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Research paper

Development of a new model of olives de-stoner machine: Evaluation of electric consumption and kernel characterization

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ABSTRACT

In this scientific paper, the quantitative and qualitative performances of three different de-stoner machines involved in an industrial olive oil plant were evaluated. The bioenergy production potential for olive stone in Italy was also estimated. The results confirmed that the best performance was obtained using the innovative partial de-stoner machine called "Moliden" because it does not lead to losses in oil extraction efficiency (as opposed to the total de-stoner machine) and it also extracts an amount of olive stone (approximately 65% of the total stone contained in the olives) that is greater than that obtained using the husk de-stoner machine (58%). In addition, the olive stone obtained by using a partial de-stoner machine contains lower oil, fine particle sizes and nitrogen compared to the olive stone obtained by using a husk de-stoner machine. This leads to advantages regarding combustion efficiency and the environment. Considering the olive production in Italy and in the Mediterranean basin, olive stone might be an attractive renewable source for energy production.

1. Introduction

The olive tree (*Olea europaea* L.) is one of the most important crops in the Mediterranean area and is one of the most important resources for the economy and diet of this region.

Mediterranean countries produce approximately 98% of the worldwide olive oil production. The leading country in olive oil production is Spain, followed by Italy and Greece, considering the average productions from crop seasons 2008 and 2009 and from 2013 to 2014 [1].

An olive oil chain produces large amounts of solid residues, resulting from olive tree plantation activities (olive tree cuttings and leaves) and olive oil extraction waste (husk).

The evolution of the olive oil extraction plant has led to the worldwide use of the continuous extraction system with the decanter centrifugal to separate the solid and the liquid, according to the work process used (two-phase or three-phase). The details of the average mass balance of the olive structural components and the division of the olive's components in the outputs of the olive oil extraction plant, are shown respectively in Refs. [2] and [3].

Three-phase processing produces olive oil, wastewater and husks having approximately 50–55% of water mass fraction [4,5]. Typically, after a preliminary husk drying, the residual oil is hexane extracted and the solid residue is used to feed standard combustion equipment. Two-phase processing produces olive oil and a wet husk having 65–70% of water mass fraction [6,7]. Due to the high water mass fraction of the wet husk, the recovery of residual oil using hexane extraction or the use of husk for energy purposes, are possible only after a drying process of this by-product; therefore, it is often used for anaerobic digestion, composting or disposed of on the ground (in accordance with local law) with an important disadvantage with regard to the costs and natural resources.

The potential use of the husks for energy purposes has been highlighted in numerous scientific publications, following some recent scientific papers [8–11]. However, the high oil mass fraction of approximately 5.0% [12–14] and the high amount of fine particle

Abbreviations: OS, olive stone; TDM, total de-stoner machine; PDM, partial de-stoner machine; HDM, husk de-stoner machine; w.b., wet basis; d.b., dry basis; *EE*, extraction efficiency (%); W_{oil}, mass of the extracted oil (kg); $W_{total\ oil}$, mass of oil in the processed olives (kg); W_{olive}, mass of processed olives (kg); *HHV*, heating value (MJ kg^{-1}); *LHV*, low heating value (MJ kg^{-1}); *H*, hydrogen percentage of the olive stone; *M*, moisture percentage of the olive stone; *Hg*, latent heat of steam in the same units as HHV and LHV; *Y*, extraction yield (%); *Oh*, oil mass fraction in the husk (%); *I*, electric current intensity (A); *P*, electric power (W); *V*, electric potential (V); *Ei*, energy index; *RS*, mass of the stone recovered (kg); *EPc*, electric power consumed to recover the stone (kW h).

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size cause problems in the combustion process within a conventional combustor system such as generating uncontrolled combustions and emissions [15,16] that result in the emissions of fumes and bad smells and the clogging of exchangers and chimneys. In addition, the oleaginous characteristics of the husks prevent the pelletizing process. Moreover, their high concentrations of certain elements exceed the specifications given by the corresponding standards [17]. Thus, pelletizing is necessary to blend the husk with other biomass residues [18].

Recently, the growing demand for high quality biomasses has caused millers to adopt equipment to extract olive stone (OS) during the olive oil extraction process.

As shown in many scientific papers, OS has a high calorific value and is a good biomass for energy production with high combustion efficiency [19–21]. In addition, OS produces a lower percentage of ash, nitrogen and oil mass fraction than the husk, and it can be used in standard combustion equipment, avoiding the pre-treatment use for husk as previously described. Therefore, OS has better combustion characteristics compared to the husk.

Literature reports on the uses of olive stone as an alternative to energy production such as activated carbon [22,23], an additive in cement lime mortar to improve thermal insulation [24] and an additive for resins [25].

In recent years, the market price of olive stone has increased.

Currently, the equipment solutions adopted in the mill are the total olive de-stoner machine (TDM) and the husk de-stoner machine (HDM).

