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Pellet as a Technological Nutrient within the Circular Economy Model: Comparative Analysis of Combustion Efficiency and CO and NO_x Emissions for Pellets from Olive and Almond Trees

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Abstract: This study analyzes the operation of Biomass System (BIO System) technology for the combustion of pellets from almond and olive trees within the circular economy model. Its aims are the reduction of greenhouse gas emissions as well as waste removal and its energy use by reintroducing that waste into the production process as technological nutrient. In order to do so, combustion efficiency under optimal conditions at nominal power was analyzed. In addition, a TESTO 350-XL analyzer was employed to measure CO and NO_x emissions. High combustion efficiency values were obtained, 87.7% and 86.3%, for pellets from olive tree and almond tree, respectively. The results of CO and NO_x emission levels were very satisfactory. Under conditions close to nominal power, CO emission levels were 225.3 ppm at 6% O_2 for pellet from almond tree and 351.6 ppm at 6% O_2 for pellet from olive tree. Regarding NO_x emissions, the values were 365.8 ppm at 6% O_2 and 333.2 ppm at 6% O_2 for pellets from almond tree and olive tree, respectively. In general, these values were below those legally established by current legislation in European countries. Therefore, BIO System technology is a perfectly feasible option in terms of energy use and circular economy.

Keywords: pellet; olive tree; almond tree; emission; efficiency; circular economy

1. Introduction

The dependence on energy resulting from the use of fossil fuels and the growing environmental concern have been the main reasons for the increase in the use of biomass as a renewable energy source for electrical and thermal energy generation, particularly in the European Union countries [1–3].

With this aim in mind, both the 2015 Paris Climate Conference and the UN Framework Convention on Climate Change developed a roadmap in order to reduce carbon dioxide emissions from the year 2020. This has all led to a new paradigm where the European Union has suggested that different sectors of production must take action within the circular economy model. It is necessary to set deadlines in order for the production sector to reduce greenhouse gas emissions and wastes [4]. Thus, the biofuel sector acquires greater relevance [5,6], and biomass is becoming an attractive resource to progressively replace fossil fuels [7].

The exploitation of biomass for energy production has gained great popularity in recent years [8–11]. Currently, biomass holds fourth place after oil, natural gas, and coal, as it supplies approximately 14% of the world's energy needs [12]. In industrialized countries, biomass accounts for 9% to 14% of the total energy supply [13]. However, this percentage increases to 35%–40% in developing countries [13,14].

The use of biomass as fuel produces substantial benefits with regard to the environment since the amount of CO_2 absorbed from the atmosphere during biomass growth is the same as that emitted during combustion. Consequently, the CO_2 net cycle does not contribute to the greenhouse effect [15]. Furthermore, biomass has a lower content of nitrogen and sulfur than fossil fuels, thereby generating lower NO_x and SO_2 emissions and reducing acid rain in areas close to combustion facilities. The ash content is also very low, with values of approximately 1% [16]. In this way, biomass can be considered as a technological nutrient within the circular economy model, as it significantly reduces the negative externalities arising from fossil fuels. Moreover, biomass is an autonomous energy source, which prevents dependence on energy supplies from other countries, enhancing in such a way the trade balance and the economic sustainability of a country. In social terms, the development of biomass as a fuel enhances job creation and avoids the depopulation of rural areas [16]. In addition, biomass is an economical energy source; one liter of diesel can be used to obtain the amount of thermal energy that corresponds to 2 kg of biomass, with a price of €1 for diesel and €0.15 to €0.25 for biomass in Spain [16].

A rapid growth in the production and consumption of wood pellet in order to obtain electrical and thermal energies has been registered in recent years [17]. According to the European Bioenergy Outlook 2013 [18], the world production of wood pellet in 2013 was approximately 24.5 Mt and 50% of that is produced in the European countries. In terms of wood pellet consumption, European countries are the largest consumers, with around 80% of the world consumption.

Pellets from olive and almond trees were used in this study. The olive oil industry is one of the agro-industrial activities producing a larger amount of by-products which can be used to produce pellets for energy applications. There are nearly 900 million olive trees occupying more than 10 million hectares worldwide, of which 98% are located in the Mediterranean countries [19]. Almond processing also produces large quantities of by-products with a potential value for energy application [20]. Chen et al. [21] carried out a detailed review of the use of waste from almond processing, including combustion, gasification, and pyrolysis. According to this review, little research has been done on energy applications for almond processing wastes. González et al. [22] used almond wastes for gasification.

There are three different ways of obtaining energy from biomass: thermochemical, chemical, and biochemical processes [23]. The thermochemical conversion is still the most frequently used [7]. Among the technologies used for thermochemical conversion of biomass, combustion accounts for 97% of global bioenergy production [15], combining a highly efficient and sustainable operation and minimal environmental impact [7].

Combustion includes a number of chemical reactions during which biomass is converted to CO_2 and water [24]. Some minority components of biomass, such as sulfur or nitrogen, may react with air oxygen obtaining SO_2 and NO_x, which includes 90% NO, 10% NO_2 and N_2O in low quantities [25]. If the necessary conditions regarding temperature, oxygen transfer, and reaction time are not present, an incomplete combustion reaction may occur, obtaining CO as a consequence [26,27]. To establish the behavior of biomass wastes during the combustion process, it is extremely important to have the appropriate knowledge in relation to their physical and chemical properties [28–30]. Physical properties determine the thermal efficiency and chemical properties regulate the combustion process [1].

This paper analyzes the operation of BIO System technology for the combustion of pellets from almond and olive trees within the circular economy model. Its aims are the reduction of greenhouse gas emissions as well as waste removal and its energy use by reintroducing that waste into the production process as technological nutrient. In order to do so, a combustion efficiency assessment, as well as CO and NO_x emissions measurements for pellets from almond and olive trees, was carried out.

2. Results and Discussion

2.1. Physicochemical Analysis

Table 1 shows the physical characteristics for the pellets from almond and olive trees.

Table 1. Physical characteristics of pellets from almond and olive trees.

