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Biomass Recovery from Olive Oil Extraction Line: Opportunities for Reuse of By-Products and Energy Saving

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There is an increasing need to produce more energy from renewable sources and improve the energy efficiency of the processes to reduce the environmental impact. At the same time, it would also be desirable to enhance the reuse of by-products from the perspective of a circular economy.

With this purpose in mind it is of great interest considering the recovery of the olive pits along the extraction process for energy reuses. From this perspective, it is of great interest to consider the recovery of olive stones along the extraction process for energy reuse, in particular for the reduction of energy consumption linked to heat treatments for the conditioning of olive pastes.

Mainly there are two ways to recover pits during the process: 1) by using a pomace destoner machine at the end of the process; 2) by using a combined crusher-destoner machine at the beginning of the process.

In this work, the quality as biofuel of olive stones recovered with both methods was considered to evaluate the possible energy savings compared to the reference case (process line without stone recovery). In addition, the sustainability of the processes was evaluated by considering the increase in electrical energy required by the addition of the new pitting machines.

The results show how an adequate organization and management of the process can lead to benefits both in terms of energy savings and plant operating costs.

1. Introduction

In recent decades, numerous innovations have been introduced in the olive oil extraction process, in order to make the process more efficient with a consequent more rational use of energy. These novel technologies mainly focused on the conditioning of the olive paste by using heat exchangers and by mild physical technologies, such as microwave-assisted systems, low-frequency ultrasound, high-frequency ultrasound, and pulsed electric field (Tamborrino et al., 2021).

However, huge amounts of by-products and waste are produced during the extraction process and they should be properly handled to avoid serious environmental impact on land and water bodies. The solid biomass residues from olive oil extraction process have become an important source of renewable energy and an economical alternative to traditional fossil fuels used for home heating, especially in rural areas (Khdair and Abu-Rumman, 2020). Since agri-food industry consume a high amount of energy, solid biomass by-product as olive stone can be used to reduce the environmental impact of the mill (Cini et al., 2008).

The olive stones represent a significative source of energy, therefore its recovery from the pomace has become common in many oil mills, since this is a low-cost operation made with a mechanical-pneumatic machine (Peri, 2014).

However, olive pits can be recovered also at the initial stage o f the extraction process, in particular at crushing stage by using a total destoner machine. Nevertheless, the total removing of the stones from the olive paste lead to a decrease of oil yield (Amirante et al., 1987). Other studies support this thesis, as reported in Tamborrino

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et al. (2020), where was presented a new partial de-stoner machine which allows to recover a variable fraction of the stone from the olive paste (at least 60 %), to avoid yield losses. In the same study (Tamborrino et al., 2020), the authors compared the main combustion parameters of the olive stone obtained both from partial destoner machine (Pa-DM) and pomace destoner machine (Po-DM). As already stated above, the practice of pits recovery could represent a valuable aid, especially for small and medium-sized mills, in the direction of reducing their environmental impact. This is even more so if the stone is used mainly within the company for conditioning olive paste. Preheating the olive paste with a tube in tube heat exchanger before malaxation is now common practice both to make the process more efficient and because the malaxer is a poor heat exchanger (Perone et al, 2021). This therefore led to an increase in the thermal energy requirement within the mill, making the use of self-produced olive stone even more attractive.

In this study, the possible energy savings by using olive stones as biofuel, recovered with both methods, was carried out by comparing the main energy parameters to the reference case (process line without stone recovery). Since the use of additional technologies for stone recovery introduces an increase in energy expenditure, it was also evaluated the sustainability of the processes from the point of view of operating costs.

2. Materials and Methods

The experimental analysis was carried out in a medium-size olive oil industrial mill equipped with two machines able to recover the stone at two different stages, i.e. at crushing and solid-liquid separation stage, respectively. The quality of the olive stone, from the point of view of the combustion parameters, varies depending on the phase in which recovery takes place (Tamborrino et al., 2020).

The energy consumption of the extraction line with the addition of the machines to recover the stone was performed and the main energy indices were evaluated.

