

Combustion of olive tree pruning pellets versus sunflower husk pellets at industrial boiler. Monitoring of emissions and combustion efficiency

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ABSTRACT: The aim of the present paper is to compare the combustion behaviour of two solid biofuels suitable for industrial applications: olive tree pruning (OTP) pellets and sunflower husk pellets. The combustion was performed in operating conditions at two industrial fixed bed biomass boilers (1.16 MW_{th} capacity each) used for greenhouse heating. Combustion tests were performed at the industrial boiler for two consecutive days. During the first day, the OTP pellets were combusted and monitored for emissions, whereas in the second day the reference fuel that is normally used in the plant (sunflower husk pellets) was monitored. OTP pellets were found to exhibit a slightly worse combustion behavior, leading to a decrease of 3.6 percentage points of the boiler efficiency compared to sunflower husk pellets. Lower emissions of CO and NO_x were also observed for OTP pellets, while the ash formation exhibited signs of reduced slagging. Dust emissions were high for both fuels, indicating that particle emission abatement equipment should be installed at the facility.

1 INTRODUCTION

Olive tree groves are a typical crop of the Mediterranean landscape that generate substantial amounts of residual biomass. From the different pruning activities that are carried out to maintain the health of the tree and to increase the fruit production, high amounts of residues are being produced and disposed year after year in Europe. In general, the thick prunings (over 5 cm diameter) are collected and used/sold as firewood. However, the thin prunings (<5 cm) remain unexploited. Prunings (branches and shoots of fruit trees) produced from the Southern European Countries amount to around 8 Million dry tons [1] from a total area of 5 Million ha of cultivated olive groves in EU-28 [2].

Until now, the management of pruning residue has generally represented a disposal problem, rather than an opportunity for additional revenue. Prunings are either mulched, chipped on site and left as soil amendment or, in the majority of cases, piled and burned in open-fires. However, olive tree prunings (OTP) represent an abundant source of energy biomass, or raw material for added value products, still largely unexploited due to the lack of cost-effective harvesting technology. Prunings can be used as feedstock for direct combustion, gasification, combined heat and power (CHP), anaerobic and aerobic digestion [3-6]. In addition, they can be also used as feedstock for bio commodities (e.g. particle board by replacing wood, bioethanol, paper etc.) [7].

The utilization of agroresidues as a source of biomass is an opportunity for supporting the expansion of the bioeconomy in Europe. Among multiple agroresidues, those produced from olive groves represent a significant potential for many EU countries. Biomass from olive tree pruning could be used as fuel for heating systems in boiler, thus helping to mitigate CO₂ emissions and reducing the dependence on fossil fuels. It also helps with indirect benefits, such as the creation of employment in rural areas. Since these fuels usually have rather low heating values, low bulk densities and are disadvantageous concerning

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their storage behaviour, pelletization of such materials represents an interesting procedure to improve their fuel properties.

Aim of the current paper is the combustion testing of OTP pellets at an industrial boiler of a greenhouse and the investigation of its combustion and emission performance in comparison to other established solid biofuels, e.g. sunflower husk pellets. The goal is to evaluate whether OTP pellets can be a competitive solid biofuel that offers advantages to operators of industrial facilities in terms of increase in efficiency, ease of boiler cleaning or reduced emissions.

2 METHODOLOGY

2.1 Boiler

The tests presented were performed using two industrial biomass boilers installed at a greenhouse in Northern Greece. The boilers have a capacity of 1.16 MW_{th} each and a common flue gas stack. The boilers employ the relative simple fixed-bed underfed technology and have been originally designed for combustion of exhausted olive cake. However, due to issues with the smell, the boiler operator has made a switch to sunflower husk pellets for heating. During the combustion tests the settings of both boilers were exactly the same.

2.2 Fuels Comparison

The OTP pellets addressed at the current paper are produced from the thin olive tree prunings as harvested from the field along with the olive leaves. The olive prunings were harvested by mechanized means (integrated harvester/ mulcher) in Agios Konstantinos, Central Greece [8]. Subsequently, the harvested olive prunings were transported to an ENplus A1 certified pellet plant in Southern Greece where the OTP pellets, addressed on the present paper, were produced. For comparison reasons, the reference fuel used at the greenhouse is also tested. The reference fuel is sunflower husk pellets, imported from Bulgaria in big bags.