Parameter	Type of Pellet	
	Almond Tree	Olive Tree
Diameter (mm)	6	6
Length (mm)	10–31	10–24
Bulk density (kg·m^{-3})	620	650

Values for pellets from almond tree were similar to those for pellets from olive tree, although the length was slightly higher and bulk density was slightly lower (Table 1). Barbanera et al. [17] also worked with pellet from olive tree whose characteristics were similar to those used in this study. The diameter was 6.1 mm, the length was 23 mm, and the bulk density was within the range of 640–650 kg·m^{-3}.

Table 2 shows the results of immediate and elemental analyses, as well as the heating values and other properties.

Table 2. Chemical characteristics of pellets from almond and olive trees.

Parameter	Type of Pellet					
	Almond Tree			Olive Tree		
	Stabilized sample	Dry sample	Received sample	Stabilized sample	Dry sample	Received sample
Immediate Analysis (% weight)						
Moisture	4.53 ± 0.04	0.00 ± 0.00	3.18 ± 0.03	4.40 ± 0.05	0.00 ± 0.00	2.93 ± 0.03
Ash	2.62 ± 0.36	2.74 ± 0.37	2.66 ± 0.36	2.54 ± 0.39	2.66 ± 0.41	2.58 ± 0.40
Volatile matter	75.73 ± 1.85	79.32 ± 1.93	76.80 ± 1.87	77.26 ± 1.98	80.82 ± 2.07	78.45 ± 2.01
Fixed carbon	17.12 ± 0.42	17.94 ± 0.44	17.36 ± 0.42	15.80 ± 0.40	16.52 ± 0.42	16.04 ± 0.41
Elemental Analysis (% weight)						
Carbon	45.27 ± 1.11	47.42 ± 1.16	45.91 ± 1.12	45.20 ± 1.16	47.28 ± 1.21	45.90 ± 1.18
Hydrogen [1]	5.66 ± 0.05	5.40 ± 0.05	5.58 ± 0.05	5.80 ± 0.07	5.55 ± 0.06	5.72 ± 0.07
Nitrogen	0.49 ± 0.07	0.51 ± 0.07	0.50 ± 0.07	0.48 ± 0.07	0.50 ± 0.08	0.49 ± 0.08
Sulfur	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Heating Value (kcal·kg^{-1})						
Upper heating value	4369	4576	4431	4373	4574	4440
Lower heating value	4048	4295	4122	4046	4285	4126
Other Properties						
Energy density (MJ·m^{-3})		11,146			11,658	
Air-fuel ratio$_{\text{stoichiometric}}$		4.751			4.711	
Adiabatic temperature of the flame (°C)		2308			2293	

[1] The hydrogen percentage includes the hydrogen coming from moisture.

Regarding immediate analysis results, it is important to mention the high content of volatile matter obtained for both types of pellets, which is an essential characteristic for the proper combustion in the BIO System equipment. In the case of pellet from almond tree, volatile matter fluctuates between 75.73% by weight for the stabilized sample and 79.32% by weight for the dry sample. Regarding pellet from olive tree, volatile matter fluctuates between 77.26% by weight for the stabilized sample and 80.82% by weight for the dry sample (Table 2). García et al. [7] obtained a volatile matter percentage of 75.6% and 78.0% for pellets from almond and olive trees, respectively, which were similar to those values obtained in this research. Aktas et al. [20] obtained a volatile matter percentage of 75.03% for pellet from almond tree, which is similar to those values previously mentioned.

When comparing both types of pellets, moisture and ash contents for pellet from olive tree were lower than in the case of pellet from almond tree (Table 2). For pellet from olive tree, García et al. [7] obtained moisture and ash percentages of 8.7% and 13.0%, respectively, which were higher than the ones obtained in this study. Moisture and ash values for pellet from almond tree were 7.1% and 5.4%, respectively [7]. In the study on pellet from almond tree carried out by Aktas et al. [20], moisture and ash values were 9.06% and 4.56%, respectively. Barbanera et al. [17] obtained an ash percentage within the range of 2.5% and 3.0% for pellet from olive tree, similar to that obtained for pellet from olive tree in this study and shown in Table 2. In addition, volatile matter/fixed carbon ratio is higher for pellet from olive tree (4.9) than for pellet from almond tree (4.4) (Table 2). This ratio has some influence on ignition, combustion, and even NO_x formation. Such a trend is also obtained by García et al. [7], in whose work the volatile matter/fixed carbon ratio was 8.7 for pellet from olive tree and 4.0 for pellet from almond tree.

Regarding the elemental analysis and heating value, both fuels have very similar properties (Table 2). Pellet from almond tree showed percentages by weight of carbon, hydrogen, nitrogen, and sulfur within these ranges: 45.27–47.42, 5.40–5.66, 0.49–0.51 and 0, respectively. For pellet from olive tree, percentages by weight of carbon, hydrogen, nitrogen, and sulfur were within these ranges: 45.20–47.28, 5.55–5.80, 0.48–0.50 and 0, respectively. García et al. [7] obtained similar values for pellets from almond and olive trees; more specifically, values for pellet from almond tree were 47.35%, 6.36%, 0.65%, and 0.16% of carbon, hydrogen, nitrogen, and sulfur, respectively. For pellet from olive tree, García et al. [7] obtained 45.36%, 5.47%, 1.47%, and 0.28% of carbon, hydrogen, nitrogen, and sulfur, respectively. The difference between the content of sulfur of this work and the research carried out by García et al. [7] could reside in the variations of quality of the pellets and the different origin of them as García et al. [7] used biomass coming from Austria and several zones of Spain, and this work was developed in Andalusia. Moreover, the presence of barks and the use of fertilizers and herbicides could increase the content of sulfur in the biomass. Aktas et al. [20] analyzed pellet from almond tree, obtaining 48.59% of carbon, 5.57% of hydrogen, 0.90% of nitrogen, and 0.22% of sulfur. Furthermore, it is remarkable that the heating value for pellet from olive tree is slightly higher than the one obtained by Barbanera et al. [17], which is close to 4200 $\text{kcal}\cdot\text{kg}^{-1}$.

