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Experimental investigation of chestnut shells gasification

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Abstract. Fossil fuels substitution with renewable energy sources is necessary for an effective decarbonization. Biomass can represent a valid alternative to fossil fuels, reducing greenhouse gas emissions. Furthermore, bioenergy generation avoids costs and problems related to biomass disposal. This study presents the energetic valorisation of chestnut shells, a byproduct of the chestnut transformation processes. Through a thermo-conversion system based on gasification, this material was considered not as a waste, but as a resource to be exploited to produce bioenergy and biochar. The fuel gas produced through the gasification process can partially replace the LPG currently used to meet the energy required for the brulage and steam peeling processes. Experimental gasification tests were carried out to evaluate this biomass by means of a laboratory scale micro-gasifier (Imbert downdraft type). Chestnut shells were pelletized with a pelletizer machine to avoid the bridging effect inside the gasifier and increase its energy density. The fuel gas obtained was sampled and analyzed to measure its composition and HHV. In addition, the gasification efficiency was calculated obtaining a value of 70%, a result in line with the ones obtained with higher quality biomasses.

1. Introduction

The agro-industrial sector is seeking strategies to reduce the waste disposal problem to improve its sustainability. The chestnut transformation process, in particular, produces a considerable amount of byproducts such as leaves, burrs and shells that need a proper disposal [1].

This work explores the energetic exploitation of one of this residues, namely chestnut shells, that represents about 20% of the total fruit weight [1]. Biomass residues such chestnut shells can represent a promising and sustainable energy resource [2]. Gasification is one of the most common thermochemical processes that can be used for bioenergy production with dry biomass [3]. It consists in the partial oxidation of the material with the consequent production of a fuel gas (producer gas from now on) composed of H_2, CO, CO_2, N_2 and CH_4 and a solid product called biochar, a porous and carbon-rich material that can be used as soil amendment [4,5]. The producer gas can be used for electric and thermal power generation in CHP systems and it can be considered a carbon negative solution if the biochar produced is used for carbon sequestration applications [6,7]. Considering the chestnut transformation process, a possible efficient way to exploit the gasification process is substituting the liquefied petroleum gas with the producer gas as fuel for the brulage and steam peeling processes [8].

In order to demonstrate the feasibility of this strategy, a gasification test have been carried out with chestnut shells as fuel in a micro scale gasifier.

2. Materials and Methods

The system used was the "*Femto Gasifier*", designed at the BEELab Laboratory of the University of Modena, at the Department of Engineering "Enzo Ferrari". It is a downdraft gasifier prototype that operates with few kg/h of biomass flow (**Fig. 1a**). **Fig. 1b** shows chestnut shell pellet produced with a 7.5 kW *Cissonius PP-200*. Chestnut shells were pelletized to prevent bridging events due to the low bulk density of the shells.

