Design and operation of a small-scale carbonization kiln for cashew nutshell valorization in Burkina Faso

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ABSTRACT

This paper describes the process of planning, design, building and first operation tests of a carbonization reactor for the valorization of cashew nutshells, obtained as byproduct from small-scale cashew cultivation and processing in Bobo-Dioulasso, Burkina Faso. The main technical requirements for the reactor were: low cost and ease of construction, robustness, autothermal operation, no need for pre or post-treatments for feedstock and products, and readily usable product fractions in a local scale. Design modifications are discussed and justified. Characterization of the raw material, data from the first successful operational tests, as well as product distribution and characterization, are presented. This carbonization prototype allows for the sustainable valorization of an otherwise problematic biomass residue, creating added-value products that would enhance the economic profitability of local processors. The use of the main charcoal product as a fuel substitute for household cooking is preliminarily assessed, and the recovery of potentially valuable cashew nutshell liquid (CNSL) is accomplished.

Keywords: Cashew shell; Pyrolysis; Carbonization; Charcoal; CNSL.

1. Introduction

Around 2.5 billion people worldwide rely on the use of forest biomass, agricultural or livestock residues, or charcoal for their energy needs; in particular, for cooking purposes (IEA, 2016). In Sub-Saharan Africa (SSA), 784 million people rely on biomass for cooking, almost 80% of the population. While this percentage has decreased by three points since 2000, due to population growth there are 240 million more people still cooking with solid biomass (IEA, 2016). Although the future projections envisage switching to other fuels, the International Energy Agency (IEA) estimates that 2.3 billion people worldwide would still rely on these energy sources in 2030.

As this energy transition would span a few decades, several related problems still need to be solved in the meantime. The main problem is that pollutant emissions from combustion of biomass resources in indoor spaces constitute a major health issue, estimated by IEA to cause 2.5 millions of premature deaths per year, mainly to women and children (IEA, 2016). The main responsible for this devastating effect is the inhalation of small particulates from smoke, which is generated from the inefficient combustion of biomass. It has been shown that the use of charcoal for cooking, instead of raw biomass, can substantially improve this issue (Amaral et al., 2016; Bailis et al., 2003; Koyuncu and Pinar, 2007). This key feature, together with its better transportability, storability, hydrophobicity and high energy density, contributes to fuel switching from raw wood to charcoal –especially in urban areas, where charcoal may be more affordable for the final consumer (Mwampamba et al., 2013).

Significant additional benefits may be attributed to fuel switching from raw wood to charcoal. On the one hand, new employment and economic opportunities in rural areas may appear. It is estimated that the charcoal sector currently provides income and livelihood to around 7 million people in SSA (Mwampamba et al., 2013) and 40 million people worldwide (van Dam, 2017), although the sector is mainly informally constituted and value chain may be improved through a better organization (Schure et al., 2013). On the other hand, there are gender and educational implications, caused by the displacement of time-consuming tasks such as fuelwood collection, and the high potential health benefits for women and children (that play a major role in household cooking).

However, some environmental risks associated with the widespread use of wood charcoal also emerge. First, deforestation and forest degradation issues may arise if forest resources are not sustainably managed (Chidumayo and Gumbo, 2013; Zulu and Richardson, 2013). Excessive forest resources may also be used as a consequence of employing traditional and inefficient charcoal making technologies. The use of such systems (pits, earthmounds and some simple kilns) also pose the risk of significant pollutant and greenhouse gases emissions during the production process. Thus, it is crucial to develop improved charcoal making technologies which can efficiently transform wood resources into high yields of high quality charcoal (Garcia-Nunez et al., 2017). These technologies must be also affordable and environmentally friendly (Sparrevik et al., 2015).