Taking into account the rest of the characteristics studied, it can be deduced that for the same fuel volume, pellets from olive tree produce a higher total power as can be seen in the energy density values shown in Table 2, since the value for pellet from olive tree is 11,658 $\text{MJ}\cdot\text{m}^{-3}$ whereas for pellet from almond tree is 11,146 $\text{MJ}\cdot\text{m}^{-3}$.

Regarding air-fuel $\text{ratio}_{\text{stoichiometric}}$, under equal fuel loads and fan operation parameters, combustion for pellets from almond tree has a higher excess of air, and consequently, combustion efficiency will be lower, although both fuels present very similar ratios (Table 2).

Table 2 shows the values of adiabatic temperature of the flame for pellets from almond and olive trees, obtaining very similar values: 2308 °C and 2293 °C, respectively. Such temperatures are the highest possible for the combustion of the pellets used in this study, as it is defined as the flame temperature during combustion taking place in a perfectly adiabatic area where enthalpy for reagents and for products are equivalent as there is no heat output.

From the results obtained in relation to the characterization of each fuel, it is possible to deduce that the transformation of these fuels in the BIO System equipment is not going to pose any problem regarding the compatibility of the technology with fuel characteristics.

2.2. CO and NO_x Emissions

Figures 1 and 2 show the results in relation to the complete development of tests with pellets from almond and olive trees.

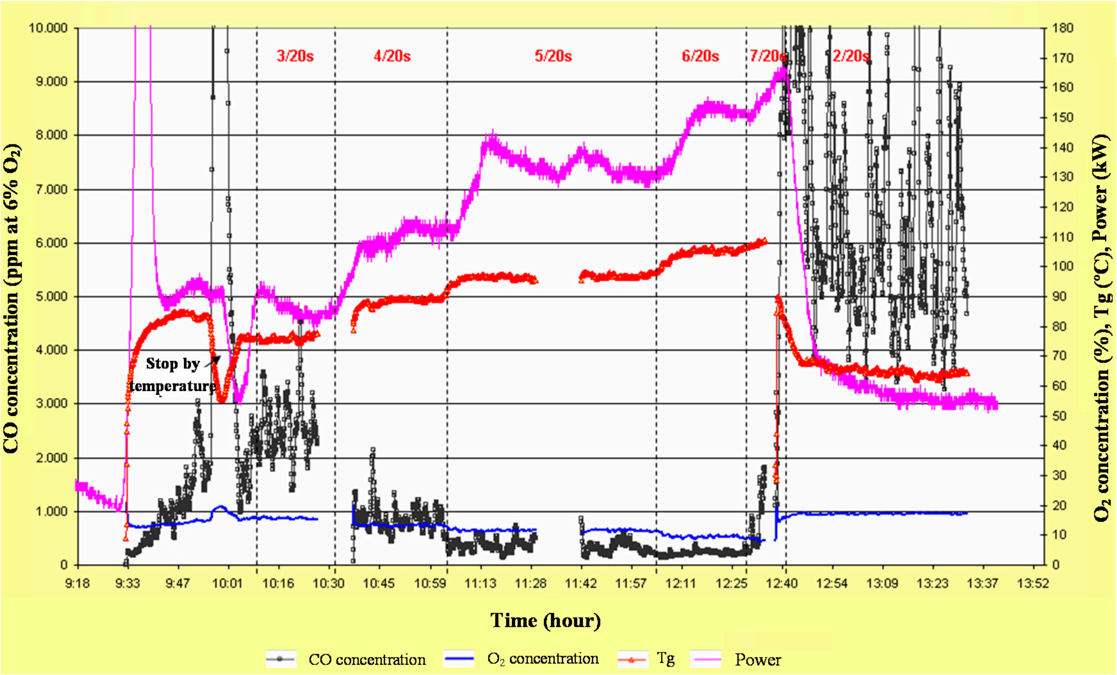

Figure 1. Evolution of CO emissions corrected to 6% O_2, O_2 concentration, exhaust gas temperature (Tg), and power during combustion tests with pellets from almond tree.

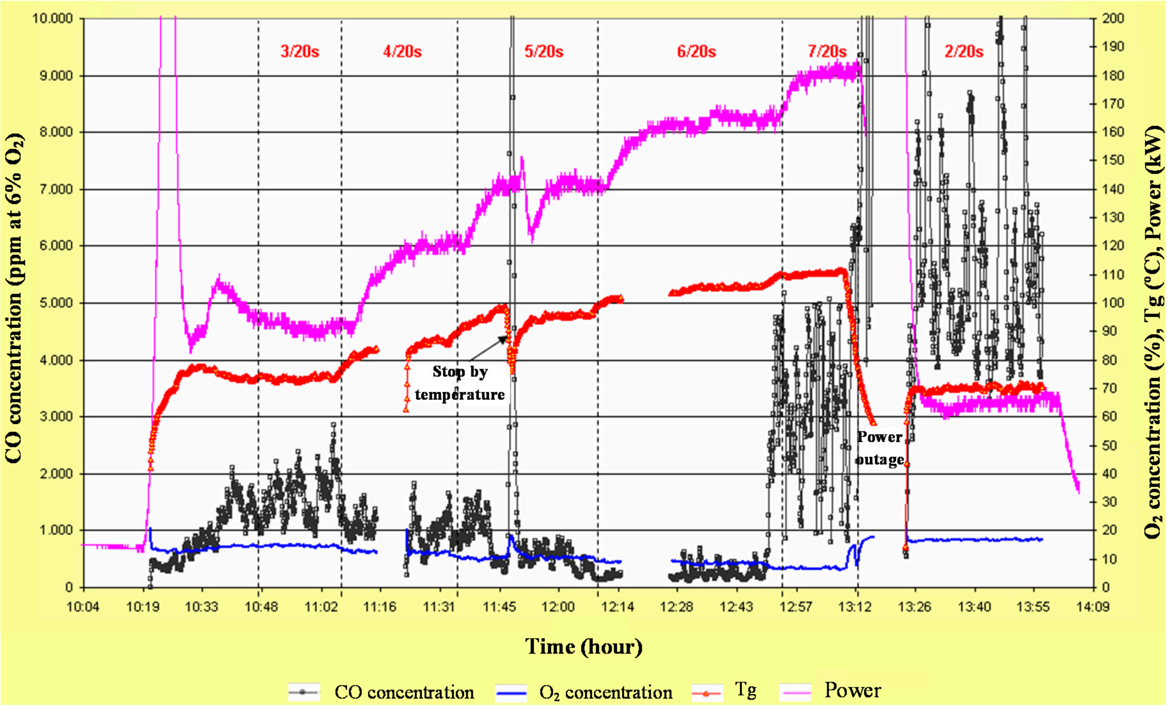

Figure 2. Evolution of CO emissions corrected to 6% O_2, O_2 concentration, exhaust gas temperature (Tg), and power during combustion tests with pellets from olive tree.