2.1 Experimental plan layout

Figure 1 represents a schematic configuration of the mill layout in which the experimental tests were carried out. The extraction process can be divided into different stages: olive cleaning, olive crushing, olive paste conditioning, solid-liquid separation and liquid-liquid separation. In the cleaning stage a batch of olives of about 700 kg are fed into the hopper to be cleaned by a first defoliation and a subsequent cleaning in the washing machine. Then a cavity pump moves the olives into the crushing stage where the olive paste is prepared by means of a hammer crusher or a partial destoner machine (Pa-DM). The three-way valve in Figure 1 exemplifies the possibility of diverting the flow of olives onto one or the other crushing machine. Pa-DM consist of a hammer crusher and a de-stoner section with a rotating perforated cylinder (holes diameter of 2 mm) which rotate at 200 rpm. Inside the cylinder there is a counter rotating shaft (900 rpm) which force the olive paste to rub the inner surface, so that the olive pulp is ejected outside the cylinder with a percentage of stone of about 40% of total, in order to avoid yield losses.

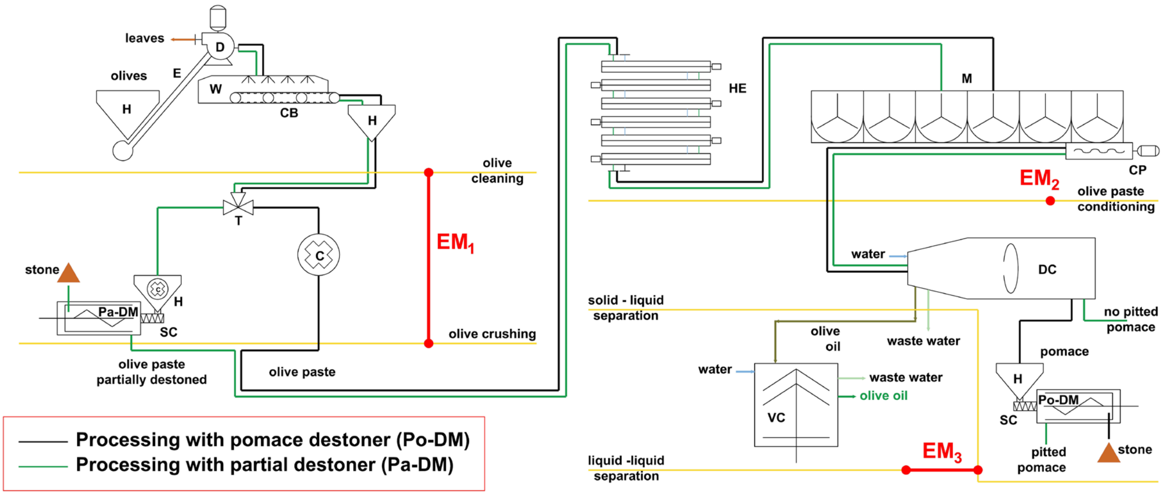

Figure 1: Layout of industrial olive mill. C, crusher; CB, conveyor belt; CP, cavity pump; D, defoliator; DC, 3-phase decanter centrifuge; E, elevator; HE, heat exchanger; H, hopper; M, malaxer; Pa-DM, partial de-stoner machine; Po-DM, pomace de-stoner machine; SC, screw conveyor; T, three-way valve; VC, vertical centrifuge; W, washing machine. EM$_1$*, EM*$_2$*, EM*$_3$*, energy meters.*

The paste obtained by one of two milling methods undergoes a pre-conditioning in a tube-in-tube heat exchanger to raise the temperature at 27 °C, and then is supplied in one of six malaxer, with a nominal capacity of 700 l. After 40 minutes of malaxation, the paste is sent to the solid-liquid separation stage, where a 3-phase decanter centrifuge produces three fractions: olive oil, wastewater and olive pomace. The latter can be treated with a pomace destoner machine (Po-DM) to recover the stone. The pomace pitting is carried by compressing the product against a grid with suitable openings so that fine soft particles pass through the grid, while olive stones are retained inside and then discharged.

The olive oil separated by means of decanter centrifuge proceeds in the vertical centrifuges for the final separation of dispersed solids and water droplets.

2.2 Electric and thermal energy

As depicted in Figure 1, the industrial mill can be operated in two different ways: by using a Pa-DM to recover the stone from olive paste at the crushing stage; by using a Po-DM to recover the stone from pomace at solid-liquid separation stage. In the first case the olives are diverted into the Pa-DM and the Po-DM is deactivated, while in the second the olives are diverted into the crusher and the Po-DM is put into operation. A third way (reference case) is also possible by deactivating both Pa-DM and Po-DM.

The electrical energy of the olive oil extraction process in each configuration was measured by means of three energy meters (EM). As shown in Figure 1, the EM_1 measured the energy consumption of the cleaning and crushing stage (olive paste preparation), EM_2 the energy absorption of the olive paste conditioning, and EM_3 the energy related to the separation process (both solid-liquid and liquid-liquid separation). In particular the energy meters were used to measure active power (P) and active energy (E). The reactive components were neglected since the electrical cabinets were equipped with power factor correction devices.