The TDM is placed at the beginning of the olive oil process line in place of the common mechanical crusher. The de-stoning operation consists of removing the whole OS and of reducing the pulp into a paste of suitable fineness, fluidity and homogeneity. The TDM removes all olive stones, whereas the pulp continues in the process, but it has had a limited spread in mills because despite possible adjustments of the decanter, the extraction yield of plants is always slightly lower than that obtained using paste containing a network of stone fragments [26].

The HDM instead is placed at the end of the olive oil process line and removes the stone fragments from the husks. It is necessary to emphasize two aspects connected to the use of this machine: 1) it involves the addition of a new machine to the process line and an increase in the covered space outside the mill; and 2) it does not recover 100% of the stone fragments but only a variable fraction.

The purpose of this scientific work is to continue the study on the efficient recovery of the OS in an olive oil extraction process by testing a new and innovative machine, the "partial de-stoner machine" (PDM), and comparing it with other technologies in an industrial olive oil extraction plant. PDM was projected and developed as part of a research project involving university and private company. The machine was patented. The goal of the research is to compare four different scenarios of an olive oil process line, three of which are performed with a machine to recover the OS and one without (control) to evaluate the energy consumption, the quality and quantity of the stone recovered and the olive oil extraction efficiency of the plant.

The final goal of the research is to evaluate the bioenergy production potential from OS in Italy.

2. Materials and methods

2.1. Experimental plant

In this research program, four different industrial plant scenarios were tested to compare three different methods to recover the OS, including the conventional olive oil extraction plant scenario without the stone recovery system (control test).

The conventional industrial olive oil mill used was constituted by:

- rotary leaf removing machine (model Condor 1, Clemente & C. Snc, Altamura, Ba, Italy) to separate without water, leaves, twigs and small solid residues, with the hourly capacity of up to 4000 kg h^{-1};
- washing machine (mod. Special Soft Washer, Alfa Laval Corporate AB, Lund - Sweden) to remove with water, leaves, dirt, stones and other heavy extraneous objects before the olives enter in the first part of processing line (crushing stage). The machine performs an efficient olives cleaning safeguarding the fruit integrity with the hourly capacity of up to 5000 kg h^{-1};
- hammer crusher (mod. Hammer Mill Crusher, Alfa Laval Corporate AB, Lund - Sweden). The machine performs an efficient crushing of the whole olives until obtained an homogeneous olive pastes. The rotor's angular velocity was of about 2900 rpm and the grid hole of 7 mm;
- # 6 open horizontal malaxers having capacity of 800 L and a reel shaft's angular velocity of about 13 rpm (mod. 700, D'Angelo Macchine Olearie, Treglio, CH, Italy);
- horizontal centrifugal decanter (mod. NX X32, Alfa Laval Corporate AB, Lund - Sweden) having an hourly capacity of up to 3000 kg h^{-1}. This machine is a 3-phase to efficient separate the oil, wastewater and husk phases.
- # 2 vertical plate centrifuge (mod. UVPX 507, Alfa Laval Corporate AB, Lund - Sweden). One machine is used to clarify oil from oil phase and the other one to recover any traces of residual oil in the olive vegetable water. The separator is designed for intermittent discharge of solids, while separating two intermixed and mutually insoluble liquid phases of different densities. The separator has a throughput capacity of 2.7 m^3 h^{-1}.

The plant in the above description was scenario A and identifies the experimental test A-Control.

In scenario B, which is identified as experimental test B-TDM, a TDM (mod. Depitting Machine, Alfa Laval Corporate AB, Lund - Sweden) was placed instead of the hammer mill.

In scenario C, which is identified as experimental test C-PDM, an innovative PDM (mod. Moliden, Pietro Leone e Figli s.n.c., Foggia, Italy) was placed instead of the hammer mill.

Finally, in scenario D, which is identified as experimental test D-HDM, an HDM (model Galaxy 2, Clemente & C. Snc, Altamura, Ba, Italy) was placed downstream of the decanter to separate stone fragments from the husk.

Fig. 1 shows the production path line of the mill process for the four different scenarios considered. Three-way valves and/or starts and stops using pumps and conveyors allow product flow switch from one scenario to the others.

Each trial was replicated five times using a homogenous batch of Coratina (*O. europaea* L.), having a maturity index of 1.4 [27] and harvested 5 h before the test.

For all experimental tests, the olive paste was malaxed for 40 min at 27 °C. The malaxing time did not include the times required to load and unload the malaxer. During all four tests, the mass flow rate of the plant was set to 3000 kg h^{-1}, corresponding to decanter's nominal mass flow rate and the amount of process water added to decanter was 10%.