It is difficult to provide reliable information about the characteristics of charcoal that is currently used in this area, because of the informal production methods, as well as the different wood species, batches and providers. In general, the most preferred tree species for fuelwood are: *Detarium microcarpum*, *Crossopteryx febrifuge*, and *Anogeissus liocarpa* (Puentes-Rodriguez et al., 2017), and *Prosopis Africana, Burkea Africana and Terminalia* species for charcoal production.

The relative importance of charcoal as a cooking fuel is much bigger in urban than in rural areas. Burkina Faso produced in 2012 some 13 million cubic metres of wood fuel (including wood for charcoal) and 0.6 million tonnes of charcoal. In rural areas, firewood burning in simple stoves is the main source of energy in 93.7% of the households, followed by wood in improved stoves (2.4% of rural households), charcoal (1.2%), gas (0.8%) and petroleum (0.3%). In urban centres, 56.8% of the households use fire-wood in simple stoves, followed by gas (15.1%), charcoal (10.2%),wood in improved stoves (9.7%), electricity (0.7%) and petroleum (0.5%) (Arevalo, 2016). A literature reference in the context of Burkina Faso gives a HHV reference value of 25.7 MJ/kg for charcoal (Yamamoto et al., 2009).

The high demand for woodfuel and charcoal from major towns has led to the overexploitation of the nearby forests, resulting in large rings of deforestation around them (Arevalo, 2016). Thus, a further step towards sustainability of the charcoal value chain would be the use of agricultural residues as raw material in substitution of forest resources (Lohri et al., 2016; van Dam, 2017), contributing to the establishment of a circular economy with zero-waste generation. Alternative uses of charcoal may also be considered. Within the agricultural sector, the conversion of underutilized waste into charcoal shows promise for soil amendment purposes (biochar) in West African low fertility soils. However, a recent study reported modest effects of combined biochar application and wastewater irrigation in Ouagadougou soils (Haring et al., 2018).

1.1. Cashew nutshells as waste biomass

West African countries represent around 45% of the world cultivation of cashew (Rabany C, 2015). Burkina Faso accounts for 2.3% of the global production (75000 metric tons per year), with 4 MHa of planted surface. It is a growing sector, and production was forecasted to almost double in 5 years in 2015. The African Cashew Initiative published a detailed report on the cashew value chain in the country (Kankoudry Bila N., 2010), highlighting that most of the production (>90%) is exported as raw nuts without processing. The average size of a plantation is around 5 Ha, and the few existing processing units have an estimated capacity of 8200 MT/year of raw cashew nuts and employ around 2200 workers, more than 90% of which are women. It can be concluded that increasing the processing capacity throughout the country would provide a substantial improvement in the overall cashew value chain. However, the market for byproducts from processing is currently underdeveloped, and care should be taken on assessing the ecological impact of small-scale processing techniques.

As shown in Figure 1, cashew nutshells are usually dumped after simple processing in small and medium-sized production sites, and only a relatively small fraction is burnt to provide heat for energy-intensive processing stages (Mohod et al., 2011). The practice of dumping involves a serious environmental issue, because of the fact that Cashew Nutshell Liquid (CNSL) comprises around 30-35% of the cashew nut total weight (Ábrego et al., 2018; Mubofu, 2016), and is contained in the nutshell. This CNSL is a reddish viscous liquid, mainly composed by a variety of long chain phenolic compounds (Abbina and Anilkumar, 2017; Lomonaco et al., 2017). This liquid is a skin irritant and it is known to impede vegetable growth if incorporated into the soil. Moreover, this practice is extremely inefficient from a value chain perspective, because CNSL is a valuable source for industrial phenolic compounds and its recovery should be a priority in the processing stages, as occurs in major producer countries such as India, with skilled labor force and processing technology (Taiwo, 2015). CNSL can be extracted from the nutshell by means of mechanical, thermal or solvent methods (Garkal and Bhande, 2014; Mgaya et al., 2019).