Figures 1 and 2 show the evolution of CO and O_2 concentrations, exhaust gas temperature (Tg), and power during combustion tests with pellets from almond and olive trees. The stop by temperature (observed in Figures 1 and 2) occurs in some systems due to the introduction of high amount of biomass, which causes an increase of temperature and the system to stop. The power outage did not influence the process as it occurred at the end of the cycle (7/20 s) and the following cycle started with similar values to those obtained for the first cycle, as shown in Figure 2. It should be noted that at nominal power, the oxygen content of the flue gases remained at around 9% (Figures 1 and 2), which shows a positive operation and allows to see a fairly high combustion efficiency.

Figures 3 and 4 show the evolution of CO and NO_x average emissions corrected to 6% O_2, corresponding to combustion tests with pellets from almond and olive trees.

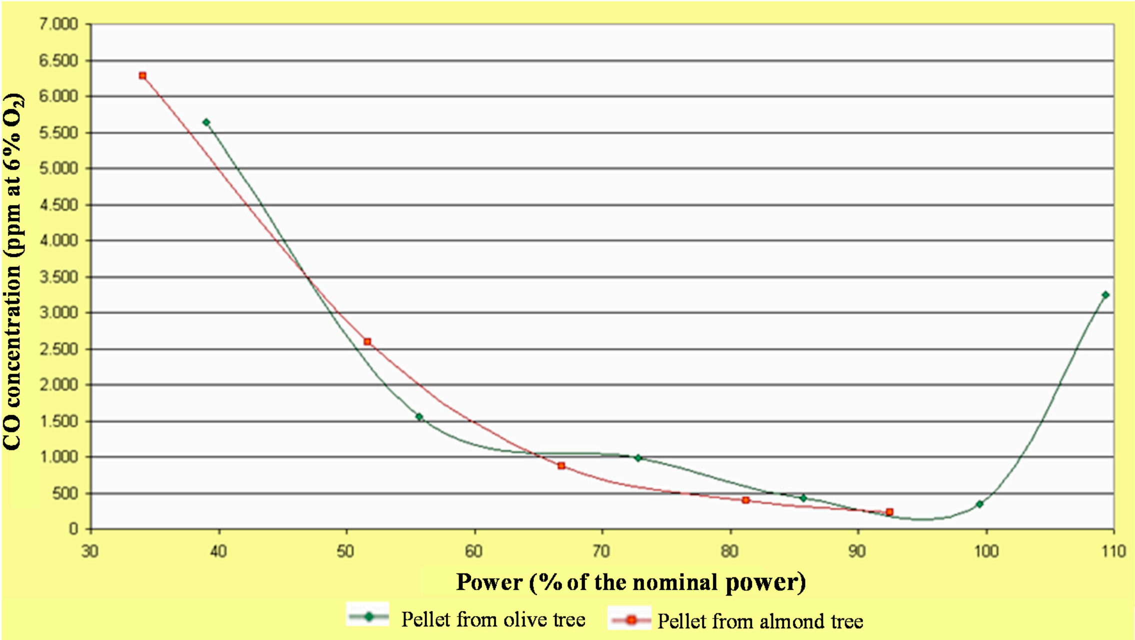

Figure 3. Evolution of CO emissions corrected to 6% O_2 depending on the partial operating load during combustion tests with pellets from almond and olive trees.

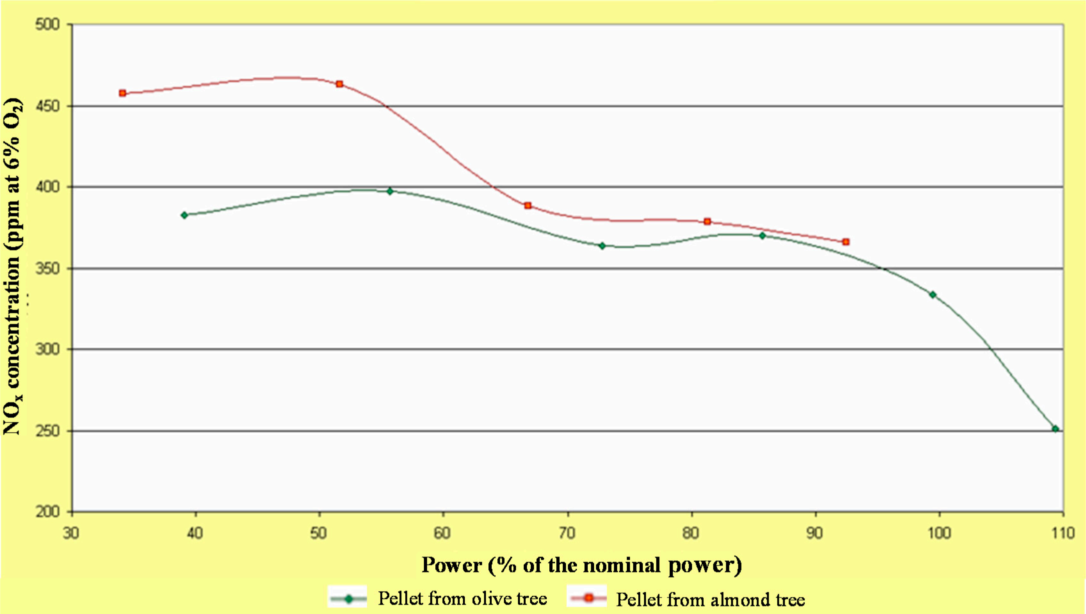

Figure 4. Evolution of NO_x emissions depending on the partial operating load during combustion tests with pellets from almond and olive trees.

