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Research Article

Pelleting of Agricultural Residues in Senegal: Study of Influencing Phenomena & Chemical Elements

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ABSTRACT

In Senegal, biomass fuels and more specifically pellets from agricultural residues have attracted interest in recent years. These fuels are eco-friendly materials and represent a better alternative to domestic fuels such as charcoal or firewood due to their availability at local scale associated to their relative uniformity (standard size, possible formulation of several residues, higher energetic density with respect to firewood). In the present work, we produced and characterized 6 mm diameter pellets from residues of groundnut shell, corn cob, palm nut shell and typha both in pure form or blended from two different residues. The characterizations of these pellets showed that the pelletizing of biomass residues makes it possible to significantly increase the Lower Heating Value (LHV) of single pellets. The mixture of different agricultural residues makes it possible to have a much higher heating value, with pellets with LHV greater than 19 MJ/kg. We also highlight the importance of the pelletizing process in reducing the ash content for blended pellets; the opposite phenomenon is observed for single pellets. Our work also shows the importance of pelletizing and blending of agricultural residues in reducing the formation of bottom ash and corrosion.

1. Introduction

The transformation of agricultural residues into pellets offers a strategic alternative to existing domestic fuels in Senegal and other Sub-Saharan countries facing the same environmental difficulties (rapid climatic change, deforestation and subsequent desertification) [1]. These pellets have the potential to substitute domestic fuels in Senegal [2], which is experiencing an increase in the price of charcoal, and the scarcity of firewood in rural areas. These pellets can also be an alternative to imported natural gas for small and medium agri-food industries, particularly in West Africa [3]. In fact, the densification of these residues under pellet form considerably increases their density, both in terms of mass and energy. The densification of biomass increases the ignition, burnout, and the composite combustion index, leading to a better performance of biomass combustion [4]. This fact has an immediate effect on their interest at the national scale, since their transport becomes economically interesting and their quality as a fuel can compete with existing supply schemes [5]. Indeed, biomass pellets are proven to constitute environmentally friendly option that contributes to the recovery of resources, energy sustainability, and effective waste management [6]. Biomass pellets can be interesting to fire industrial equipment such as furnaces, boilers, etc., and other equipment using different biomass

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conversion technologies such as gasification or pyrolysis. Although it is a complex process to be yet fully comprehended, granulation or pelletizing of biomass residues makes it possible to overcome several logistical obstacles posed by biomass. It is increasingly implemented as a pre-treatment step for the production of energy from biomass, as it has several advantages among which are densification and standardization of the geometry of the fuel [7].

However, this pretreatment step is subjecting the biomass to mechanical and thermal stresses. In fact, the effects of bonding in densified biomass pellets can be explained from different viewpoints ranging from theories such as attraction forces between solid particles, adhesion and cohesion forces, interfacial forces and capillary pressure, solid bridges and mechanical interlocking bonds [8]. Other parameters, such as velocity and temperature can also impact the thermo-physical parameters of the biomass pellets and the pelletization process. Indeed, an increase in the value of temperature-dependent fluid viscosity parameter, can increase the velocity, thus the intrinsic characteristics of the pellets [9]. It is therefore necessary to first determine whether the Pelleting process itself could have an influence on the thermal degradation of the biomass.

In the literature, several biomass chemical elements are reported to cause technical issues in biomass conversion systems, namely clogging, slagging and corrosion. The different nature of the mineral and phase composition of biomass ash makes it complicated to predict slagging and fouling behavior. Slagging and fouling occur when the ash particles become molten and adhere to the boiler surface [10]. Inorganic vapors may also condense on solid particles at lower temperatures, coating their surface in a sticky molten film [11].

High-chlorine fuels (>0,2%) generate the risk of intensified corrosion process and a limited steel mechanical strength is observed [12]. These elements play an important role, especially in the technical and environmental problems caused by the energy valorization of biomass [13,14]. For our studies, three main phenomena at the technical level can be retained, namely clogging, fouling and corrosion. For environmental problems, we will mainly focus on NOx & SOx emissions, and particulate emissions.

The following table summarizes the list of chemical elements contained in the biomass, identified as problematic during thermal conversion processes.