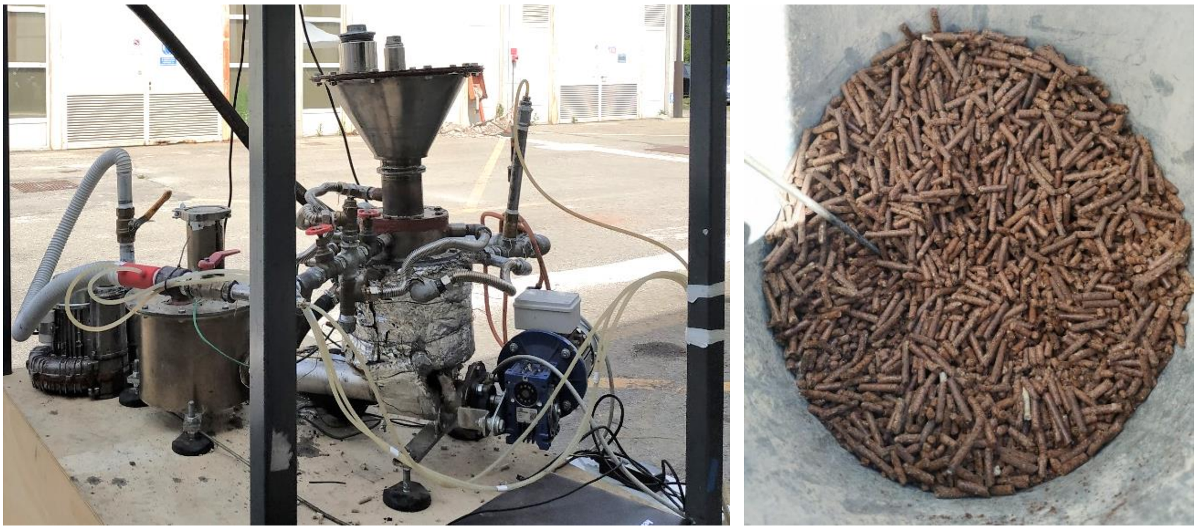

a) b)

Fig. 1 a) *Femto Gasifier* **b)** Chestnut shell pellets

Ultimate and ash analyses were performed on the produced pellet to verify that its chemical-physical characteristics were not altered by the process, and on the biochar obtained during the gasification test.

Knowing its elemental composition, it was possible to estimate the higher heating value in MJ/kg (*HHVbio*) by means of the Channiwala and Parikh correlation [9]. The gasification test was performed monitoring the gas temperature at the outlet of the gasifier, the gas composition, the biomass flow and the reactor pressure drop. The producer gas temperature was measured with a K-type thermocouple, while the pressure was monitored with a pressure sensor *MPXV5004DP* (*NXP Semiconductors*) connected to an *Arduino* Board. The gas composition was measure by means of a *MicroGC GCX* gas analyzer while the biomass flow input was measured by weighing it with a *Kern* precision balance.

Char yield was estimated dividing the ash content of the chestnut by the ash content of the produced biochar.

The producer gas flow can be estimated knowing the elemental composition of biochar, its mass flow and the producer gas composition. This calculation is performed with the following equations by assuming that all the carbon content in the biomass is transferred in the gas, forming CO, CO_2 and CH_4, and in the biochar:

$$\dot{C}_{in} = \dot{m}_{bio} \cdot \frac{C[\%]_{bio}}{100} \tag{1}$$

Where $\dot{C}_{in}$ is the mass flow of carbon entering in the gasifier. $C[\%]_{bio}$ is the carbon content in the biomass and $\dot{m}_{bio}$ is the biomass flow entering in the gasifer.

$$\dot{C}_{out} = \dot{m}_{char} \cdot \frac{C[\%]_{char}}{100} + \dot{C}_{gas} \tag{2}$$

$\dot{C}_{out}$ is the carbon mass outflow from the gasifier. $C[\%]_{char}$ is the carbon content of the biochar. $\dot{m}_{char}$ is the mass of char outflow from the gasifier. $\dot{C}_{gas}$ is the mass flow of carbon exiting the gasifier contained in the producer gas.

$$\dot{C}_{gas} = \dot{C}_{in} - \dot{m}_{char} \cdot \frac{C[\%]_{char}}{100} \tag{3}$$

$$\dot{C}_{CO} = \dot{C}_{gas} \cdot \frac{CO[\%]}{CO[\%] + CO_2[\%] + CH_4[\%]} \tag{4}$$

$\dot{C}_{CO}$ is the mass flow of carbon exiting the gasifier contained in the carbon monoxide.

$$\dot{m}_{CO} = \frac{\dot{C}_{CO}}{MA_C} \cdot (MA_C + MA_O) \tag{5}$$

$\dot{m}_{CO}$ is the mass flow of carbon monoxide. MA_C and MA_O are the atomic masses of carbon and oxygen, respectively.

$$\dot{V}_{CO} = \frac{\dot{m}_{CO}}{\rho_{CO}} \tag{6}$$

$\dot{V}_{CO}$ is the volume flow of carbon monoxide

$$\dot{V}_{gas} = \frac{\dot{V}_{CO}}{CO[\%]} \times 100 \tag{7}$$

$\dot{V}_{gas}$ is the volume flow of producer gas.