The first comparison is that between the fuel properties of the biofuels. Samples of each fuel were retrieved for fuel analyses prior to the combustion tests. Table 1 presents the main properties of both fuels whereas Fig. 1 compares the minor and major elements of the fuels. A fuel characterization of the reference fuel (sunflower) and the OTP pellet was performed in CERTH/CPERI's laboratories in Ptolemaida by applying established standards (ISO 18134-1 for moisture, ISO 18134-3 for ash, ISO/DIS 18125 for heating value, ISO 16948 for ultimate analysis, ISO 16967 for major elements, ISO 16968 for minor elements and ISO 17831-1 for mechanical durability).

Table 1. Main fuel characteristics of OTP and sunflower pellets

Property	Units	Sunflower Pellets	OTP pellets
Moisture	%, a.r.	11.9	6.3
Ash	%, d.b.	3.9	6.2
Volatiles	%, d.b.	75.6	77.2
Carbon, C	%, d.b.	50.07	50.02
Hydrogen, H	%, d.b.	6.42	6.55
Nitrogen, N	%, d.b.	0.83	1.17
Sulphur, S	%, d.b.	0.13	0.08
Chlorine, Cl	%, d.b.	0.06	0.05
Gross Calorific Value	MJ/kg, d.b.	19.72	19.71
Net Calorific Value	MJ/kg, d.b.	18.15	18.13
Gross Calorific Value	MJ/kg, a.r.	17.38	18.47
Net Calorific Value	MJ/kg, a.r.	15.71	16.84
Bulk density	kg/m ³ , a.r.	540	670
Mechanical Durability	(%)	95.9	98.4

a.r.: as received, d.b.: dry basis

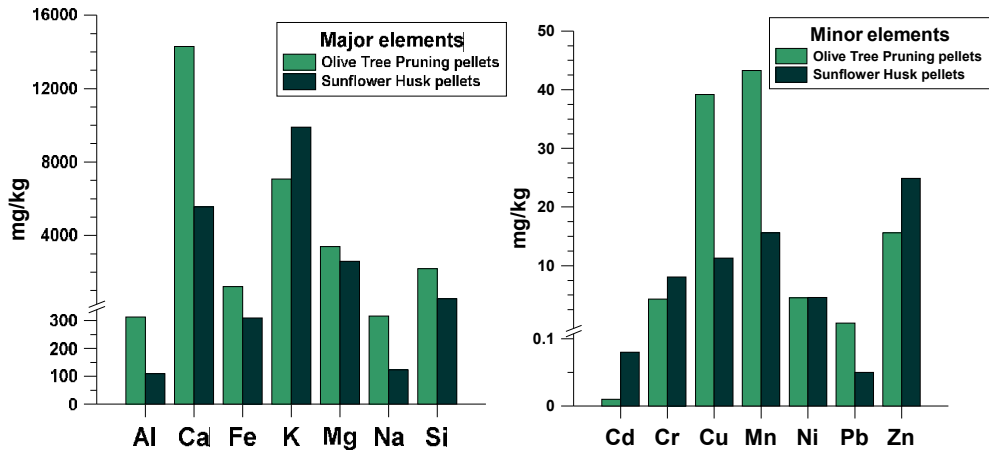


Fig. 1. Comparison of major (left) and minor elements (right) of OTP and Sunflower husk pellets (mg/kg, dry, in fuel)

The ash content of the OTP pellets is higher than that of sunflower husk pellet. This is due to the existence of olive leaves on the prunings and perhaps some soil contamination from the mechanized harvesting of the prunings. However, the bulk density and mechanical durability of OTP pellets are higher. Even though both fuels have similar heating values in dry base, due to the difference in moisture content and bulk density, the as received energy density of the sunflower husk pellets is 24.8% lower compared to OTP pellets. During the pelletization of OTP pellets no additive was used (e.g. corn starch). Regarding the major elements, OTP pellets have increased Ca and Si due to increased soil contamination. Moreover, Cu is increased in OTP pellets due to the fact that olive trees are sprayed with copper for plant protection from diseases. In overall, apart from Cu, both pellets are in line with the limits of ISO 17225-2 for wood pellets regarding minor elements.

2.3 Emissions measurements methods

The measurements took place over two consecutive days (14-15 March 2019). On the first day, the boilers were fed with OTP pellets and on the second day, they were fed with sunflower husk pellets. Prior to every combustion trial with different fuel, the fixed bed of the boilers were firstly cleaned from ashes. For all measurements, the procedures described in the corresponding EN or ISO standard methods (Table 2) were followed.