During the comparative tests, the following items were determined for the four plant scenarios:

- The process extraction yield is the amount of oil extracted from 100 kg of processed olives and is expressed as a percentage. The yield (Y) was calculated using the following equation:

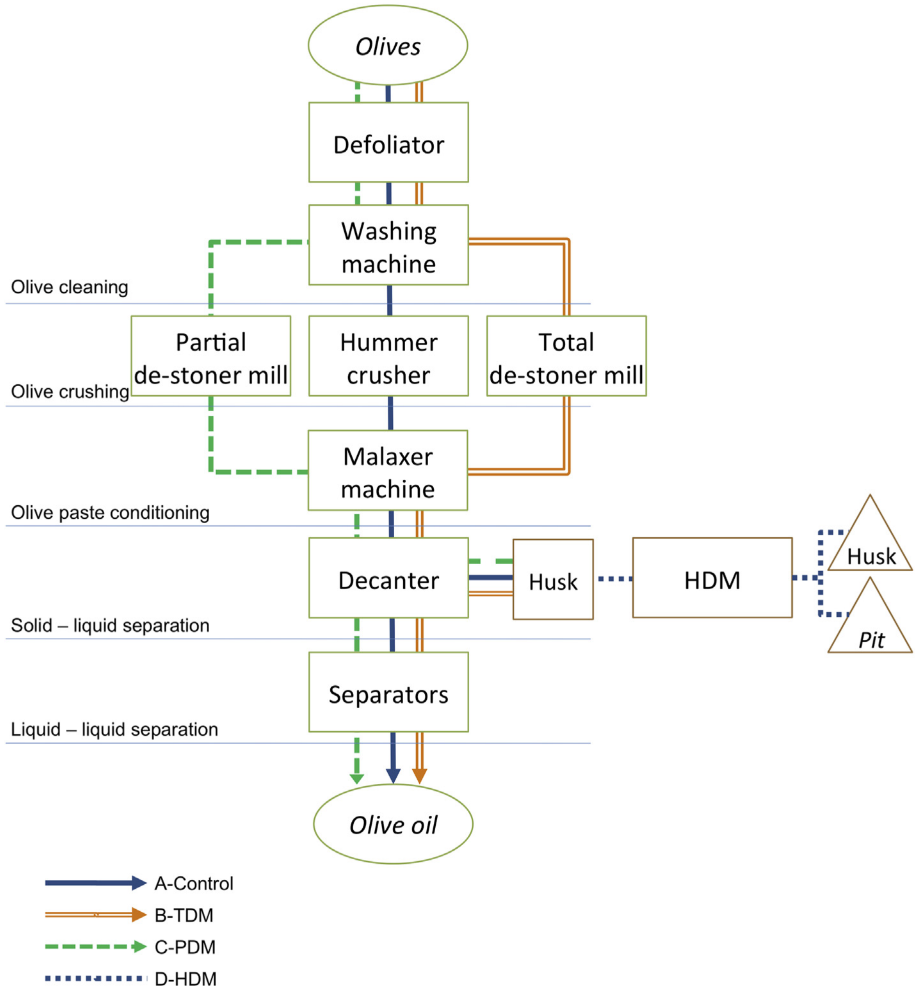

Fig. 1. Path lines of olive oil extraction plant in the differents scenarios.

$$Y = \frac{W_{oil}}{W_{olives}} 100 \quad (1)$$

where *Woil* is the mass of the extracted oil (kg), and *Wolives* is the mass of the olives processed (kg);

- The extraction efficiency of the plant was calculated using the following equation:

$$EE = \frac{W_{oil}}{W_{total\ oil}} 100 \quad (2)$$

where W_{oil} is the mass of the extracted oil (kg) and $W_{total\ oil}$ is the mass of the total oil (kg) content in the processed olives determined using the hexane extraction process;

- The oil mass fraction in the husk (*Oh*) is the oil percentage in the husk determined using the hexane extraction process. For the husk obtained by using the TDM and PDM has been used the *Oh* calculated, by adding the mass of the husk and the mass of stone recovered;
- Quantity and quality of the pits recovery;
- Electric energy consumption.

Finally, the bioenergy production potential was evaluated from OS in Italy and in different regions to estimate the amount of olive pits recoverable by using a de-stoner machine.

2.2. The innovative de-stoner machine "Moliden"

The partial de-stoner machine model Moliden was built and patented by Pietro Leone e Figli s.n.c., Foggia, Italy. It consists of three sections: the first section crushes the olives by using a hammer mill; the second section partially separates the stone fragments from the olive pulp; and the third section absolves to temporary storage for de-stoned olive paste (Fig. 2).

The obtained paste by means of the mechanical crusher is fed into the second section by a screw. This section consists of a horizontal cylindrical perforated rotating drum, with small holes (2.5–3.5 mm) and a reel (with rubber-coated rods) counter-rotating compared with the drum. The paste is fed from the first to the second drum where the rotating shaft (700–800 rpm) forces it to rub on the perforated walls of the drum, pushing it out of the holes. The hole size is such that some stone fragments exit with the paste, while others stay in the grill and are discharged from the opposite end of the feeder. The pulp exits through the holes in the drum and falls into the external collection tank. The olive paste discharge is facilitated by the counter-rotation of the drum and by a bar cleaner that strips it externally.