Producer gas higher heating value in MJ/m^3 (HHV_{gas}) was calculated as the weighted average of the HHV of the various fuel gas components considering their volume fraction [10]. Cold gasification efficiency η_{CG} was measure with the Equation 8 [11]:

$$\eta_{CG} = \frac{\dot{V}_{gas} \cdot HHV_{gas}}{\dot{m}_{bio} \cdot HHV_{bio}} \tag{8}$$

$\dot{V}_{gas}$ and $\dot{m}_{bio}$ were monitored during the time span of the test in which the producer gas was calorific enough to sustain the combustion in the flare.

A Brunauer–Emmett–Teller analysis was carried out to determine the specific surface area of the biochar produced during the gasification process. The instrument used was the *Micrometrics ChemiSorb* and the measurement was repeated three times.

Both chestnut shells and biochar microstructure were examinate under Scansion Electron Microscope with Field Emission Gun (FEG) (*FEI Nova NanoSEM 450*) at various magnifications to observe the alterations in structure and morphology due to the gasification process.

3. Results

The results of the ultimate and ash analysis performed on chestnut shells and biochar are summarized in **Table 1**.

Table 1. Elemental composition, ash content and HHV

	Chestnut shells	Chestnut shell Biochar	Vine Pruning [12]
Carbon	44.42%	61.56%	46.27%
Hydrogen	5.23%	1.40%	6.28%
Nitrogen	0.34%	0.53%	0.54%
Oxygen	46.68	20.93%	46.89%
Sulphur	Not detected	Not detected	0.0185%
Ash	1.33%	15.58%	1.42%
HHV	16.6 MJ/kg	20.64 MJ/kg	18.95 MJ/kg

As can be seen in the **Table 1**, chestnut shell composition is quite similar to woodchips or other lignocellulosic biomasses such as vine pruning [12], while biochar shows a significant increase in the carbon content.

Fig. 2 shows the producer gas temperature trend measured during the test. This trend was in line with other biomass gasified with the same apparatus, indicating a proper operating condition in the reduction zone.

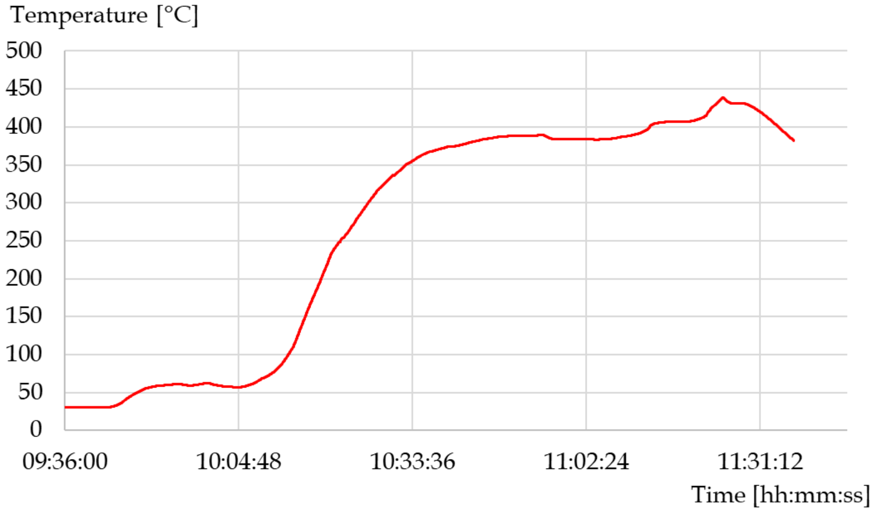


Fig. 2 Producer gas temperature trend

Fig. 3 depicts the pressure drop measured across the gasifier reactor. It is possible to see that during the regime gasifier operation it was quite stable between 1000 and 2500 Pa. The drops to near zero corresponds to the loading operations that were performed with the blower turned off. The absence of abrupt increases of pressure drops across the reactor indicates a smooth operation, without the formation of clinkers that can clog the gasifier throat compromising the functioning of the system.