Table 2. Parameters measured

Parameter	Method	
TSP (dust)	ISO 9096	isokinetic sampling
O ₂	ISO 12039	electrochemical sensors
CO		electrochemical sensors
CO ₂		Nondispersive Infrared sensor (NDIR)
NO _x /NO ₂	in-house method	electrochemical sensors
SO ₂	EN 14791	H ₂ O ₂ absorber solutions
HCl	EN 1911	Cl-free water absorption
OGC	EN 12619	Flame Ionization Detector (FID)

The dust emissions measurements were performed based on the principles of isokinetic sampling. Flue gas was sampled using a suction nozzle and passed through a filter that retains particulate matter. Fig. 2 presents the nozzle before and after the measurements along with its filter for both fuels.



Fig. 2. Nozzle before (top) and after the measurements and the respective filters (right)

Gaseous emissions of O_2 , CO , CO_2 and NO_x were measured using a Horiba portable flue gas analyser equipped with all the appropriate electrochemical and nondispersive infrared sensors. Organic Gaseous Carbon (OGC), was calculated based from the measured TVOC (Total Volatile Organic Carbon) emissions, using a Flame Ionization Detector (FID). Finally, for the SO_2 and HCl emissions, a flue gas sample of known volume was split in half and each half passed through three scrubbers connected in series and containing appropriate absorber solutions (H_2O_2 for the measurement of SO_2 and Cl -free water for the measurement of HCl) placed in an ice bath. The devices used are depicted in Fig. 3.

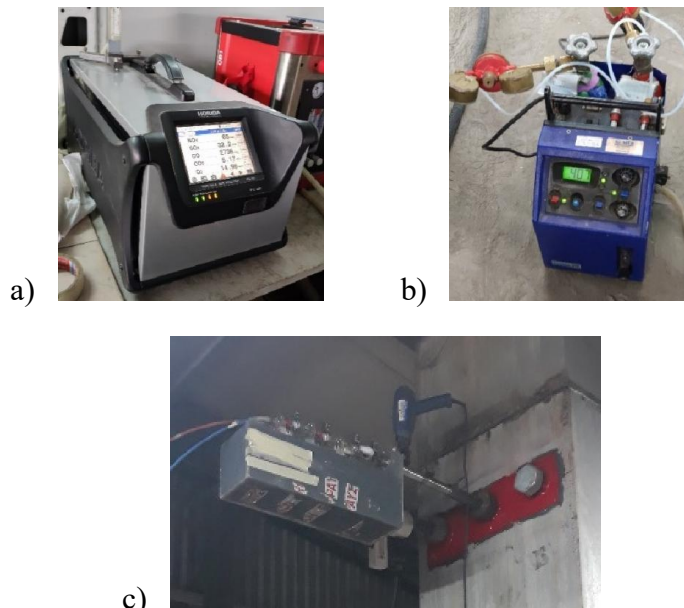


Fig. 3. Emissions measurements equipment: a) Flue gas analyser; b) Flame Ionization Detector and c) SO_2 and HCl measurement

3 RESULTS

During two consecutive days, the combustion of OTP pellets and sunflower husk pellets was monitored. Fig. 4 shows photographs from the inside of the combustion chamber during the combustion of the fuels along with the ash formation. As can be seen from the photographs, the flame produced during the combustion of OTP pellets was brighter than the flame produced with the sunflower husk pellet. The brighter flame shows a better quality combustion. Furthermore, from the inside of the

combustion chamber, apart from the more vivid flame produced from the OTP pellet, the interior walls of the chambers are different. The walls of the chamber in the case of the OTP pellets are darker whereas in the case of the sunflower husk pellets the walls are more grey, because of the different properties of the ash. The ash formation of both fuels can be also seen in the last row of the following figure. The ash produced from the combustion of OTP pellets is more granular and non-melted than the ash produced from the sunflower husk pellets. Thus, the ash from the combustion of OTP fuel is easier for removal/cleaning whereas the ash from the sunflower husk pellets can cause slagging.



Fig. 4. Combustion of OTP pellets (left) vs sunflower husk pellets (right) at industrial boiler: flame inspection (first row), combustion chamber inspection (second row) and ash formation inspection (third row)

Main gaseous emissions from sunflower husk and OTP pellets combustion at the industrial boiler are presented on Table 3. The results are presented for 6 % reference O₂ and compared with the respective limits posed by the Medium Combustion Plant Directive. Table 4 presents the flue gas characteristics such as temperature, flow rate, moisture and air excess ratio.