As expected, CO content of the fumes decreased substantially with the partial load (Figure 3). CO content depends on the oxygen percentage in the system. In light of this, the BIO System operates with an excess of air, and CO concentration decreases since the combustion is completed with the increase of power (Figure 3). Regarding the NO_x concentration, this will rise if the combustion temperature increases to high values, but these values are lowered with the increase of power, and a decreasing trend can be observed for the NO_x concentration (Figure 4). Close to nominal power, CO content tends to reach a minimum value for pellets from almond tree (225.3 ppm CO at 6% O_2) and from olive tree (351.6 ppm CO at 6% O_2), according to Table 3, which shows a comparison of CO and NO_x average emissions, measured during stable operation periods of tests with pellets from almond and olive trees at a similar nominal power.

Table 3. Comparison of CO and NO_x concentrations of exhaust gases for pellets from almond and olive trees during combustion in the BIO System burner.

Type of Pellet	**Nominal Power (kW)**	**Emissions**			
		CO (ppm at 6% O_2)	**CO (ppm at 13% O_2)**	**NO_x (ppm at 6% O_2)**	**NO_x (ppm at 13% O_2)**
Almond tree	150	225.3	119.5	365.8	259.4
Olive tree	165	351.6	186.4	333.2	236.3

These CO values indicate a high degree of oxidation of combustible matter as well as the suitability of BIO System burner technology for those fuels analyzed in relation to the behavior required in countries with boiler emission regulations for biomass fuels.

When comparing the behavior of NO_x emissions, the results obtained are similar to those of CO emissions, as emission evolutions of these gases decrease with power, reaching values of 365.8 ppm NO_x at 6% O_2 for pellet from almond tree and 333.2 ppm NO_x at 6% O_2 for pellet from olive tree, corresponding to operation under conditions very close to nominal power.

Values in Table 3 can be compared to the emission levels of pollutants into the atmosphere allowed by European Union countries for low-power biomass boilers. Denmark, Germany, and Austria limit CO emissions to 725 ppm at 13% O_2, 1000 ppm at 13% O_2, and 1400 ppm at 13% O_2, respectively [31]. In addition, NO_x emissions in Austria are limited to 230 ppm at 13% O_2 [31]. In both cases, CO emissions obtained during stable periods at nominal power are below those legally established in other European countries, such as Denmark, Germany, and Austria, which are pioneers in the use of automated and low-power biomass boilers. When comparing the behavior of NO_x emissions, the results obtained for olive tree are similar to the reference value according to the legislative requirements in Austria although it is slightly to high for almond tree (Table 3).

A similar analysis was carried out by Fernández et al. [16], who studied CO and NO_x emissions during combustion of different types of biomass, which included biomass from almond tree. Oxygen concentration and combustion temperature were also measured in this study. Such authors obtained levels of CO emissions below 600 ppm and NO_x emissions below 10 ppm for pellet from almond tree.

2.3. Combustion Efficiency

Table 4 shows the results of combustion efficiency obtained during the tests using both fuels, pellets from almond and olive trees, and for different partial loads. Table 4 also shows combustion efficiency calculated based on a gas temperature of 120 °C. The temperature registered by the gas analysis equipment is not considered for this calculation. However, an exhaust temperature of 120 °C was estimated when working at nominal power, which is perfectly acceptable for a system designed with a larger heat exchanger.

Table 4. Efficiency results obtained during combustion tests for pellets from olive and almond trees.

Parameter	**Fuel**											
	Pellet from Olive Tree						**Pellet from Almond Tree**					
	Operation Parameters											
Operation time (s)	2	3	4	5	6	7	2	3	4	5	6	7
Shutdown time (s)	20	20	20	20	20	20	20	20	20	20	20	20
Delta temperature (°C)	4.7	6.7	8.7	10.3	11.9	13.1	4.1	6.2	8.0	9.7	11.1	12.1
Power (kW)	64.5	91.8	120.2	141.4	164.2	180.5	56.3	85.2	110.3	134.1	152.6	166.1
Partial load (%)	39	56	73	86	99	109	34	52	67	81	92	100
	Gas Emission											
Oxygen concentration (%)	16.7	14.5	12.1	10.4	8.4	6.7	17.2	15.5	13.3	11.5	9.5	8.0
CO (ppm at 6% O_2)	5634.8	1558.8	977.1	429.5	351.6	3248.6	6275.0	2589.0	865.5	387.9	225.3	3542.6
CO (ppm at 13% O_2)	2987.6	826.5	518.1	227.7	186.4	1722.4	3327.0	1372.7	458.9	205.7	119.5	1878.3
NO_x (ppm at 6% O_2)	382.3	397.2	363.4	369.8	333.2	251.0	457.4	463.1	388.4	378.0	365.8	356.9
NO_x (ppm at 13% O_2)	271.1	281.7	257.7	262.2	236.3	178.0	324.4	328.4	275.4	268.1	259.4	253.1
	Combustion Efficiency											
Gas temperature (°C)	140.5	148.4	173.5	192.6	211.2	221.2	128.2	152.6	177.6	192.9	211.2	224.5
Combustion efficiency (%)	76.7	84.2	86.2	87.0	87.7	84.9	76.5	81.0	84.2	85.9	86.3	84.7
Combustion efficiency [1] (%)	79.9	87.2	90.4	92.0	93.1	89.8	78.0	85.0	89.4	91.4	92.1	90.2
Air flow ($m^3 \cdot h^{-1}$)	397.9	340.4	315.4	309.6	293.7	417.4	375.9	383.8	339.2	327.6	299.7	371.4
Excess of air (%)	386.7	223.3	135.1	97.9	62.0	100.9	441.6	283.2	171.6	120.2	78.9	101.5
Fuel flow ($kg \cdot h^{-1}$)	17.6	22.0	28.1	32.8	37.8	42.8	15.0	21.0	26.0	31.0	35.0	37.9
Radiation and convection losses (%)	2.6	1.8	1.4	1.2	1.0	1.0	2.9	1.9	1.5	1.2	1.1	1.0

[1] Results of combustion efficiency based on a temperature of Tg = 120 °C for the gas emissions.