As for the thermal energy supplied to olive paste in the conditioning stage, it was computed by installing a mass flow rate of the olive paste at the inlet of the heat exchanger and two thermocouples at its inlet and outlet. In the same way, a flow meter of the hot water and its temperature at the inlet and outlet of the external jacket of malaxers were used to evaluate the heat requirement during malaxation.

The energy efficiency of the process was evaluated, as reported in Perone et al. (2022), by evaluating the following indices and referring them to the single processing cycle (cyc subscript):

$$Net\ Energy\ (NE) = Energy\ output\ \left(\frac{MJ}{cyc}\right) - Energy\ input\ \left(\frac{MJ}{cyc}\right) \tag{6}$$

$$Energy\ Productivity\ (EP) = \frac{Yield\ output\ \left(\frac{kg_{oil}}{cyc}\right)}{Energy\ input\ \left(\frac{MJ}{cyc}\right)} \tag{7}$$

$$Specific\ Energy\ (SE) = \frac{Energy\ input\ \left(\frac{MJ}{cyc}\right)}{Yield\ output\ \left(\frac{kg_{oil}}{cyc}\right)} \tag{8}$$

$$Energy\ Use\ Efficiency\ (EUE) = \frac{Energy\ output\ \left(\frac{MJ}{cyc}\right)}{Energy\ input\ \left(\frac{MJ}{cyc}\right)} \tag{9}$$

In order to obtain the primary energy, it was used the national energy efficiency (GSE) for electricity and an overall efficiency for thermal energy by considering generation, distribution regulation and emission losses.

3. Results and discussions

Table 1 shows the power and electric active energy consumption for each extraction process configuration over one working day (12 hours of operation), which means 24 processing cycles at 3000 kg/h capacity. It could be noted that the electric energy consumption increases with the introduction of technologies to recover the stone from the olive paste. However, the consumption is higher when the stone are recovered by Po-DM. This is mainly due to the fact that Pa-DM is operated for about 15 minutes every processing cycle, while Po-DM works almost continuously, being connected to the outlet of the decanter centrifuge. In fact, the separation stage as an almost constant power request, due to the common practice of the operator to withholds the olive paste of the following batch in the malaxer until the decanter centrifuge is completely drained from the previous batch (Perone et al., 2022). This can be also seen by analysing the mean value and standard deviation of electric power requested by the crushing stage of the extraction process with Pa-Dm. Although the pitting phase introduces approximately 15 kW of additional power, the average value was 12.67 kW (P_{csh}), with a standard deviation of 11.22 kW, which indicates the cyclical nature of the operation. Instead, taking into consideration the separation phase with Po-DM, it can be seen that this constantly requires an additional power of around 8 kW (P_{sep} equal to 18.21 ± 0.47 kW) respect to that with Pa-DM (P_{sep} equal to 8.21 ± 0.47 kW), and that of the reference case (P_{sep} equal to 8.71 ± 0.54 kW).

Definitely, the energy consumption was 352.13 kWh (23.09 % crushing stage, 47.11 % conditioning stage and 29.80 % separation stage) for the reference case, 411.32 kWh (37.11 % crushing stage, 38.83 % conditioning stage and 24.06 % separation stage) for Pa-DM case, and 464.32 kWh (18.41 % crushing stage, 37.25 % conditioning stage and 44.35 % separation stage) for Po-DM case. As expected, the Pa-DM line introduces an increase in energy consumption in the crushing stage and the Po-DM line in the separation stage, if compared to the reference case.

Table 1: Power and active energy over two hours of working. E_a, active energy; P, electric power. Subscripts – tot, total; csh, crushing stage; cond, conditioning stage; sep, separation stage

		$E_{a,tot}$ (kWh)	P_{gen} (kW)	$E_{a,csh}$ (kWh)	P_{csh} (kW)	$E_{a,cond}$ (kWh)	P_{cond} (kW)	$E_{a,sep}$ (kWh)	P_{sep} (kW)
Reference	μ	352.13	29.22	81.29	6.75	165.89	13.77	104.95	8.71
	σ	-	3.36	-	2.99	-	2.54	-	0.54
	%	100.00		23.09		47.11		29.80	
Pa-DM	μ	411.32	34.13	152.65	12.67	159.72	13.25	98.95	8.21
	σ	-	11.22	-	11.22	-	2.52	-	0.47
	%	100.00		37.11		38.83		24.06	
Po-DM	μ	440.52	36.56	81.09	6.73	164.08	13.62	195.35	16.21
	σ	-	3.32	-	2.98	-	2.52	-	0.47
	%	100.00		18.41		37.25		44.35	