Table 1. List of chemical elements from biomass with positive or negative impact on the process [15,16]

Phenomena	Aggravating elements	Positive elements
Clogging	K, Na, Cl, Si-K, Si-Na, Si-K-Mg, Si-K-Ca	Si-Al, Si, Si-Ca, Si-Mg, Si-Ca-Mg
Fouling	K, Na, Si, S, P	Ca, Mg
Corrosion	Cl, K, Na, S	Si-Al
NOx	N	Ca, K, Mg, Fe
SOx	S	Ca

In our work, we have carried out the pelletizing of various agricultural residues in order to be able to address the problems posed by raw agricultural residues. We show how the densification of agricultural residues facilitates combustion, in particular the reduction of clinker formation. This phenomenon is even more visible when we make blended pellets from agricultural residues. Nevertheless, the combustion and pyrolysis is dependent on pellet's characteristics such as particle shape, particle size, isothermal and non-isothermal heating conditions, and convective and radiative heat transfer [17].

Biomass pelleting influences other parameters such as NOx emissions, as demonstrated by Piednoir et al., highlighting the linear correlation between NOx emissions from single pellets and the percentage of nitrogen contained in biomasses when they are burned alone. For the blended pellets, Piednoir et al. also observed a reduction in NOx emissions for biomasses with high nitrogen content and high NOx emissions, when they were associated with other biomasses with lower nitrogen (N) contents, but especially with high levels of calcium (Ca) [18].

Our paper presents the design and characterization of new agricultural biomass fuels, namely single pellets and blended pellets of agricultural residues. The pellets are designed to be able to compete with domestic fossil fuels in Senegal in terms of heating value, but also to solve the technical and environmental problems caused by the combustion of conventional agricultural biomass.

2. Materials and Methods

The steps of the pelletizing protocol used to make our agricultural residue pellets are schematized in figure 1.

The crop residues are dried, then crushed using a hammer mill, densified with a press and finally transformed into pellets.

Fig. 1. Diagram of the pelletizing protocol

Fig. 2. Pictures of the hammer mill and pellet machine

To obtain consistent pellets, a small amount of water is added to the crushed residues before compacting. The moisture content of these residues is the critical parameter of our pelletizing protocol. The tests carried out have shown that its ideal value is around 12%. In our experiments, we use a GEMCO model TFS420 hammer mill of 7.5 kW, with a capacity of 50 kg/h and a GEMCO model ZLSP 200B pellet machine (7.5 kW), with a capacity of 50 kg/h.

Different percentages of agri-residues were mixed according to the LHV of each biomass in order to reach a minimum value of 18MJ/kg. This specific value was chosen in order to have pellets that can compete with conventional domestic solid fuels: charcoal (22MJ/kg) and firewood (15.12 MJ/kg). This would make it possible to have a fuel with a higher heating value and at a more competitive cost.

The lower heating value for the different residues is given in figure 3.

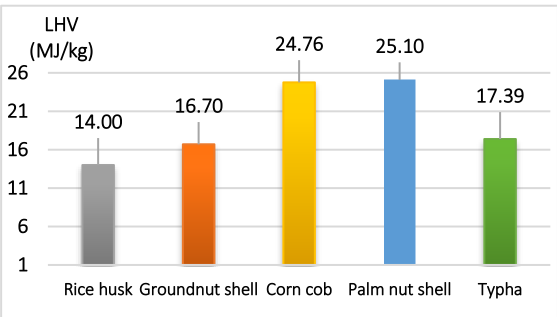

Fig. 3. Compared Lower Heating Value of the selected agricultural biomasses

Six (6) types of pellets could thus be produced:

(1) Groundnut shell pellets
(2) Typha pellets
(3) Corn cob pellets
(4) Blended pellets of groundnut shell (70%) and palm nut shell (30%)
(5) Blended pellets of typha (67%) and palm nut shell (33%)
(6) Blended pellets of typha (60%) and corn cob (40%)

Fig. 4. Picture of groundnut & corn cob pellets produced

To determine the characteristics of our pellets, we carried out an immediate analysis and an elemental analysis in order to determine the quality of each fuel (pellet) and to be able to compare them.