Figure 5 shows the combustion efficiency values for the different loads and both fuels.

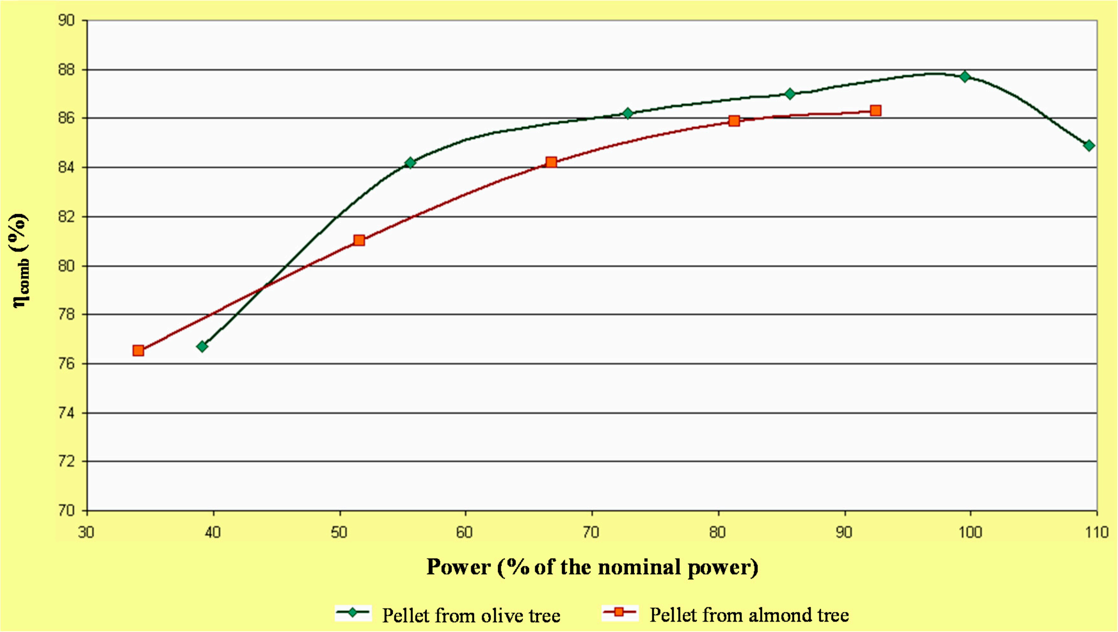

Figure 5. Evolution of combustion efficiency depending on the load for pellets from olive and almond trees.

As can be seen in Table 4, the efficiency obtained for pellet from olive tree was higher than for pellet from almond tree, with values of 87.7% at nominal power for pellet from olive tree and 86.3% for pellet from almond tree.

González et al. [1] obtained a similar tendency for combustion efficiency with pellet from almond tree depending on the biofuel mass flow, with an efficiency of 88.3% when mass flow was 100%.

Figure 6 shows the excess of air for the combustion tests with pellets from almond and olive trees.

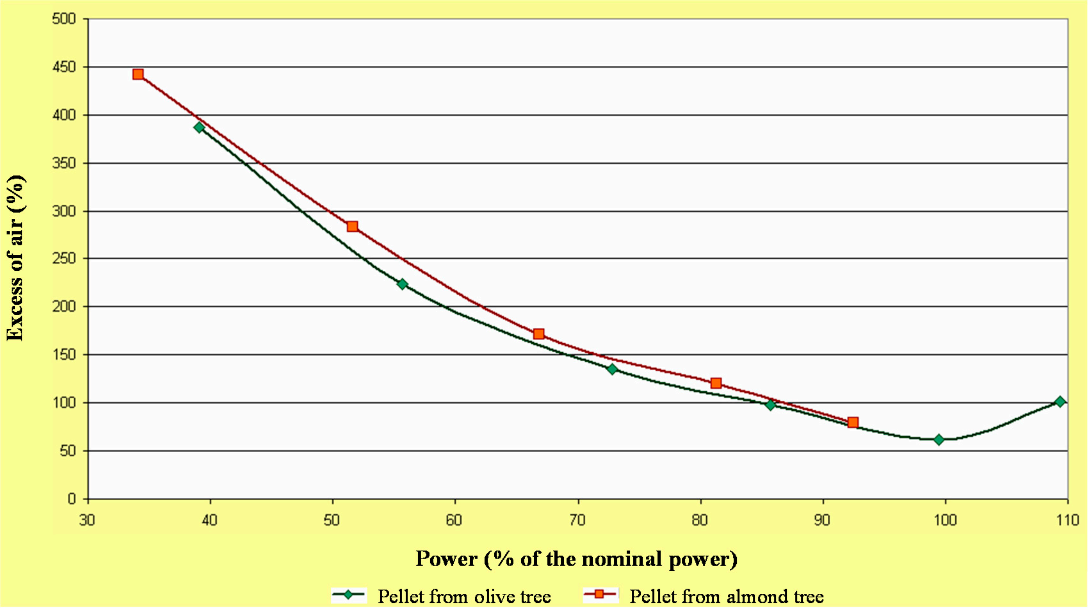

Figure 6. Evolution of excess of air depending on the load for pellets from olive and almond trees.

Regarding the excess of air, this parameter is highly linked to the efficiency of the system. The excess air during combustion can be defined as the percentage of additional air over the amount of stoichiometric air necessary to develop combustion under optimal conditions.

Consequently, the higher combustion efficiency for pellet from olive tree is due to the fact that the excess air was higher when carrying out the combustion test for almond tree, using equal conditions regarding fuel load and fan operation, as can be seen in Figure 6. It can be said that in order to achieve nominal power, the system requires 62.0% of excess air when using pellet from olive tree as fuel and 78.9% of excess air in the case of pellet from almond tree. These results validate those predictions specified in Section 2.1 obtained from the results regarding air-fuel ratio$_{\text{stoichiometric}}$ for both fuels, which are indicated in Table 2.