After extracting CNSL, the remaining nutshell can be carbonized and marketed as a high quality charcoal (as proposed in this work), used as soil amendment or directly burnt for heat and/or electricity. Recently, Sawadogo et al. proposed the production of fuel briquettes from the carbonized press cake resulting from the CNSL mechanical extraction from the cashew nut shells (Sawadogo et al., 2018). However, although this cashew by-product derived fuel exhibit the same combustion performances as that of wood charcoal, the prerequisite extraction of CNSL requires an equipment investment that could be profitable only at industrial or semi-industrial scales and as far as stable and substantial enough markets are found for CNSL.

Figure 1. Dumping site of cashew nutshells in Bobo-Dioulasso.

1.2. Carbonization processes for wood and waste

Production of charcoal by biomass pyrolysis has been carried out for millennia (Antal and Gronli, 2003). The most widely used technologies for charcoal production in developing countries are still the traditional ones: pits, earthmounds and kilns (Emrich, 1985; Garcia-Nunez et al., 2017). These systems are inherently inefficient due to several factors: (i) no byproduct recovery is usually accomplished, (ii) heat management is poor and process control is difficult and heavily dependent on the operator skills, (iii) the product is inhomogeneous and often mixed with soil and dirt, and (iv) large quantities of atmospheric pollutants are released.

To overcome some of these issues, improved batch reactors have been proposed, such as the Adam retort (Adam, 2009), beehive, Missouri or TPI kilns (FAO, 1987; Garcia-Nunez et al., 2017), amongst others. These are simple and robust designs that allow for small scale, decentralized production of charcoal for local markets. They do not require highly skilled operators, and batch operation is suitable for using seasonal agricultural residues as feedstock. However, byproduct recovery and pollutant emissions are still unresolved in many of these designs and special attention must be paid on both issues. In particular, the release of CNSL during heating of cashew nutshells imposes an additional difficulty when considering pyrolysis as an alternative for residue valorization; thus, new small-scale reactor designs are required to accomplish this purpose.

The main objective of this work is to develop and operate a simple and affordable carbonization reactor, suitable for the effective conversion of cashew nutshells into useful products within the scenario of the cashew sector in Burkina Faso. Additionally, the information available in this paper (including operational experience, a detailed account of the detected problems and the design choices adopted) can be useful for future small-scale designs for pyrolysis reactors using agricultural residues as a feedstock. The need for open-source designs in this field has been pointed out recently (Woolf et al., 2017), and in particular, there is scarce information in the literature detailing the specific difficulties encountered during the design and startup stages of such affordable carbonizers. Thus, in order to achieve these objectives, a set of design specifications were first defined to build a first prototype and further design modifications were later implemented according to experimental work. The detailed methodology will be explained in the following Section.

2. Materials and Methods

2.1. Feedstock characteristics

Empty cashew nutshells were collected from a production site in Bobo-Dioulasso. The feedstock characteristics are summarized in Table 1. As can be seen from the Table, the nutshells present a low moisture content, relatively high ash content for a biomass material, and a significant HHV.

CNSL was extracted using a Soxhlet as described elsewhere (Ábrego et al., 2018). The extracted fraction was 31.2% w/w, which is within the range of values obtained by other authors (Mubofu, 2016).