This machine can remove stone fragments in variable

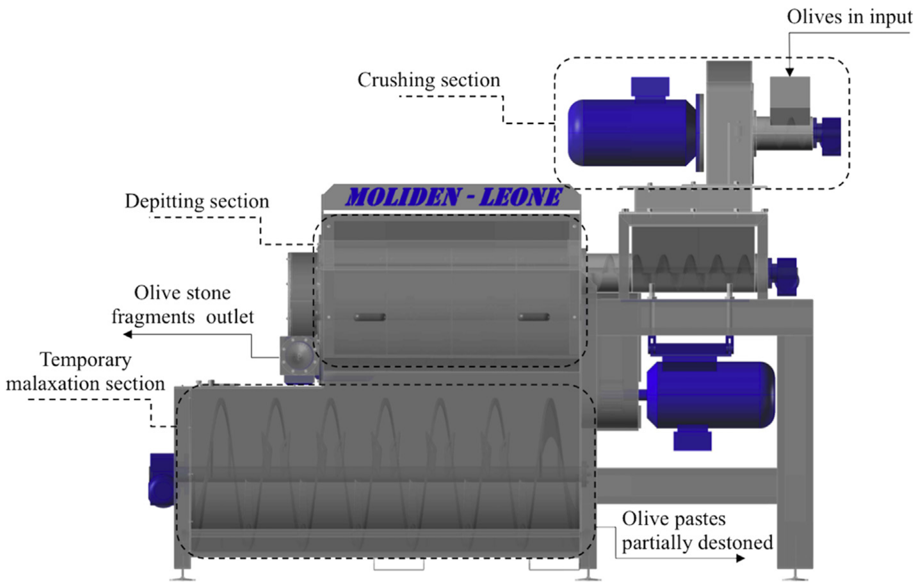

Fig. 2. The innovative de-stoner machine “Moliden”.

proportions from 0 to 100%. During the test, approximately 65% of the stone fragments were extracted, whereas the remaining 35% of the fragments of stone and the pulp continued in the process. The hourly capacity is modular until 5000 kg h^{-1} of olives, but during the experimental test, the olive paste mass flow rate was lower to 3000 kg h^{-1} to make it equal to the decanter's nominal mass flow rate used during the tests. The functionality tests of the PDM were performed in collaboration with the Department of the Science of Agriculture, Food and Environment, University of Foggia.

2.3. Sampling

For each test, olives were sampled and stored at +1 °C until analysis. The husks were sampled from the decanter at regular time intervals and stored at +1 °C until analysis.

2.4. Determination of OS in the olives and OS recovered by the de-stoners

To determinate the OS percentage in the olives, a sample of 5 kg of olives was sampled from the uniform batch of olives used for all experimental tests. The olives were first soaked in boiling water for 10 min, manually de-stoned, cleaned from the pulp and weighed.

To determine the amount of stone recovered from the TDM, PDM and HDM, during each experimental test, all of the OS output from the machines were stored in a bin and were subsequently weighed.

2.5. Proximate and elemental composition of olive stone

In this chapter, the methods for the determination of the quality parameters for the OS are reported according to the official methods established by the European Standard Technology Committee.

The elemental analysis of C, H, N and S of stone was determined using a LECO Analyser 628 series according to official standards [28].

The analysis of (Cl) content was performed according to official standards [29].

The determination of ash and moisture was performed according to [30] and [31], respectively.

The oxygen content has been calculated as the difference between 100 and the sum of the carbon, hydrogen, nitrogen, sulphur, chlorine, and ash contents.

The carbon, hydrogen, nitrogen, sulphur, chlorine and oxygen contents are expressed as percentages on a dry weight basis.

The heating values of the OS were determined using LECO AC500 Isoperibol Calorimeter (Leco Corp., St. Joseph, MI) by determining the high heating values (*HHV*). The low heating values (*LHV*) were calculated using the relationship between *HHV* and *LHV* according to the official standards [32] and are reported as follows:

$$LHV = HHV - hg(9H + M)/100 \quad (3)$$

where:

- H and M are the hydrogen percentage and the moisture percentage of the OS, respectively;
- hg is the latent heat of steam in the same units as *HHV* and *LHV*.

The total oil mass fraction was determined on a 40 g sample that was previously dehydrated until it reached a constant weight. The olive sample was also previously milled. The sample was extracted with hexane in an automatic extractor (Randall 148, Velp Scientifica, Milano, Italy) following the analytical technique described by Refs. [33,12].

Finally, the percentage of the particle size for the OS < 1.4 mm according to [34] was determined by using a sieves machine Retsch AS200 basic. As reported in the literature, fine particles (<1.4 mm) are responsible for emissions and uncontrolled combustions [15,16].