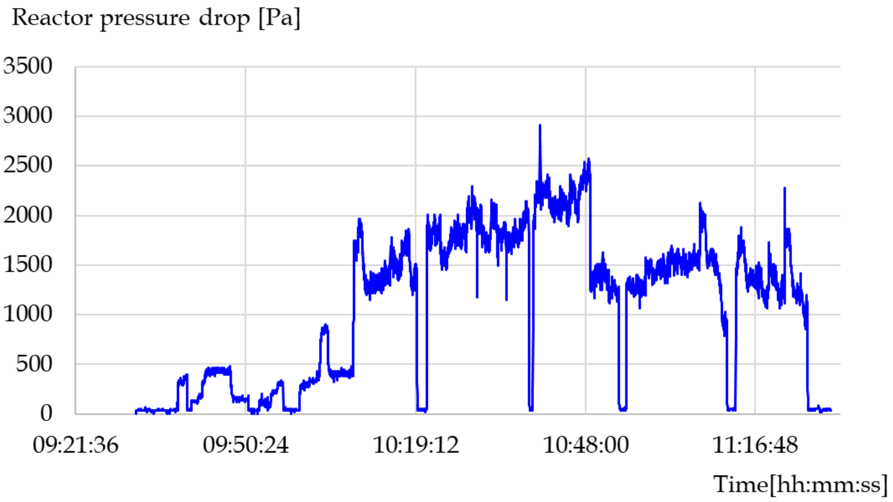


Fig. 3 Reactor pressure drop

Table 2 summarizes the characteristics of the three samples of producer gas analyzed with the *microGC* gas analyzer.

Table 2. Producer gas composition and HHV

	Sample 1	Sample 2	Sample 3
H_2 [%]	17.4	16.4	13.5
N_2 [%]	46.4	47.9	47.9
CO [%]	25.6	21.8	21.1
CO_2 [%]	10.7	13.5	9.5
CH_4 [%]	Not detected	Not detected	Not detected
HHV	5.4 MJ/kg	4.8 MJ/kg	4.4 MJ/kg

In regard to composition and calorific value as well, the results are similar to those obtained with other more common fuels such as pellet A1. **Table 3** outlines the main test parameters and results.

Table 3. Test parameters

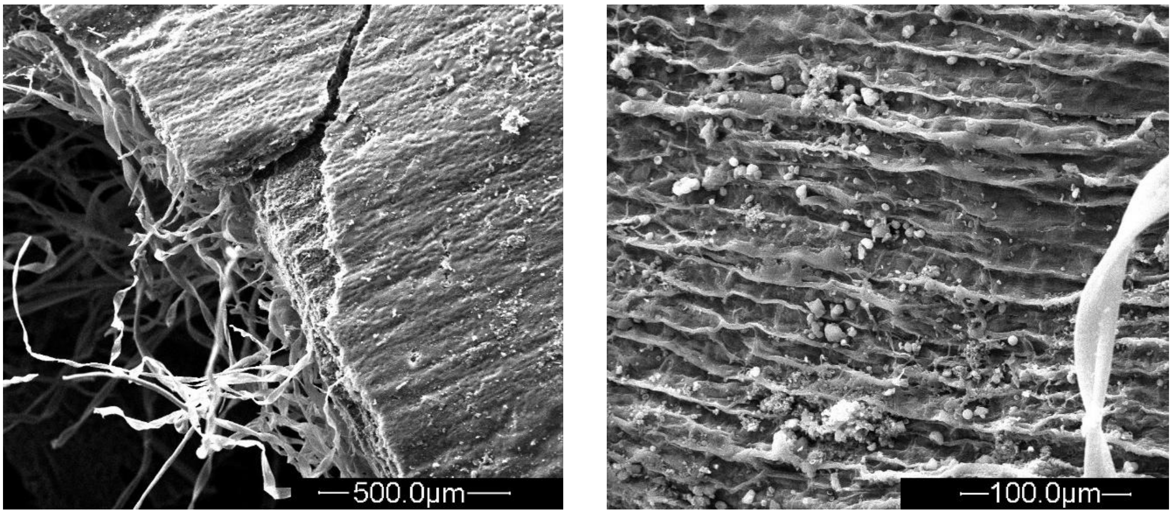
	Values
Biomass consumed	1.015 kg
$\dot{m}_{bio}$	0.937 kg/h
Gas produced	2.45 m^3
$\dot{V}_{gas}$	2.26 m^3/h
Efficiency test duration	65 minutes
Thermal Power Output	3.06 kW
Cold gas efficiency	70.8%