To preliminarily assess the decomposition behavior of cashew nutshells, it is illustrative to present thermogravimetric analyses (TGA and DTG) of both extracted and unextracted cashew nutshells (Ábrego et al., 2018). Part of the discussion presented in the mentioned reference is summarized here. The TGA curves are shown in Figure 2. These runs were performed by means of a Netzsch 440A apparatus, with a heating rate of 10 ºC/min for raw and extracted nutshells (without CNSL), and under nitrogen atmosphere. As expected, the mass loss behavior of untreated and extracted samples is quite different. Both the raw and the extracted materials experience the greater mass loss in the temperature interval between 200-350 ºC. For the unextracted material, it is possible to distinguish four weight loss peaks at 175, 263, 311, and 412 ºC, the two at intermediate temperatures being very marked. Tsamba et al. (Tsamba et al., 2006) observed a similar behavior for the thermal decomposition of cashew nutshell, although with a higher temperature in the second of the main peaks. For the extracted sample, only two relevant peaks appear in the whole temperature range. The first one appears as a shoulder (270 ºC) and could correspond to hemicellulose decomposition, while the second (320 ºC) corresponds to the cellulose degradation. Comparing both samples, there is a huge difference in the mass loss caused by the peak at 263 ºC that can be attributed to the evaporation of most of CNSL constituents from the unextracted sample. The last mentioned peak at 412 ºC would correspond to the decomposition of remaining, polymerized CNSL material (Lomonaco et al., 2017). Previously, the observed peak at 175 ºC could be caused by the conversion of anacardic acid from CNSL to cardanol. As can be concluded from Figure 2, from approximately 300 °C the figures corresponding to the weight of the sample are similar for both cases, which indicates that before this temperature the CNSL of the raw material has practically disappeared. This has relevant implication for the design of a pyrolysis system with in-situ CNSL recovery.

Table 1. Characteristics of cashew nutshells.

Figure 2. TGA (full lines) and DTG (dashed lines) for untreated and extracted CNS (Ábrego et al., 2018).

2.2. Design Methodology

As commented in the Introduction section, the design of the prototype has been influenced by the characteristics of the equipment location so, in order to build a first prototype, the following list of requirements have been taken into account:

- Simple and flexible design.
- Autothermal operation (by burning the gas fraction from pyrolysis).
- Maximization of the solid product fraction.
- Recovery of CNSL.
- Small scale, batchwise operation, modular design.
- Easy replacement of parts if necessary by local workshops and workers.
- Use of readily available materials.
- Affordability in the specified scenario.
- Easy operation; no advanced operational skills required.
- Low particle and unburnt gases emissions.
- High availability of the equipment along time.

Scale-up of the system has not been considered in this work, since the core of the carbonization reactor is made from a standard size (220 L) steel drum, and the target cashew production sites are small-scale plantations in which parallel units could be used if necessary.

According to the previous considerations, literature works and the experience of the research group, the following design guidelines were adopted:

- Pyrolysis should take place in a cylindrical, metallic retort operated batchwise. A standard steel drum can be adapted for this purpose.
- This retort should be placed inside a stationary combustion chamber made of metal or refractory bricks.
- The liquid produced (CNSL and biooil) should be directed out from the retort and cooled down in order to collect it. Uncondensed phase is channeled into the combustion chamber and burnt, thus heating the retort.
- Due to the low-temperature release of CNSL from the nutshells (as it can be seen in Figure 2), this liquid and bio-oil can be collected at different stages of a batch pyrolysis operation; therefore, two different condensation circuits should be designed to achieve separate collection of both products.
- The process is initiated by burning a limited amount of fuel inside the combustion chamber, ideally, agricultural residues or a small amount of previously produced charcoal).
- The entire carbonization process must be manual handling.

After applying these design guidelines and obtaining the initial reaction system, operational tests, product distribution and analysis of the products obtained would provide the information needed for implementing design improvements, according to the scheme depicted in Figure 3.

Figure 3. Steps followed in the implementation of design improvements for the pyrolysis prototype.

2.3. Prototypes

Throughout the work period, two different prototypes were built.

2.3.1. Prototype 1

The main characteristics of prototype 1 were adopted according to the design guidelines and can be observed in Table 2.

Table 2.- Main characteristics of prototype 1.

The core part of the prototype is a standard 220 L steel drum with the necessary modifications, which plays the key role of the reactor. The election of an ordinary oil drum and not a specifically made kiln for the reactor is justified by the design guidelines shown above. While a reactor specifically made of a more resistant metal would perform better and endure more, an ordinary oil drum (made from a thin layer of steel) can be found everywhere, both in urban areas and in rural areas. They are also economically affordable (around 9 000 CFA – 13 €) thus assuring an easy replacement.