Within the framework of our study, the main parameters of comparison are the PCI and the ash content. Immediate analysis of the single and blended pellets produced allowed to determine their LHV, ash content, humidity content, and fixed carbon content. The elemental analysis determined the carbon, hydrogen, oxygen and nitrogen compositions of the different pellets. These analyses were carried out on anhydride and raw materials. Moisture content was determined using a desiccator. The ash content and the volatile matter content were determined using a muffle furnace, following the same process. The LHV of the pellets were determined using a bomb calorimeter. The analysis of the mineral content made it possible to predict the combustion behavior of each of them; by thermogravimetric analysis using a laboratory furnace equipped with a precise balance to 0.1mg. The full experimental methodology is described by Saldarriaga & al. [19]. The characterizations were carried out at the BioWooEB laboratory of CIRAD in Montpellier (France).

3. Results & Discussions

3.1. Characterization of the single pellets

The intrinsic characteristics of peanut shell pellets, corn cob, and typha are recorded in table 2.

Table 2. Characterization of single pellets produced

Pellets	Immediate analysis			
	Moisture content	**Ash content**	**Volatile content**	**Fixed carbon**
Groundnut pellets	8.6%	6.7%	71.1%	22.1%
Typha pellets	10.2%	9.1%	72.4%	18.5%
Corn cob pellets	12.0%	6.0%	78.83%	15.17%

Pellets	Elementary analysis				Lower Heating Value (MJ/kg)
	%C	**%H**	**%O**	**%N**	
Groundnut pellets	49.9%	5.5%	42.8%	1.8%	**16.56**
Typha pellets	45.6%	5.3%	48.7%	0.4%	**16.67**
Corn cob pellets	-	-	-	-	**17.08**

We made the following findings from the characterization of the single pellets produced:

A slight increase in the moisture content and ash content of the single pellets compared to their respective agri-residues; the initial moisture content of the groundnut shell, corn cob, and typha are respectively 7.88%, 7.04% and 16%. This is mainly due to the addition of water (used as a binder for the production of pellets).

It should be noted that the other intrinsic characteristics (in particular the carbon, hydrogen, oxygen and nitrogen content) remain substantially the same after the pelletizing process; the carbon, hydrogen, oxygen and nitrogen compositions are 49.32%, 7.27%, 39.15%, and 1.16% for groundnut shell, and 45.3%, 6.3%, 47, 6% and 0.8% for typha [18]. We can then conclude that the pelletizing of pure biomass residues, without blending, does not modify the intrinsic characteristics of the biomasses.

A slight increase in the heating value of the biomasses after pelletizing; the LHV of groundnut shell, corn cob, and typha are respectively 15.87, 16.38 and 15.98 MJ/kg [20]. This shows the importance of pelleting for increasing the heating value of biomass residues, in addition to its densification and increase of mass density.

3.2. Characterization of the Blended Pellets

The intrinsic characteristics of our blended pellets are given in table 3.

Table 3. Characterization of blended pellets produced

Pellets	Immediate analysis			
	Moisture content	**Ash content**	**Volatile content**	**Fixed carbon**
Groundnut shell + palm nut shell Pellet	8.6%	3.3%	73.2%	23.6%
Typha + palm nut shell Pellet	8.5%	7.8%	72.1%	22.1%
Typha + corn cob Pellet	8.4%	8.7%	72.9%	18.4%

Pellets	Elementary analysis				Lower Heating Value (MJ/kg)
	%C	**%H**	**%O**	**%N**	
Groundnut shell + palm nut shell Pellet	50.8%	5.5%	42.3%	1.4%	**19.18**
Typha + palm nut shell Pellet	47.7%	5.4%	46%	0.9%	**17.75**
Typha + corn cob Pellet	46.2%	5.3%	47.6%	0.9%	**16.88**

Unlike single pellets, our results show that the moisture contents of the blended pellets are all around 8.5%, after pelleting regardless of the residues that are used. The moisture content of agri-residues and single pellets, even after drying, are often higher than 10%. This shows that this uniform moisture content of the blended pellets is largely due to the mixing of agri-residues. The biomass blending process for pelletizing therefore allows stabilization of the moisture content, regardless of the difference in the moisture content of the different biomasses used. The blended pellets also have intrinsic characteristics quite similar to their original biomass (almost in proportion to the percentages of biomass used for each blended pellet).