2.6. Electric energy consumption evaluation

The energy consumption evaluation was performed on machines characterizing the four plant configurations considered. For the A-control configuration, only the crusher was considered. For the B-TDM and C-PDM, the total de-stoner machine and the partial de-stoner machine were considered, respectively. For the D-HDM configuration, the crusher machine and the husk de-stoner machine were considered. The electric current intensity (I) of each machine considered was measured by means of an amperometric clamp (model PCE-830-1, PCE Italia S.R.L. Capannori (LU), Italy), placed around the power wire of the electric motor. I value was relieved 10 min after the machine start to allow its stabilization. The electric power (*P*) consumed by each machine was determined considering the electric potential (*V*) detected on the switchboard. Then, the *P* value was determined by multiplying *I* value by the *V* value.

The energy performances of the different machines related to the amount of recovered stone respect the electric energy consumed, was estimated using the dimensionless index *Ei* calculated by following equation:

$$Ei = \frac{RS \cdot HHV}{EPc} \tag{4}$$

where *RS* is the mass of the stone recovered (kg), *HHV* is the heating value (kW h kg^{-1}) and *EPc* is the electric power consumed to recover the stone (kW h);

2.7. Bioenergy potential from olive stone in Italy

An estimation of the bioenergy production potential for olive kernel in Italy was made by starting with the olive production data collected by the Agency for Agricultural Payments (AGEA). AGEA is Italy's paying agency, which manages the funds that the European Union makes in support of agriculture for the Member Countries. The AGEA through the National Agricultural Information System (SIAN) collects all data related to the different productive agricultural sectors including the olive and olive oil sector.

To estimate the amount of OS potential products in Italy and in each region, the authors assume a mean percentage of stone in olives of 12% d.b. as experimentally calculated.

The total thermal bioenergy potential value from olive kernel on an annual basis (MJ y^{-1}) was estimated using the following expression:

$$E = Op\, 0.12\, HHV \tag{5}$$

where:

- *Op* is the average mass of olive milled that is available on an annual basis (kg y^{-1} w.b.);
- *HHV* is the higher heating value of the OS experimentally calculated (20.0 MJ kg^{-1} d.b.).

2.8. Statistical analysis

All of the experimental data were analysed via an analysis of variance (ANOVA), and Tukey's test was used for means separation with $p < 0.05$, using the MATLAB® statistics toolbox (Mathworks Inc., Natik, MA, USA).

3. Results and discussion

3.1. Quantitative performance of the virgin olive oil extraction plant

The performances of the extraction plant for each scenario considered are shown in Table 1.

It is important to emphasize that for this evaluation, the A-Control test coincides with the D-HDM test. In fact, unlike the A-Control test, the D-HDM test has an HDM located downstream of the decanter. This machine does not affect the quantitative parameters of the extraction plant.

As shown in Table 1, the *Y* in the B-TDM test is significantly lower and is approximately 1.6% compared to the A-Control test of approximately 2.2% compared to the C-PDM test. This determines differences in *EE*.

In fact, considering that the olive pastes contain the same percentage in olive oil (17.7%), the scenario B that use the TDM exhibit an *EE* significantly lower compared the others.

In addition between A/D and C scenarios there was not significant differences in *EE*.

Table 1 does not show the statistical analysis of the three theses compared to the oil mass fraction in the husks because the percentage of OS in the husks is different. In fact, the husk obtained in tests A and D contains all of the stone contained in the olive. The husk obtained in the B-TDM test does not contain fragments of stone, whereas the husk obtained in the C-PDM test contains only a fraction of the stones. The different composition of the husk does not permit a comparison of the data between different theses. To statistically compare the data in Table 1, the oil mass fraction compared to the husk is shown to which was added the mass of stone previously separated by the de-stoner machine. These final data confirm the *EE* values. In fact, the oil mass fraction in the husk increases significantly from its value when the TDM was used compared to tests A and C.

The significantly lower yield was also observed in previous research performed by Amirante et al. [35]. The researchers assert that the employment of the de-stoner machine instead of the stone mill causes a decrease in yield that is equal to approximately 1.5%.

As Leone (2014) [2] reported, the total absence of stones in the olive pastes may cause problems in the first stage of malaxation and in decanter extraction. In malaxation, the absence of stone fragments reduces the effect of breaking cell walls and vacuoles. In addition, in the decanter centrifugation, the absence of stone fragments causes a reduction in draining effects, making the separation of liquids and solids more difficult. To limit the olive oil losses in the husk, a significant increase in the malaxation time of de-stoned pastes, a reduction of the olive paste mass flow rate to the decanter and an adjustment of the differential speed between the bowl and screw conveyor may be used, but it may consequently reduce the working capacity of the plant.

It is interesting to note that as with the use of the PDM, the partial presence of the stone fragment in the olive pastes avoids all of the technological problems described above. This means that the partial presence of the stone fragments is sufficient for a good efficient effect of the malaxation and a good draining effect during the decanter centrifugation to avoid a significantly decreasing *EE*.