In any case, the efficiency results obtained from both tests at nominal power were very satisfactory. In addition, this efficiency can increase significantly with the decrease of the temperature of exhaust gases by means of the addition of one or more modules to the boiler.

In this regard, BIO System technology could be considered as a suitable technical and economic option for combustion of pellets from olive and almond trees as this system introduces technical modifications that favor the increase of power and the reduction of the excess air (Table 4). This could have positive economic implications since this system could work under higher values of power due to the existence of two separate zones for the burner and boiler, and this technology could increase the combustion efficiency due to the reduction of the excess air.

3. Materials and Methods

3.1. Physicochemical Characterization of Fuels

Previously to the physicochemical characterization, the pellet manufacturing is described. The product was received in the plant of pellet processing. Then, the material was weighed and a moisture control was carried out. A wood chipper reduced the size of the product to fragments of 10 cm. Subsequently, the product was dried by hot air and then underwent a settling process to collect the material. Next, a milling process was performed to reduce the size of the pellets. Finally, the material was compacted, cut, and cooled down to get the characteristics that are shown in Table 1. Chemical characteristics of pellets from almond and olive trees depend on the type of cultivation.

Figure 7 shows two images of both types of pellets.

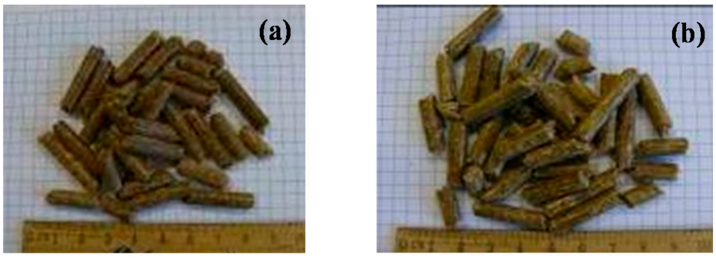

Figure 7. Visual comparison of both types of pellets. (**a**) Image of pellet from almond tree; (**b**) Image of pellet from olive tree.

Bulk density is an important parameter in the physical characterization of fuel, as it allows for the definition of the control parameters of pellet storage and transport systems. Another relevant parameter is pellet size, that is, its diameter and length. A random sampling of each fuel, pellets from almond and olive trees, was carried out in order to define these characteristics. The length and the diameter of the pellets were determined according to ISO 17829:2015 [32], and the bulk density was evaluated according to EN 15150:2011 [33].

For three samples of each fuel, immediate and elemental analyses and determination of heating value were carried out. More specifically, the sampling was carried out using the received, stabilized, and dry samples of each type of pellet analyzed. The received sample is the sample as it is received in the laboratory. The dry sample is the sample after undergoing a drying process in order to eliminate moisture. The stabilized sample is that sample which has been allowed to stand for some hours so that it returns to its natural state, as samples are collected in bags and may contain moisture.

Moisture, ash content, volatile matter, and fixed carbon percentages of pellets from almond and olive trees were identified during immediate analysis. Moisture was determined in accordance with the norm ISO 18134-2:2015 [34], ash content based on the norm ISO 18122:2015 [35], and volatile matter according to the norm ISO 18123:2015 [36].

The elemental analysis includes the determination of percentage by weight of carbon, hydrogen, nitrogen, and sulfur. The percentages of carbon, hydrogen, and nitrogen were determined in accordance with the norm ISO 16948:2015 [37], and the percentage of sulfur was assessed according to ISO 16994:2015 [38].

Upper and low heating values were evaluated according to EN 14918:2009 [39] scientific norm.

Moreover, other relevant parameters to predict the combustion process and efficiency, such as energy density, air-fuel ratio$_{\text{stoichiometric}}$ (AFR), and adiabatic temperature of the flame, can be calculated from the heating value, pile density, and elemental analysis of a fuel.

3.2. Description of BIO System Equipment

The BIO System equipment used for this study consists of a boiler, a complete burner and a control cabinet (Figure 8). The boiler is modular and composed of cast iron elements and three fume passages. The working pressure is 4 bar. The cascade biomass burner has automatic ignition, flame viewing, and easy access for cleaning and maintenance. The adjustment of that system enables the control of all the boiler functions and the fuel transportation in a cabinet with display.

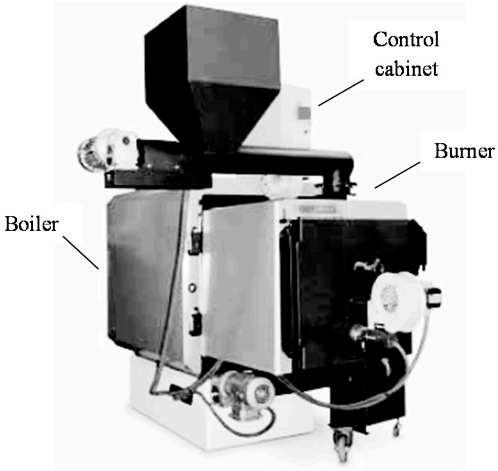

Figure 8. Flow chart of the BIO System equipment.

Several authors have worked with other technologies for the combustion of different kinds of pellets from agriculture and wood waste. In this regard, Verma et al. [40] worked with a 40 kW boiler. Furthermore, Dias et al. [41] and González et al. [26] studied the behavior of domestic boilers and analyzed the emissions generated from the combustion process. In light of this, Verma et al. [42] and Verma et al. [43] carried out a comparative study of the efficiency of different equipment in the frame of technical specifications. Persson et al. [44] developed several mathematical models to describe the performance of different types of boilers.

3.3. Experimental Procedure

Combustion tests with pellets from almond and olive trees were carried out in the BIO System in order to determine the variables studied for a stable combustion process, such as CO and NO_x emissions, combustion efficiency under optimal conditions, at nominal power, and at different partial loads, as well as the excess of air during combustion. In addition, an assessment of the behavior of the BIO System burner with these two fuels, pellets from almond and olive trees, was obtained during long periods of operation.