Table 3. Flue gas emissions

	Units	Sunflower Pellets	OTP pellets	Medium Combustion Plant Directive Limits
Dust	mg/Nm ³ (dry, @ 6% O ₂)	1372.2	1770.9	50
SO ₂	mg/Nm ³ (dry, @ 6% O ₂)	1.1	2.4	200
NO _x	mg/Nm ³ (dry, @ 6% O ₂)	411.4	349.2	650
OGC	mg/Nm ³ (dry, @ 6% O ₂)	195.2	2518.1	
HCl	mg/Nm ³ (dry, @ 6% O ₂)	0.9	5.5	
CO	mg/Nm ³ (dry, @ 6% O ₂)	12291.1	7815.8	
CO ₂	% (dry, @ 6% O ₂)	13.2	12.6	

Table 4. Flue gas characteristics

	Units	Sunflower Pellets	OTP pellets
Air excess ratio	% dry	4.67	3.23
Temperature	°C	123.6	203.7
Flow rate	Nm ³ /h (dry)	4,709	4,300
Moisture	%	4.1	4.7

For both fuels, emissions of SO₂ and NO_x are below the MCP Directive limits. OTP pellets have lower emissions of CO that implies a better combustion performance. Furthermore, NO_x emissions were lower with the OTP pellets, whereas OGC was higher than sunflower husk pellets. However, for both fuels the dust emissions are significantly higher than the 50 mg/Nm³ limit. In order to deal with such a high value of dust emissions, a cyclone alone may not be adequate to achieve compliance with the MCP Directive limits. An installation of an ESP filter after the cyclone is needed to restrain the dust emissions and ensure compliance with the directive.

Based on the results of the measurements, the boiler efficiency (indirect method) for both cases was calculated with a simplified equation based on EN 12952-15:2003, considering flue gas losses, losses due to unburned CO and losses due to radiation and convection. The same pair of boilers were used for each day of measurement with each fuel and the calculations of the efficiency refer to one of the two identical boilers with a 1.16 MW nominal power each. The following equations were used for the calculation of the boiler's efficiency (Table 5).

$$\eta_{(N)B} = \frac{1 - l_{(N)GF} - l_{(N)COF}}{1 + \frac{\dot{Q}_{RC}}{\dot{Q}_N}} \quad (1)$$

$$l_{(N)GF} = \frac{\mu_G}{NCV} \cdot \bar{c}_{pG} \cdot (T_G - T_r) \quad (2)$$

$$l_{(N)COF} = \frac{V_{Gd}}{NCV} \cdot y_{COd} \cdot NCV_{CO} \quad (3)$$

$$\dot{Q}_{RC} = 0.0315 \cdot \dot{Q}_N^{0.7} \quad (4)$$

Where:

$\eta_{(N)B}$	boiler efficiency
$l_{(N)GF}$	flue gas losses
$l_{(N)COF}$	losses due to unburned CO
\dot{Q}_{RC}	losses due to radiation and convection [MW]
\dot{Q}_N	maximum useful heat output of the boiler [MW]; in this case it equals 1.16 MW
\bar{c}_{pG}	integral specific heat of flue gas [kcal/kg K]
CV_{CO}	calorific value of carbon monoxide [kcal/m ³]
μ_G	flue gas content [kg/kg fuel]
NCV	Net Calorific Value, as received [kcal/kg]

T_G	flue gas temperature [°C]
T_p	ambient temperature [°C]
V_{Gd}	dry flue gas volume [m ³]
y_{COd}	CO content by volume of dry flue gas

Table 5. Boiler efficiency calculation (indirect method)

Parameter	Sunflower Pellets	OTP Pellets
$l_{(N)GF}$	0.2025	0.2407
$l_{(N)COF}$	0.0047	0.0031
\dot{Q}_{RC}	0.035 MW	
\dot{Q}_N	1.16 MW	
$\eta_{(N)B}$	76.96 %	73.42 %