3.2. Olive stone recovery and its characterization

Table 2 shows the percentage of stone recovered by the three different machines. Considering that the OS was 11.9% as a mass fraction of olives, the TDM recovered the total amount (99.2%), which is significantly greater than PDM (64.7%) and HDM (58.0%). In addition, the PDM recovered 64.7% of stone, which is significantly greater than the HDM (58.0%).

Table 3 shows the chemical-physical characteristics of different OS. Between TDM-OS and OS-PDM, there are no significant differences for both the chemical and physical parameters. However, both TDM-OS and OS-PDM differ statistically from OS-HDM.

As shown in Table 3, the olive stone moisture content of the samples varies from 21.3 to 22.1%. Moisture is an important quality parameter of biomass because it influences the heating value and the combustion temperatures; both decrease with moisture content. This affects the efficiency of thermal processes and determines maintenance difficulties. It is important to emphasize that the water mass fraction of the olive stone decreases to values <10%

Table 1
Quantitative performance parameters of the extraction plant.

Tests	Y (%)	EE (%)	Oh (% w.b.)	Oh (% d.b.)	Calculated Oh (% w.b.)	Calculated Oh (% d.b.)
A-Control D-HDM	14.6 ± 0.5 a	82.4 ± 2.9 a	5.7 ± 0.2	12.4 ± 0.5	5.7 ± 0.2 b	12.4 ± 0.5 c
B-TDM	13.0 ± 0.2 b	73.7 ± 1.3 b	9.5 ± 0.2	27.3 ± 0.6	[a] 6.8 ± 0.1 a	[a] 19.5 ± 0.4 a
C-PDM	15.2 ± 0.4 a	85.9 ± 2.5 a	7.1 ± 0.2	18.1 ± 0.6	[a] 5.6 ± 0.2 b	[a] 14.3 ± 0.5 b

Different letters denotes significant statistical differences ($p < 0.05$).
[a] The value were calculated by adding to the mass of husk to the mass of stone recovered.

Table 2
Stone recovered by different machines.

Tests	Stone in olive (% d.b.)	Stone recovered by the machines (% d.b.)	Machines' recovery yield (% d.b.)
A-Control	11.9 ± 0.2	0.0	0.0
B-TDM	11.9 ± 0.2	11.8 ± 0.1 a	99.2 ± 0.8 a
C-PDM	11.9 ± 0.2	7.7 ± 0.1 b	64.7 ± 0.8 b
D-HDM	11.9 ± 0.2	6.9 ± 0.1 c	58.0 ± 0.8 c

Different letters denotes significant statistical differences ($p < 0.05$).

after a few days of storage.

Ash is the inorganic component that remains after combustion. The lower value of ash is another quality parameter of biomass. Infect during the combustion in standard equipment can be melted, producing hard slag deposits that can produce combustion problems and the corrosion of heating devices [36]. In this study, there were significant differences between the ash content in OS-HDM (0.55%) compared to the ash content in OS-TDP (0.20%) and OS-PDM (0.21%). However, it is important to note that the ash content in olive stone is lower than other agricultural waste such as olive tree pruning (4.75%), cotton stalks (13.3%), corn stalks (6.4), rice straw (13.4%) [23] and residual pomace (5.55) [37].

The differences are also significant between the *HHV* from 21.5 MJ kg^{-1} in OS-HDM to 20.1 and 20.0 MJ kg^{-1} in OS-TDM and OS, respectively. This difference is easily explained by analysing the oil mass fraction in the stone. In fact, it is interesting to note that the OS-HDM has an oil mass fraction that is significantly higher compared to the others tests. This difference is easily explained by considering the extraction point of the OS in the olive oil process line. The OS for tests B and C was extracted at the beginning of the process before the majority of the cell vacuoles have issued small oil droplets, reducing a few seconds of contact time between the OS and olive oil. This limits the absorption of oil by the OS.

The OS-HDM is instead extracted from the husks at the end of the process. This OS was in contact with oil for the entire extraction cycle, including the malaxation step during which it came into close contact with the oil for times that may be up to an hour. The long contact time allows the OS-HDM to absorb a relatively greater amount of oil compared with other tests.

Table 3
Physicochemical characteristics of olive stone.

Parameter	OS-TDM	OS-PDM	OS-HDM
Moisture (%)	22.1 a	22.0 a	21.3 b
Ash (% d.b.)	0.20 b	0.21 b	0.55 a
HHV (MJ kg^{-1})	20.1 b	20.0 b	21.3 a
LHV (MJ kg^{-1})	18.2 a	18.1 a	19.4 a
Oil mass fraction (% d.b.)	0.46 b	0.44 b	0.55 a
C (% d.b.)	49.7 b	49.6 b	52.5 a
H (% d.b.)	7.02 a	7.05 a	7.14 a
N (% d.b.)	0.041 b	0.044 b	0.567 a
S (% d.b.)	0.020 a	0.023 a	0.025 a
Cl (% d.b.)	0.022 a	0.024 a	0.023 a
O (% d.b.)	43.0 a	43.1 a	39.2 b
Particle size < 1.4 mm (%)	0.18 c	0.25 b	1.02 a

Different letters denotes significant statistical differences ($p < 0.05$).