The combustion process developed in the BIO System burner comprises five stages:

1. Initial fuel filling and turning-on of the BIO System burner by means of a hot-air igniter oriented towards the fuel pile (Figure 9). During this first stage, primary and secondary air fans are switched on, so there is a high excess of air in the chamber.

Figure 9. Filling of BIO System burner with pellets from almond tree.

2. The BIO System burner is fed with new particles of biomass. The operating times for the screw feeder are 3 s in ON position and 20 s in OFF position. During this stage, there is a gradual increase of CO in flue gases, which corresponds to a slow progressive rise in the flow of the biomass introduced into the chamber until the mass flow necessary to obtain the nominal power of the experimental system (165 kW) is reached. In the case of the BIO System burner, the mass flow is within the range of 35 $kg \cdot h^{-1}$ and 40 $kg \cdot h^{-1}$. There is a soft start-up of the system in this way.
3. Combustion stabilization with screw feeder times of 3/20 s. A stable situation is reached after several minutes when the combustion is maintained with only the heat contribution of the biomass (there is no need to use the hot-air igniter). In this regard, the total air flow needed is a key parameter to ensure the correct operation of the system and a stable combustion process. In this case, total air flow presents a value ranging between 290 $m^3 \cdot h^{-1}$ and 300 $m^3 \cdot h^{-1}$, with an excess of air fluctuating between 60% and 80%.
4. Rise in fuel load. When the combustion process and resulting power are in steady conditions, such conditions are kept for as long as data collection lasts in order to compare the emissions obtained for each of the partial loads until they reach nominal power.

5. Turning-off of the BIO System burner. The biomass feeding system is switched off whereas primary and secondary air fans are on, so that any remaining material that may remain in the burner is consumed.

After the system was switched on, an optimal steady combustion was achieved in the BIO System burner for both types of pellets, obtaining the data necessary to measure emissions and calculate efficiency.

3.4. Analysis of CO and NO_x Emissions

During the tests with pellets from almond and olive trees, collection and saving of several measurements were carried out for CO and NO_x emissions and their O_2 percentage in the flue. For this purpose, the gas analyzer Testo 350-XL was used. This portable and versatile measuring system comprises a control unit, a combustion analyzer, and a sampling probe. The control unit can be removed and is provided with built-in printer and display. The analyzer includes built-in measuring sensors for O_2, CO, and NO_x, Peltier gas preparation with peristaltic pump for controlled condensate outlet, and a cleaning valve for long-lasting measurements. The analyzer also measures temperature and differential pressure. The sampling probe is 700 mm long, made of stainless steel 1.4841, and its diameter is 8 mm. As a consequence of dusty gases, it is possible to attach a filter with a pore size of 3 μm to the probe in order to protect it against dust. The hose length is 2.2 m. The maximum operating temperature is 1000 °C.

3.5. Combustion Efficiency

It is possible to calculate combustion efficiency on the basis of the data collected from the gas analysis equipment. The efficiency of combustion equipment can be calculated as the quotient between the energy generated by the system and the potential energy of the fuel by means of the upper heating value or lower heating value. However, due to inaccuracies inherent to the measurement of the solid matter flow (this depends on factors that are difficult to take into account such as fuel agglomeration before it is fed into the chamber or its homogeneity), a different method can be used in plants where solid fuels are used in order to calculate the efficiency. As it can be seen in Equations (1) and (2), this is obtained by subtracting system losses, expressed in parts per unit, from the highest notional efficiency, which is 1.

$$\eta_{comb} = 1 - Q_T \tag{1}$$

where η_{comb} is the combustion efficiency and Q_T is the total of system losses.

$$Q_T = \sum Q_i = Q_g + Q_{rad} + Q_{conv} + Q_{n-b,g} + Q_{n-b,s} + Q_{sa} \tag{2}$$

where Q_i is each of the system losses, Q_g is gas loss, Q_{rad} is radiation loss, Q_{conv} is convection loss, $Q_{n-b,g}$ is the total of non-burnt gaseous losses, $Q_{n-b,s}$ is the total of non-burnt solid losses, and Q_{sa} is the solid ash loss.

The following scenarios have been taken into account when using this calculation method:

- Non-burnt solid losses, $Q_{n-b,s}$, have not been quantified, as the operating time under stable conditions was not long enough to obtain a representative value for each power range studied. Consequently, no non-burnt solid losses have been assumed.
- As the ash content of the fuel was lower than 3% (Table 2), the value of Q_{sa}, which refers to sensitive heat losses in ash, has not been considered, since those losses are considered to be practically insignificant.
- For this calculation, the following constants were used: 11.8421 $m^3 \cdot h^{-1}$ for water volumetric flow and 4.185 $kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$ for water specific heat.

Taking these considerations into account, combustion efficiency can be obtained from Equation (3):

$$\eta_{comb} = 1 - Q_T = 1 - \left(Q_g + Q_{rad} + Q_{conv} + Q_{n-b,g}\right) \quad (3)$$

4. Conclusions

From the beginning of the study, physical and chemical fuel characterization shows the feasibility of the use of fuel in the BIO System burner. Both the medium size of pellets and high content of volatile matters favor a proper combustion by means of the use of this technology.

Once emissions of pollutant gases and efficiency calculations have been carried out, the results obtained are highly acceptable, with levels of CO emissions below those legally required by current legislation in European countries and high combustion efficiency, with values of 87.7% for pellet from olive tree and 86.3% for pellet from almond tree. As for NO_x emissions, results are close to those required by European regulations, which is a very satisfactory condition.

In conclusion, the use of BIO System technology is seen as a perfectly feasible option from both a technical and an economic point of view for the combustion of pellets from olive and almond trees due to the fact that this system allows for an increase in power by placing the burner of pellets out of the boiler zone and it allows for an increase in the efficiency of the system by reducing the excess of air. Thus, these pellets from olive and almond trees can be considered as technological nutrients within the circular economy model.

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