However, the conditioning stage introduces also a thermal energy requirement. Table 2 shows the energy consumption, both electrical and thermal, consumed for each processing cycle. The conditioning stage is exactly the same in each configuration. Heat requirement to preheat the olive paste in the heat exchanger and to warm the service fluid in the external jacket of the malaxers was estimated using the calorimetric formula and the measurements carried out as reported in section 2.2. The influence of thermal energy was 37.53 % in the reference case, while it decreased in the case of Pa-DM (33.97 %) and Po-DM (31.29 %), since the electric energy increased due to the additional absorption for stone recovery. The output energy due to the energy value of the olive oil (34.5 MJ/kg), by considering an average yield of 17 % was 4398.75 MJ in each configuration.

Table 2: Energy balance for each extraction process configuration.

	Reference		Pa-DM		Po-DM	
Input	Energy (MJ/cyc)	Ratio (%)	Energy (MJ/cyc)	Ratio (%)	Energy (MJ/cyc)	Ratio (%)
Electricity	52.82	62.47%	61.70	66.03%	66.08	67.55%
Heat	31.74	37.53%	31.74	33.97%	31.74	32.45%
Total	84.56	100.00%	93.44	100.00%	97.82	100.00%

	Reference		Pa-DM		Po-DM	
Output	Energy (MJ/cyc)	Ratio (%)	Energy (MJ/cyc)	Ratio (%)	Energy (MJ/cyc)	Ratio (%)
Total(*)	4398.75	100.00%	4398.75	100.00%	4398.75	100.00%

* calculated with an average yield of 17 % and an energy value of 34.5 MJ/kg

Tables 3 reports the energy indices estimated on the basis of primary energy consumption. The primary energy was obtained by considering the national energy efficiency (GSE) of 46 % for electricity and an overall efficiency for thermal energy of about 81 % in the reference case, with condensing boiler, and of about 77 % in the case of Pa-DM and Po-DM, with biomass (stone) boiler. In the estimation of primary energy, the conversion factors of the energy carriers into primary energy were also taken into account (provided by GSE). The primary energy conversion factor of the individual energy carrier is the sum of the non-renewable and renewable contribution. It was 1.05 (non-renewable) and zero (renewable) for natural gas, and 0.2 (non-renewable) and 0.8 (renewable) for stone biofuel. Therefore, it is important to note that a significant portion of the energy produced by the combustion of the olive stone is renewable, contributing to the reduction of the environmental impact of the extraction process.

The specific energy (ES) on the basis of primary energy was 1.22 MJ/kg in the reference case and it increases to 1.37 MJ/kg in Pa-DM configuration process and to 1.45 MJ/kg in Po-DM one. The energy productivity was calculated as the inverse of SE, thus it was 0.82, 0.73 and 0.69 for reference, Pa-DM and Po-DM case, respectively. The net energy (NE) is almost the same in each case, since the energy of the output product (olive oil) is an order of magnitude higher. The energy use efficiency (EUE) was 28.16 in the reference case and 25.10 and 23.81 for Pa-DM and Po-DM configuration, respectively. However, these values do not consider the self-produced heat in the case of stone recovery. When taking this contribution into account, the thermal energy requirement must be deducted, both in Pa-DM and Po-DM cases, since it is obtained from the combustion of a process by-product. As a result, SE become 1.05 MJ/kg for Pa-DM processing line and 1.13 MJ/kg in the case of Po-DM. This means that the SE required outside the system boundaries is reduced by about 13.9 % and 7.3 %, respectively. Regarding EUE it increased to 32.80 (14.1 %) for Pa-DM and to 30.62 (8.0 %) for Po-DM.

Table 3: Energy indices for each extraction process configuration with and without (total) self- produced heat.