It was necessary to make some modifications. The front base of the cylinder was cut and a lid was built for the drum with steel sheet 3 mm wide. The lid included a handle, which was attached to the drum with three screws.

The CNSL recovery process principle is gravity: it is expected to be released in liquid form when the decomposition of the nutshell constituents (mainly hemicellulose and cellulose) begins, at relatively low temperatures. Therefore, three rows of small orifices with a diameter of 1.2 cm, were drilled along the longitude of the drum, pointing at the bottom. Below the puncture arrays, the recovery tube system is constituted of two parts: an outer pipe welded to the bottom part of the kiln, with a slight inclination of 5º for facilitating the exit of the highly viscous CNSL; and an inner removable half-tube which encloses into the outer tube by means of a metal flange. This removable tube facilitates the removal and cleaning of stuck CNSL at the end of the carbonization process. This double tube extends some 60cm in front of the reactor, and it is connected at its lower level to the CNSL recovery tank. This desing for CNSL collection ensures that the liquid is always channeled in a closed environment without air, which avoids its combustion in the chamber.

Figure 4. Sketch of this first prototype (made using Solidworks).

Figure 4 depicts the general design features of this first prototype. At the back of the drum, an upper orifice was done in order to allow the exit of pyrolysis vapors (bio-oil plus non condensable gases). A vertical downward pipe connects the outlet of the gases with the burners that provide the heat for the pyrolysis. Another purpose of this pipe is to allow the gas to cool down and condense the bio-oil, which can be recovered independently of the CNSL. The utilization of permanent gases for the heating of the retort was achieved by two cylindrical gas burners, which are connected to the upper gas exhaust of the drum. On the lowest point of the gas recirculation, a small pipe was included to recover the condensed tar into a closed tank. In order to monitor the temperature of the process, two type K thermocouples were installed in the prototype. Previous experiments carried out in our laboratory with this material confirmed that at 500ºC the amount and heating value of gas produced is enough to supply all the energy necessary for the pyrolysis process (Ábrego et al., 2018).

It was decided to operate this equipment inside a combustion chamber that consisted of a metallic dome supported on four legs, with walls made from hollow bricks at the sides. The metal-brick joints were sealed with clay. Although this approach imposed several limitations on the overall system performance of this first prototype (e.g. lower energy efficiency and increased emissions from incomplete combustion of gases), it allowed us to focus on the retort operation and liquid byproduct recovery systems, monitoring the temperature evolution of the pyrolysis process more easily.

2.3.2. Prototype 2

Table 3.- Main characteristics of prototype 2.

From the results obtained with the first prototype, changes were made to the initial design. A second prototype was built incorporating these modifications. The main changes and characteristics of this second prototype are summarized in Table 3.

Because the quantities of recovered bio-oil were very small, and given the little interest for this product in the local context and the added complexity of working with two different liquid recovery lines, in this second prototype the bio-oil recovery line was removed, burning the small amounts produced with the gases.

With the aim of improving the thermal efficiency of the equipment, the metallic combustion chamber was substituted for a chamber made of bricks (Figure 5). The material chosen was mechanically compressed clay mud brick, instead of firebricks, which are more resistant but might not be so available in rural zones in Burkina Faso. The compressed bricks had been already tested satisfactorily in pizza ovens. The arch and walls were constructed using two different sizes of bricks (22x10.5x5 cm for the arch, and 29.5x14x9 for the base). Four ventilation holes were performed at the bottom of the walls, which can also be easily covered by bricks if no additional air inlet is needed. The stack is metallic and embedded into the brick structure, with a small gap between the materials for allowing metal thermal expansion.