The boiler efficiency when combusting sunflower husk pellets was calculated at 76.96%, whereas for the OTP pellet at 73.42%. A boiler efficiency decrease of 3.54 percentage points from the fuel switch, from the reference fuel to OTP pellets, was found. The loss of efficiency is mostly caused by the increase of the temperature of the flue gases. An explanation for this observance is related to the increased energy density of the OTP pellets compared to the sunflower husk pellets; in fact, the operator of the boiler had to reduce the feeding rate to keep the firing condition steady. A further decrease of the feeding rate is expected to have equated the heat input of OTP pellets to the boiler with the level of the sunflower husk pellets; hence temperature could have been maintained at lower levels and reduced efficiency loss observed. The efficiency values calculated are comparable with the EU-average annual efficiency of 80 % quoted for biomass heating boilers in the range of 1 -5 MW using wood chips [9]. Therefore, the results can be considered as quite good, considering also the non-standard characteristics of these types of fuels. Especially for OTP pellets, the lack of experience of the operator with this fuel coupled with the absence of sophisticated boiler control systems have also played a role for the efficiency decrease. Installation of improved controls, e.g lambda sensors and flue gas temperature monitoring systems, should contribute to the increase of the boiler efficiency and an improved combustion performance.

A further comparison of the fuels and the evaluation of potential combustion issues is based on the calculation of several “fuel indices” [10], which are presented in Table 6. The fuel index (K+Na+Zn+Pb) can be used as an indicator for the estimation of aerosol emissions. A portion of the partially volatile elements S, Cl, K, Na, Zn and Pb are released from the fuel into the gas phase during combustion. Fuels can be categorized in low (<1000 mg/kg db), medium (1000 – 10000 mg/kg db) and high PM1 emission range (>10,000 mg/kg db). Based on this, Sunflower husk pellets are categorized as high PM1 and OTP pellets as medium PM1 emission range fuels. The actual dust emissions observed were higher in the case of the OTP pellets, mainly due to the higher ash content of the fuel. However, the increased index for Sunflower husk pellets indicated that although the total dust emissions are lower, the expected emissions of PM1 would be high and thus more difficult to control using equipment for particle emissions reduction.

On the basis of the molar 2S/Cl ratio in the fuel, the risk of high temperature corrosion can be assessed. 2S/Cl ratios <2 indicate that a severe corrosion risk has to be taken into account. Both of the fuels studied in the present study exceed this limit; hence, no high temperature corrosion risk is expected. Finally, the index (Si)/(Ca+Mg) can be used to evaluate ash melting behaviour. It is known that Si in combination with K can lead to low-melting eutectic phases [10]. On the contrary, elements such as Ca, Mg and Al in tendency raise the melting point. Therefore, indices with smaller values are related with high ash melting temperatures. Fuels with values above 1 are expected to have ash-sintering temperatures below 1100°C, even though that is not the case with either fuel, ash-sintering issues were observed in the case of sunflower husk pellets. This could be due to a high P concentration.

Table 6. Fuel indices

Fuel index	Units	Sunflower Pellets	OTP Pellets
K+Na+Zn+Pb	mg/kg d.b.	11466.45	7133.76
2S/Cl	mol/mol	8.86	2.77
Si/(Ca+Mg)	mol/mol	0.0921	0.0909

4 CONCLUSIONS

In overall, the OTP pellet consist a competitive fuel compared to other alternative industrial fuels (e.g. sunflower husk pellets, exhausted olive cake etc.). OTP pellets have high energy content but also increased ash content due to the existence of leaves and soil contamination deriving from the harvesting of prunings. During the combustion monitoring, OTP pellets slightly decreased the boiler's efficiency by 3.5 percentage points compared to the reference fuel. The loss of efficiency is mostly related to the increased energy density of the OTP pellets compared to the sunflower husk pellets (24.8% higher). The higher energy density led to the decrease of the feeding rate by the boiler operator. However, the setting of the boiler was not optimum, thus higher losses were observed (high flue gas temperature). Installation of improved controls, e.g lamda sensors and flue gas temperature monitoring systems, should contribute to the increase of the boiler efficiency and an improved combustion performance while using OTP pellets. Apart from the slightly decreased efficiency, the emissions for OTP pellets were lower for CO, NO_x and CO₂. On the other hand, OGC emissions were much higher with OTP pellets compared to sunflower husk pellets. With both fuels, the boiler emissions were within the MCPD limits for NO_x and SO₂ emissions. The dust emissions however were much higher than the limits. Nonetheless, this challenge can be addressed by installing a cyclone and ESP filter in order to comply with the limit of 50 mg/Nm³. Consequently, OTP pellets can compete with well-established industrial fuels, in terms of combustion efficiency and emissions. The vast amount of untapped biomass of olive tree prunings along with cost-effective harvesting configurations and logistics constitute OTP pellet a solid biofuel with great potential and future.

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