obtained with *A. leiocarpa* and *T. grandis*. Similar results were obtained by Mundhenk et al. (2010) in community forest Sambande, Kaolack in Senegal (102 kg/stere with 45% of humidity).

Similarly, a stere of wood in Madagascar gave 90 kg of charcoal (Bugnicourt and Mhlanga, 1985). The results obtained are relatively higher than those found by Ogouvidé (2010), in the same study area for the species *Senna siamea*, and *A. leiocarpa* which produced 62 and 72.73 kg/stere with traditional wheel respectively. Although the yield with the mass of wood put into the oven is to be considered for calculation, the mass yield of dry wood is preferable for comparisons, because it eliminates the effect of humidity factor especially since this factor strongly influences the performance.

Thus, differences in yields between species would be even greater if this factor is taken into account. The quantities of dry wood per stere for each species appear on average in a proportion of 75%. *P. africana*, showed the highest yield of dry wood which is an average of 31.38%. *A. leiocarpa* and the mixture of species gave intermediate values of yields of anhydrous wood with average of 21.5 and 22%, respectively. *T. grandis* considered as a light wood among the species studied appears with the lowest yield which is 15.25% in wet and mixed states and 21.5% in the semi-wet and dry states. The yield of *T. grandis* also known as Teak, is relatively high compared to the yield found in the literature on teak wood carbonization.

Coulibaly and Lessard (2006) evoked in an experimental study of charcoal production of commercial timber from thinnings of teak plantations in Tene forest in Côte d'Ivoire, a yield on dry wood of 15%. Ogouvidé and Mama (2007) by testing the adaptability of the circular type of Casamance wheel on the wood species *A. leiocarpa* in the charcoal production areas of Central Benin, found a yield of 25 and 19% for the Casamance and traditional wheel, respectively. In the same area and to the same species, PBF2 (2009) referred to a yield of 22%. Mundhenk et al. (2010), indicate in a general case, a yield of 15-17% for the traditional wheel. However, there may be exceptions where yields are up to 45% (Robinson, 1988). In Senegal CILSS (2008), PERACOD (2007), and World Bank (2008) reported yields of dry wood from 30 to 35%. In Chad, Hughes (2001) gave a yield of dry wood from 25 to 30% for the Casamance wheel and 18 to 23% for traditional wheel. CILSS-PREDAS (2004) reported a yield of dry wood from 16 to 20% for the traditional wheel and 20 to 40% for improved wheel. The same trends of yields are noted by other authors including FAO (1983), Leclerc (2002) and Dejonc (2003).

Strong disparities between the yields can be explained by several factors. On the whole, the dry wood with humidity levels below 15% gives the best yields while the wet wood with humidity above 20% have average yields. The differences between species were also mentioned by other authors. Rameau (2009) reported values as 28, 26 and 22% yield respectively for charcoal of beech, oak and fir. These differences may also come from the expertise of coal makers whose practices can help offset some of the technical constraints of the density or the humidity of wood. For example, the mastery of the difficulties of firing charges of wet or semi-wet wood especially for dense species reduces the consumption of a significant portion of wood. This may explain some of the results including equality between the quantities of charcoal obtained for Teck and *P. africana* in semi-wet state. Indeed, the consumption of wet and semi-wet wood of dense species leads to a significant loss of wood during carbonization process. However, in the dry state, while hardwoods are difficult to ignite, they burn slowly and are therefore more suited to heating. This difficulty of firing wet or semi-wet wood results in an increase in the duration of carbonization.

Wood carbonization is a three stages process. The first step is the drying of wood at 100°C, during this step, the complete evaporation of the water contained in the timber to make it dry is performed. During the second stage, the temperature of the dry wood is raised to about 280°C. In the last stage, is exothermic decomposition of the timber which is stopped at about 400°C when there is no external energy (FAO, 1983). The first step will be much longer as there is more quantity of water to be evaporated. If the wood is already dry, this step is greatly reduced and the duration of carbonization is consequently shorter.

The duration of carbonization of dry wood is estimated at three days and four days per stere of wet wood. There is a wide disparity in the duration of carbonization reported in the literature. Mundhenk et al. (2010) noted in their study on the traditional wheel, two to three days duration of carbonization respectively of 30 and 50% of humidity in community forest Sambandé in Senegal. Briane and Haberman (1984) gave in France the duration of two days for a weel of 7 stere with a degree of wood humidity ranging from 29.9 to 42.9%. Hibajene (1994) mentioned in Zambia the duration of twenty-seven to thirty-one days to 6 stere and wood degrees of humidity ranging from 28.2 to 34.4%.

Schenkel (1991), mentioned 43 days for 15 stere of wood with the wood humidity ranging from 70.2 to 118.5%. This disparity is due to the fact that experiments are carried out in highly variable conditions (experimental sites, operator qualification, precision measurements). There is also a lack of information on these tests carried out in situ including characteristics such as humidity, size of logs and species.

The influence of humidity on the duration of carbonization has been mentioned by other authors including Larzilliere (1978), FAO (1983), Leclerc (2002), Jeffrey and Stedford (1983), CRA-Wallonie (2009) and Girard (1992). Mildred and Wilfrid (2003) made nuance and pointed out that wood humidity affects much more than the density of the species. For these authors, the humidity above 20% is already considered high and remarkably influences the yield of charcoal obtained. Comte (1975), and Roos and Roos (1979) pointed out, however, that the dry wood can have up to 25% of humidity. This may explain the differences in performance observed in the four states of humidity. CRA-Wallonie (2009) showed the strong influence of humidity on the yield; and the authors qualify as the secondary effects, other physical parameters as density, size, shape, etc. They also mentioned that humidity, as the heating rate increases, have a negative impact on the flow of mass and energy. This emphasizes the important aspect of the calorific value of charcoal. Indeed, consumers are looking out more for a heavy and hard charcoal with a slow consummation rate. This leads producers to make a selection of species to be cut for charcoal production.

Selective cutting means that certain trees providing good quality charcoals are selected and cut for charcoal production. Preference and suitability of trees used for charcoal production varies with size, availability and accessibility of the tree species. Large tree species (>20 cm diameter) with high caloric values are the most preferred, due to the large quantity of dense and hard charcoal they produce (Beukering et al., 2007).

Upon completion of the experiment, a survey carried out among producers in the study area revealed that charcoals are obtained from dense species such as *P. africana*, *P. erinaceus*, *V. paradoxa*, *Burkea africana*, *A. leiocarpa* and *Senna siamea*. Ogouvidé (2010) showed that the charcoal from most of these species has a calorific value higher than 90% in accordance with the standards of 52 to96% defined by Schenkel et al. (1997).

Conclusion

Production of charcoal in Benin is a rural activity, which is increasing due to the demand of charcoal which is increasing widely in major urban centers. Although, this activity has a great deal of income contribution of coalman, it is characterized by a low yield with a high pressure on forest resources. Looking for an improvement of the production process in relation to farming practices helped to highlight the influence of wood humidity and species used in the process. The humidity of wood negatively affects the process, while the density has a positive effect on the process. The mixture of species and mixture of wood at different state of humidity also yielded good results than the use of a single species in the dry state. The best yields are obtained in the dry state with about 13% humidity. These results are close to the yield provided by the new carbonization techniques such as Casamance wheel whose performance varies from 30 to 35% (PERACOD, 2007).

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