Figure 5.- Image of prototype 2

2.4. Experimental work.

Throughout the experimental period, with the different prototypes, the following experimental work has been carried out:

- Pyrolysis experiments of cashew nuts in different conditions. The experiments were carried out with both prototypes. The duration of the experiments ranged between 3 and 5 hours. Because not all the experiments carried out were satisfactory, we report here data corresponding to successful (or partially successful) tests, and mention the main detected problems in the unsuccessful ones, that at least were useful to implement the necessary design modifications in the prototypes.
- Characterization of the final products: the final products of the successful experiments were analyzed, measuring the following properties: The elemental composition (C, H, N) of the solid product and CNSL was measured using a LECO TruSpec CHN Instrument according to ASTM D5373-08. Oxygen was calculated by difference. Water content was determined by Karl-Fischer titration. Proximate analyses were done according to standards ISO-589-1981 (moisture), ISO-5623-1974 (volatiles) and ISO-1171-1976 (ashes), with fixed carbon calculated by difference. Higher heating values of liquids and chars were also determined in a calorimetric bomb following ISO-1928-2009.
- Water boiling tests. Experiments were carried out in which the local use of the obtained charcoals was studied and compared with other materials. In these experiments, the time needed and the amount of charcoal consumed for boiling a known amount of water was compared against identical tests using the biomass normally available in the area where the prototype was installed. These tests were a custom modification of the Water Boiling Test (WBT), which is utilized for comparative study of the emissions and performance of cookstoves (Global Alliance for Clean Cookstove, 2014; Obeng et al., 2017).

3. Results

3.1. Carbonization results

Table 4 presents the main results from the pyrolysis experiments of cashew nutshell, using both prototypes 1 and 2. As mentioned before, the results of other non-successful tests are not included. As also mentioned, the initial operation of the prototypes was not autothermal, and it was necessary to burn a certain amount of nutshells to provide the necessary heat for the process. Table 4 also includes the charcoal and CNSL yields ($y_{CH,py}$ and y_{CNSL}, respectively) and the charcoal yield related to the total consumption of nutshells ($y_{CH,total}$), defined as follows (all in mass percentage):

$$y_{CH,py} = \frac{W_{CH}}{W_{CNS,reactor}} \times 100 \qquad \text{(Ec. 1)}$$

$$y_{CH,total} = \frac{W_{CH}}{W_{CNS,reactor}+W_{CNS,ext}} \times 100 \qquad \text{(Ec. 2)}$$

$$y_{CNSL} = \frac{W_{CNSL}}{W_{CNS,reactor}} \times 100 \qquad \text{(Ec. 3)}$$

where W_{CH} is the amount of charcoal produced in each run; $W_{CNS,reactor}$ and $W_{CNS,ext}$ are the amount of nutshells pyrolyzed inside the reactor and burned in the combustion chamber, respectively, and W_{CNSL} is the amount of CNSL recovered.

Table 4. Summary of the quantitative results from the experimental tests

As can be seen in Table 4, a 'normal' run using 40-50 kg of nutshells as pyrolysis feedstock (that, according to the apparent density presented in Table 1, correspond to 50-60% of the 220 L reactor volume) produces a char yield that ranges for most of the experiments between 21 and 29 % ($y_{CH,py}$), or 11-17% ($y_{CH,total}$). These results are similar to those obtained by other authors using cashew nutshells (Mashuni et al., 2017) and by our group in a recent work at laboratory scale (charcoal yields slightly below 30% in the interval 400-600 ºC) (Ábrego et al., 2018).

It can be seen that, for both prototypes, a part of the CNSL is recovered which, in the best case, corresponds to approximately 20% of the total CNSL content of the pyrolyzed material (31.2 % w/w of the raw material). In this sense, the built prototypes have a clear margin of improvement, so that a greater recovery of this product is possible.