We also note a clear improvement in the heating value of the blended pellets, with LHV greater than 17 MJ/kg, compared to single pellets where the LHV is less than 17 MJ/kg. The high LHV of the palm nut shell, and its lignocellulosic composition make it possible to increase the overall LHV of the blended pellets, despite the low proportion of the palm nut shell in the mixture. This was our initial objective, to increase the heating value of pellets through the blending of different agricultural residues, in order to be able to compete with domestic fuels available on the market (charcoal, firewood, LPG). This shows that the pelleting of agricultural biomass represents a very good option for the use as domestic fuels.

3.3. Ash Residues Analysis

The analysis of the mineral content of the pellets produced makes it possible to reveal the chemical elements of importance, as well as the possible aggravating phenomena for each type of pellet.

After the study of the chemical elements of importance in the combustion of the biomass, we retained three (3) principal phenomena in our application for the pyro-gasification (combustion) of the pellets, namely the formation of clinkers, the emissions of SO_x and NO_x emissions.

The results of the ash analysis are recorded In table 4.

Table 4. Composition of inorganic elements of the pellets (expressed in the form of oxides)

Pellets	Inorganic elements content						
	% SiO_2	% K	% Mg	% Na	% Cl	Fe (mg/kg)	Al (mg/kg)
Groundnut	3.0	0.69	0.07	0.02	0.06	1,838.7	447.2
Typha	0.82	1.09	0.41	0.92	3.12	2,629.2	301.2
Corn cob	0.66	0.63	0.05	0.02	0.24	1,302.7	651.8
Groundnut + palm nut	0.87	0.51	0.05	0.02	0.03	7,043.6	619.6
Typha + palm nut	4.35	0.70	0.06	0.09	0.51	5,124.5	386.6
Typha + corn cob	4.92	0.68	0.07	0.09	0.48	5,518.1	265.9

The results show a low level of silica (SiO_2) in general for the single pellets and blended pellets, compared to the silica levels of the residues (10.4% for the groundnut shell and 8.74% for the corn cob). Single pellets of corn cob, and blended pellets of groundnut shell and palm nut shell have low levels of silica, despite the high level of silica contained in the corn cob and groundnut shell. This shows the effect of pelletizing, but also of the blending of biomass in reducing the silica rate.

The non-negligible levels of silica for the blended pellets of typha and palm nut shell (4.35%), and blended pellets of typha & corncob (4.92%), could prove to be a source of problems for the formation of bottom ash, and blocking of the combustion chamber. Nevertheless, the very low rate of sodium (Na) (less than 0.1%) and potassium (K) (less than 0.7%) in the ashes of the different pellets allows us to predict an inhibition the effect of bottom ash formation which could have been caused by the high level of silica (SiO_2) in these pellets.

Ash analysis does not, however, certify or predict SOx and NOx emissions. These emissions will then have to be measured during the combustion tests that we will carry out.

4. Conclusions

This work highlights the importance of pelleting to better valorize agricultural residues, by allowing its densification, but also by increasing their heating value. The blending of different agri-residues makes it possible to increase interestingly the heating value of the blended pellets obtained, while keeping the intrinsic properties of the biomasses. In this sense, the blended pellets of groundnut shell (70%) and palm nut shell (30%) represent the best type of pellets for use as domestic fuel due to their high heating value (19.18 MJ/kg), but also its low ash content (3.3%).

Although the blending of different biomass residues did not always allow a linear reduction in the level of silica (SiO_2), the low levels of sodium (Na) and potassium (K) in the ashes of the different pellets allow us to predict an inhibition of the effect of bottom ash formation which could have been caused by the silica level. This shows the importance of the blending of agricultural biomasses for reducing the formation of bottom ash in industrial furnaces.

The pelleting and blending of different agricultural residues therefore make it possible to use eco-friendly fuels and reduce at the same the negative impact of certain parameters during the combustion of these residues, thus offering a wide range of possible uses (domestic/industrial fuels, usable in direct combustion or pyrolysis and gasification). Our work will continue with the analysis of combustion gases to assess NOx and SOx emissions, and the development of a pilot technology to carry out combustion tests of our pellets.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the authors have entirely observed the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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