The power output of the test was in line with the characteristics of the gasifier. Gasification efficiency was satisfactory, and typical for this kind of architecture [13].

The specific surface area of the biochar produced was 48.2 ± 2.5 m^2/g.

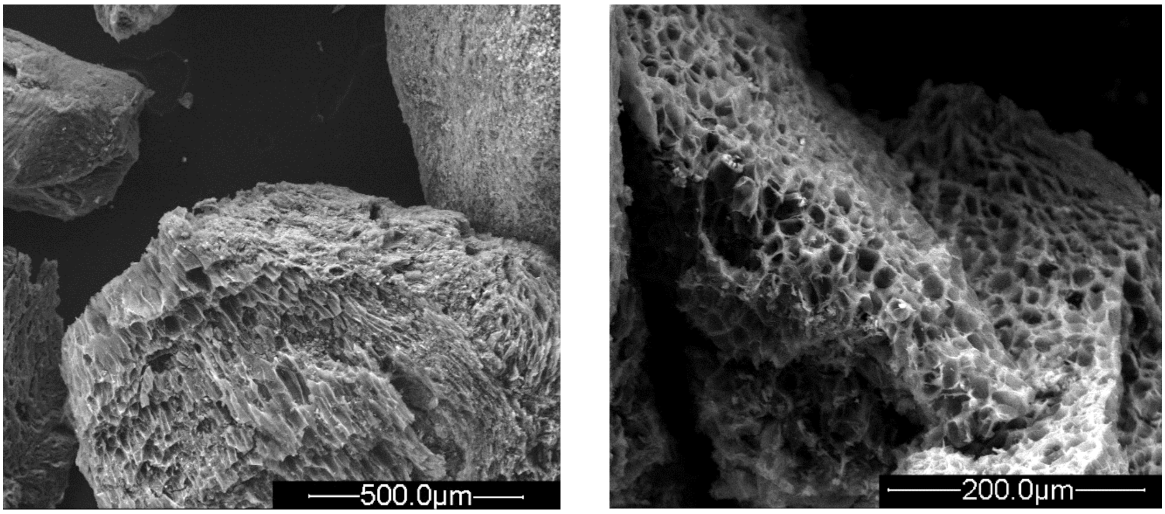
Although this result is noteworthy, it is important to notice that biochar with surface areas an order of magnitude larger can be obtained.

In **Fig. 4** and **5** the microstructure of chestnut before the and after the gasification process can be observed under various magnification.



a) **b)**

Fig. 4 a) chestnut shell under 180× magnification **b)** chestnut shell under 800× magnification



a) **b)**

Fig. 5 a) chestnut shell biochar under 200× magnification **b)** chestnut shell biochar under 600× magnification

From the images it is clear that the material's porosity has significantly increased. Porosity and specific surface area crucial physicochemical properties of biochar because they indicates the quantity of active cites that are important for various applications such as soil remediation or wastewater treatment [14].

4. Conclusions

In this work, the gasification of chestnut shells for power generation was explored. Through the pelletization a proper fuel for a small-scale gasifier prototype was obtained. The results showed satisfactory performance in terms of power output and efficiency. For these reasons, using chestnut shells for power generation or as a substitute of fossil fuels in the chestnut brulage process can be considered a promising alternative. The biochar obtained as a byproduct of the chestnut shell gasification can add value to this strategy, increasing its advantages compared to traditional transformation process. Further tests should be carried out to assess the behavior of this biomass during long-run operation.

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