In view of these results, an additional experiment was carried out with the objective of studying the pyrolysis of cashew cake (CNSL extracted before the pyrolysis). This cake was obtained by performing a previous extraction of the CNSL by means of a cold extraction in a screw press. In this extraction the 22% of the initial weight was removed as CNSL, being the rest the cashew cake. For this new test, 30 kg of cake where introduced in the reactor, obtaining a pyrolysis yield ($y_{CH,py}$) of 25%, and a low value of CNSL yield (0.66%). The physical aspect of the coal obtained in this experiment was good. The results of this experiment suggests that the use of a two-stage process, with an initial extraction of the CNSL and the subsequent pyrolysis of the extracted material, may be appropriate, and the proposed system could be useful for recovering an additional, albeit small, amount of valuable CNSL.

In Figure 6, a typical temperature profile inside the reactor is shown. As can be seen, during the first hour of experiment the reactor increases its temperature until reaching a constant regime. However, there are important oscillations in the temperature of the process due to the absence of control in the prototype. Throughout the different tests carried out, it was found that, in order to obtain an appropriate charcoal (without the presence of tars or unburned material inside the reactor), a temperature exceeding 500ºC in the gas exit must be reached, keeping the reactor above that value for 2-3 hours.

Figure 6. Temperature profile inside the reactor (Experiment 7)

In Figure 7, the ratio between burned nutshells and loaded nutshells in the prototype is plotted against the time needed to reach 300ºC in the gas exhaust, in different experiments and for both prototypes. As can be seen, this ratio ranges between 0.7 and 1.2 in all cases. Interestingly, the heating time is much lower in the second prototype (25-40 minutes against 75 minutes) due to its better thermal insulation, that results in greater energy efficiency and therefore in lower relative consumption of nutshells as startup fuel. This is obviously preferable from the point of view of performance. However, the second prototype practically doubles the cost of the first. This is an important fact since the cashew nut is a raw material available at no cost in Bobo-Dioulasso.

Figure 7. Ratio between burned nutshells ($W_{CNS,ext}$) and shells loaded in the prototype ($W_{CNS,reactor}$) vs. time necessary to reach 300ºC in the gas exhaust.

Complete cooling time of the reactor is about 16 hours for the second prototype, and considerably lower in the first; thus, in both prototypes it is possible to carry out a daily operation. The use of more than one reactor vessel in parallel would allow semi-continuous operation and therefore a higher daily throughput.

The proximate and elemental analyses of the products from experiment number 7 are taken as representative of the reactor performance and are shown in Table 5; additionally, and for the sake of comparison, the analyses of local wood char (purchased from local dealers and commonly used for cooking in the region) and the cashew cake char (produced in the additional experiment) have been included.

Table 5.- Properties of the products.

All the solid materials analyzed present a higher heating value close to 30 MJ/kg, and there are no significant differences between HHV of cashew char and wood char. Additionally, the difference in HHV between cashew char and cashew cake is small, although statistically significant. Regarding proximate analysis, it can be seen that the ash content of both chars produced from cashew nutshell is higher than that of wood char. Fixed carbon is higher for chars from cashew, mainly in the case of the nutshell cake. Mehetre et al. and Ramanan et al. have reported much lower values of fixed carbon (55.67% and 59% respectively) and similar ash content (5.91% and 6% respectively) for cashew nutshell char (Mehetre et al., 2016; Ramanan et al., 2008). The HHV is slightly higher than that reported by Moreira et al. (Moreira et al., 2017), with values between 25-28 MJ/kg.

3.2 Water boiling test.

In order to investigate the suitability of cashew nutshell char as a fuel, a preliminary assessment of its performance for domestic cooking in conditions similar to those commonly used in Bobo-Dioulasso was carried out, including comparison with locally used wood charcoal. Three boiling water test (WBT) were done for three chars obtained from prototype 2, with a custom adaptation of the WBT protocol developed by the Global Alliance for Clean Cookstoves (Global Alliance for Clean Cookstove, 2014).