This aspect is also due to the greater amount of residual pulp in OS-HDM that determines an higher oil mass fraction than those of other tests. This oil with a high *HHV* (42 MJ kg^{-1}) increases the *HHV* of the olive stone, but it also causes problems in the combustion processes within domestic heating appliances, generating uncontrolled combustions and emissions [38].

The differences in oil mass fraction can probably be correlated with the significant differences in total carbon between the OS samples.

As shown in Table 3, the nitrogen content in OS-HDM (0.567%) is significant higher than OS-TDM (0.041%) and OS-PDM (0.044%). The nitrogen content is an important parameter for the quality of the combustion processes. After combustion, nitrogen is converted to N_2 and nitrogen oxides (NOx), which represent the main environmental impact of biomass burning [38].

Nitrogen oxides are the most threatening and widespread gaseous pollutants that lead to acid rain formation and the depletion of the ozone layer [39]. NOx are also involved in various secondary processes, generating harmful molecules as ozone and acid compounds.

The nitrogen content of olive stones analysed is lower than that contained in the husk of 1.98% [37] or pellets of 0.61 [40] and is comparable to other crop residues according to the data reported in the literature [41].

Regarding the total chlorine content of OS analysed, there are no significant differences between the samples. The chlorine content is the most important parameter for the corrosion of the combustion equipment and the pipeline of plants; therefore, a cleaning section is necessary to restrict their concentrations and to preserve the devices. The combustion of biomass results in a significant formation of acidic pollutants, the high mass loading of aerosols and the agglomeration of these aerosols on heat-transfer surfaces [42–46].

Concerning the sulphur content in olive stones analysed in ranges from 0.020% to 0.025%, there are no significant differences between the samples. As with nitrogen, sulphur has an environmental impact. Sulphur (approximately 50–60%) is predominantly incorporated into organic structures such as amino acids, cysteine and methionine, while the remaining sulphur originates from inorganic salts, mainly sulphates [47]. The organic form of sulphur contained in the OS may produce SOx emission during the combustion, which contributes to acid rain [38].

The sulphur and chlorine contents are similar to the data obtained from 176 samples of olive stone analysed and reported by Mata-Sánchez et al. 2014 [18] and from other crop residues

Table 4
Electric energy consumption.

Test	Electric power consumption (kW h)	Recovered stone (kg_{stone} h^{-1})	Ei[b]
A-Control	9.50	0.00	0.00
B-TDM	11.40	354.14	172.72
C-PDM	19.00	230.98	67.59
D-HDM[a]	24.70	207.06	46.61

Different letters denotes significant statistical differences ($p < 0.05$).
[a] For the D-HDM configuration either the crusher machine and the husk de-stoner machine were considered.
[b] *Ei* = Energy index (ratio between thermal energy of recovered stone and electric energy consumed by machine).

according to the data reported in the literature [48].

Finally, as Table 3 shows, the OS-HDM contain a significant higher percentage of fine particles (<1.4 mm), mainly pulp particles, compared the other tests. As reported in chapter 1, the percentage of fine particles strongly influences the emissions and uncontrolled combustions [15].

3.3. Electric energy consumption evaluation

Table 4 shows the electric power consumption, the amount of recovered stone and the recovery index for each test scenario considered. The HDM has the highest electric power consumption (24.70 kW h), followed by PDM (19.00 kW h), TDM (11.40 kW h) and the hammer crusher used in the A-Control test (9.50 kW h). The highest electric power consumption of HDM is explainable by considering that this machine is placed in addition to the hammer crusher. Considering scenarios B and C, the de-stoner machine substitutes for the hammer crusher. The energy performances of the different machines related to the amount of recovered stone were evaluated by the *Ei* (Table 4). The *Ei* value was the highest for TDM (172.72) and the lowest for HDM (46.61). PDM shows an *Ei* value equal to 67.59. It is important to note that *Ei* must be evaluated in relation to *EE* values, which is the most important quantitative performance parameter for the oil extraction process.

It is clear that TDM has the best *Ei*, but considering the low extraction efficiency (Table 1), this machine cannot be compared with the other de-stoner machines that have the same *EE* value. However, the PDM shows an *Ei* value 31% higher than those of HDM.

3.4. Bioenergy production potential for olive stone in Italy

Table 5 shows the data concerning the olive production of the last three crop seasons. According to the latest available data, Italy produces 2,247,414 Mg y^{-1} of milled olives, and Puglia Region produces approximately 1,211,132 Mg y^{-1}, corresponding to approximately 52% of the national olive oil production. Considering an estimated value of 12% of olive stone in d.b., it is possible to calculate the average amount of OS, resulting in approximately 272,177 Mg y^{-1} in Italy with more than 50% produced in Puglia. In Italy, it is possible to estimate the contribution of energy from olive stone of approximately 5.54 GJ y^{-1}. Clearly, this value should be modulated according to the type of de-stoner machine used in the olive oil extraction process to recover the OS.