The test employed a domestic stove (Figure 8) to boil a certain amount of water in a pot by burning a pre-weighted bundle of the tested fuel. The water content in the pot shown in the figure was 3 L. During the heating processes, time and temperature of water were monitored. The boiling temperature was maintained for around 10 minutes; after that time the pot was removed and the amount of unburned fuel was weighed in order to calculate fuel consumption.

Figure 8.- Cookstove used for the boiling test.

For the three experiments, the results were similar, and Figure 9-a shows a typical result obtained for the water boiling tests (using charcoal from Experiment 7). In all the experiments, it could be seen that heating was faster, and that the boiling temperature of 100 ºC was reached before (8 minutes in the case of the experiment depicted in Figure 9-a) by using cashew charcoal as a fuel, compared to wood charcoal. Additionally, the charcoal consumption (represented in Figure 9-b for two of the experiments) was considerably lower for nutshell charcoal (a decrease between 32 and 55%, compared to wood charcoal usage). This result is interesting, taking into account that both materials have similar values of Higher Heating Value. A possible explanation is that both the much more homogeneous size and higher hardness of the nutshell char, compared to the varying dimensions of the wood charcoal lumps and its brittleness, could play a role in the superior performance of the former.

Figure 9.- Results of water boiling test (WBT) for cashew and wood charcoal. a) Water temperature vs. time for char from exp 7 and wood char. B) Weight of charcoal consumed vs. boiling time for char from exp 6 and 7.

4. Conclusions

As a result of this work, a reactor for the pyrolysis of cashew nutshell has been designed and built. This reactor meets the specifications initially proposed for use in Bobo-Doulasso (Burkina Faso). The main conclusions obtained from the results obtained are the following:

- The design and construction of a low-cost and easy-to-maintain cashew nutshell pyrolysis equipment, to produce charcoal and recover part of the CNSL (up to 20%) contained in the raw material, is possible.
- A retort for the processing of 50kg of nutshell can be autothermic and allow a daily use.
- Charcoal yields up to 40% can be reached in the reactor.

- Although a combustion chamber made of bricks is thermally more efficient, the use of a metal chamber is more economical considering the free availability of cashew nuts in Bobo-Dioulasso.

- The pyrolysis e of the cashew nutshells produces an increase in the energy density of the produced solid higher than 30% with respect to the raw material.

- Compared to the wood charcoals, commonly used for cooking in Bobo-Diaulasso, the charcoal produced from cashew nutshell allows faster heating, with lower fuel consumption, despite having similar HHV.

- Given the relatively low cost of the proposed prototype, further inexpensive modifications would be advisable and could be tested for improving operational stability; for instance, simple control devices (flap venting valve or similar).

- For future implementations, it could be possible a semi-continuous operation achieved by substitution of the cylindrical retort with a second retort filled with fresh feedstock, once the batch process is finished. This operation mode would increase energy efficiency of the process by maintaining high temperatures in the combustion chamber.

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Nomenclature and Abbreviations

ASTM: American Society for Testing and Materials
CFA: Franc de la communauté financière d'Afrique. West African Franc.
CNS: Cashew nutshell
CNSL: Cashew nutshell liquid
DTG: Differential Thermogravimetry
FAO: Food and Agriculture Organization of the United Nations
HHV: High Heating Value
IEA: International Energy Agency
ISO: International Organization for Standarization.

SSA: Sub-Saharan Africa
TGA: Thermogravimetric Analysis
TPI: Tropical Products Institute
WBT: Water Boiling Test
W_{CH}: Weight of charcoal produced in each run
$W_{CNS,ext}$: Weight of nutshells burned in the combustion chamber
$W_{CNS,reactor}$: Weight of nutshells pyrolyzed inside the reactor
W_{CNSL}: Weight of CNSL recovered
$y_{CH,py}$: Yield to charcoal after pyrolysis
$y_{CH,total}$: Charcoal yield related to the total consumption of nutshells
y_{CNSL}: Yield to CNSL

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