According to the Observatory for Renewable Energy, the amount of renewable sources from which it is possible to generate electricity or heat including UE solid biomass (wood, wood waste, pellets and other green or animal waste) reached a value of primary energy about to $3446 \cdot 10^6$ GJ (of which 170 10^6 GJ was for Italy) in 2012, increasing by 57.0% with respect to 2000 [49].

Energy recovery from the OS for Italy and especially for the southern regions will play an important role in the achievement of energy policy targets at the EU level by 2020. The European Union defined a policy in support of renewable sources with Directive 2009/28/EC (better known as the "20–20–20" targets) that set as an objective for the EU to achieve a share of 20% from renewable sources in 2020 in the consumed energy mix [50].

4. Conclusions

Currently, the goal of environmental sustainability is oriented toward renewable energy usage instead of fossil fuels. It represents a global environmental challenge and an economic challenge for the world. Environmental protection is included in worldwide political government strategies, supporting, promoting and disseminating actions for the incentive of renewable energy development.

Table 5
Bioenergy potential from olive stone in Italy.

Region	Olive milled 2011–2012 (Mg y^{-1})	Olive milled 2012–2013 (Mg y^{-1})	Olive milled 2013–2014 (Mg y^{-1})	Average olive milled (Mg y^{-1})	[a]Recovered stone (Mg y^{-1} d.b.)	[b]E (GJ y^{-1})
Puglia	1,211,132	1,210,336	1,107,120	1,176,196	141,144	2,822,870
Calabria	293,932	265,566	237,901	265,800	31,896	637,919
Sicilia	229,180	250,443	185,882	221,835	26,620	532,404
Campania	122,899	122,482	101,790	115,724	13,887	277,737
Lazio	101,363	166,735	86,522	118,207	14,185	283,696
Abruzzo	93,446	79,331	96,863	89,880	10,786	215,712
Toscana	85,756	135,379	139,594	120,243	14,429	288,583
Umbria	37,907	28,523	50,797	39,076	4689	93,782
Molise	30,133	20,657	28,767	26,519	3,182	63,646
Sardegna	21,994	117,154	–	46,383	5566	111,318
Liguria	15,433	24,005	25,258	21,565	2588	51,757
Lombardia	4239	4608	–	2949	354	7078
Basilicata	–	31,433	39,863	23,765	2852	57,037
Italy	**2,247,414**	**2,456,652**	**2,100,357**	**2,268,141**	**272,177**	**5,443,538**

Bold represents the sum of values relative to each Italian Region mentioned in each column (then, total amount considering in Italy).
[a] Calculate considering a percentage of stone in olives of 12% d.b.
[b] E = Total thermal bioenergy potential value from olive stone on annual basis (MJ y^{-1}) calculated considering HHV = 20.0 MJ kg^{-1} d.b.

From this perspective, a linkage between researchers and industries is necessary to find engineering and technological solutions that allow the efficient production of energy from renewable sources.

At this regard, the present study shows a new olive de-stoner machine able to recover pit fragments, from the olive oil process, to be used as biomass. The new machine, developed as part of a research project involving university and private company, it has been patented.

The study shown the excellent functionality of PDM, which fit perfectly inside of the oil extraction process already existing, showing the same decanter's *EE* obtained using the traditional mechanical crusher and a greater decanter's *EE* compared to TDM.

In fact, the TDM did not have large diffusion probably because its low *EE* is not compensated by the value of OS recovered.

By comparing the PDM and HDM, it is clear that the PDM is more advantageous than HDM. In fact, the PDM permits the recovery of approximately 10% more OS compared to HDM and an electric consumption of approximately 23% less compared to HDM.

Considering the OS, the OS-PDM quality results were better than OS-HDM, thanks to lower nitrogen content and smaller content of oil and fine particle size.

Better quality OS-PDM is currently validated by a greater market price equal to approximately 0.03 € kg^{-1}. In addition, the employment of PDM instead of HDM in an olive oil extraction plant leads to additional advantages:

- higher mass flow rate of olives processed by the machines that are after the PDM, as a direct consequence of the mass reduction of the product to process, thanks to the preliminary OS extraction;
- less space occupied by machines. By using the HDM, it is necessary to introduce a new machine in the conventional layout. On the contrary, the PDM substitutes the mechanical crusher;
- less electrical power consumption.

Considering experimental evidences, the authors can assert that the use of PDM represents a better solution to produce a new value added for the olive oil chain and also an important advantage for the environment, related to the productive potential of different countries in the Mediterranean basin.

Nevertheless, it is important to emphasize that the machine object of the present study is the first partial de-stoner tested in an industrial olive oil extraction plant. Thus, further studies to investigate the best percentage of stone removed, olive oil quality and an overall economic assessment will be necessary.

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