	Reference		Pa-DM		Po-DM	
	Total	Self-produced heat	Total	Self-produced heat	Total	Self-produced heat
ES (MJ/kg)	1.22	-	1.37	1.05	1.45	1.13
NE (Mj/cyc)	4,242.57	-	4,223.52	4,264.62	4214.00	4255.10
EUE (-)	28.16	-	25.10	32.80	23.81	30.62
EP (kg/MJ)	0.82	-	0.73	0.95	0.69	0.89

In terms of operating costs, the extra electricity costs must be considered in the case of Pa-DM and Po-DM, but at the same time the costs due to the production of heat for conditioning the olive paste must be eliminated. Table 4 summarize the energy costs by considering only the net costs of the energy carrier. The working day is 12 hours, while one year of processing was assumed to be 60 days.

As reported in Tamborrino et al. (2020) the lower heating value (LHV) of stone is about 16.61 MJ/kg when recovered with Pa-DM, and 16.11 MJ/kg when recovered by Po-DM. Therefore 2.47 kg/cyc of olive stone are used in the case of Pa-DM and 2.55 kg/cyc in the Po-DM configuration. This biofuel is completely self-produced in the mill, therefore it does not introduce any additional cost, other than the indirect one due to the introduction of the Pa-DM and Po-DM machines and already computed in electricity costs. In fact, the extraction line with Pa-DM introduces an additional electricity cost of 1,235.30 €/year, while the one with Po-DM is 1,844.59 €/year. In these two configurations, however, an economic saving of 2,067.89 €/year is due to the self-produced heat. Consequently, the net saving amounts to 832.59 €/year and 223.30 €/year for Pa-DM and Po-DM, respectively.

Table 4: Energy costs and savings for each energy source and in each configuration.

		Energy (MJ/cyc)	U.M. (unit)	LHV (MJ/unit)	Fuel/energy (unit/cyc)	Cost (€/unit)	Cost/cyc (€/cyc)	Cost/day (€/day)	Cost/year (€/year)	Saving (€/year)
Reference	Electricity	114.83	MJ	-	114.83	0.04 €	5.10 €	122.48 €	7,348.86 €	0.00 €
	Heat	41.36	Sm3	34.56	1.20	1.20 €	1.44 €	34.46 €	2,067.89 €	0.00 €
	Total	156.18	MJ	-	156.18	-	6.54 €	156.95 €	9,416.75 €	0.00 €
Pa-DM	Electricity	134.13	MJ	-	134.13	0.04 €	5.96 €	143.07 €	8,584.16 €	-1,235.30 €
	Heat	41.10	kg	16.61	2.47	0.40 €	0.00 €	0.00 €	0.00 €	2,067.89 €
	Total	175.23	MJ	-	175.23	-	5.96 €	143.07 €	8,584.16 €	832.59 €
Po-DM	Electricity	143.65	MJ	-	143.65	0.04 €	6.38 €	153.22 €	9,193.45 €	-1,844.59 €
	Heat	41.10	kg	16.11	2.55	0.40 €	0.00 €	0.00 €	0.00 €	2,067.89 €
	Total	184.75	MJ	-	184.75	-	6.38 €	153.22 €	9,193.45 €	223.30 €

Since both Pa-DM and Po-DM can recover on average about 50 % of olive stone (which represent about 26 % in the olive mass balance), the annual production can be estimated to be about 131 t/year. Of these, approximately 3.5 t/year must be used to produce heat during the olive paste conditioning stage. Approximately

127.5 kg of olive pits remain available to the mill which can potentially be sold at around €0.4/kg generating an additional income of around 51,000.00 €/year.

4. Conclusions

In this study, the possibility of improving the energy efficiency of a medium-sized oil mill was evaluated by evaluating the use of one of its by-products, i.e. olive stone, with a view to the circular economy. In order to recover the olive stone during the extraction process the introduction of two different technologies was taken into consideration. A solution involves the introduction of a pomace destoner machine (Po-DM) at the exit of the three-phase decanter centrifuge, the other the introduction of a new partial destoning machine (Pa-DM) as an alternative to the classic crusher. Hence, when the stone are recovered from pomace a new machine was added to the extraction process, while to recover the stone in the crushing stage a new machine completely replace the crusher. Pa-DM consists of two main units: hammer crusher and destoner machine.

The energy consumption of the extraction lines configured with both Pa-DM and Po-D were evaluated and compared with the reference case (with hammer crusher and Po-DM deactivated). To evaluate the energy performance in each configuration four energy indices were evaluated: specific energy (SE in MJ/kg); energy productivity EP in kg/MJ), net energy (NE in MJ) and energy use efficiency (EUE as the ratio on energy output to the input). Among these, SE and EUE better explain the efficiency of the system. It was found that SE was 1.22 MJ/kg in the reference case and increased to 1.37 MJ/kg and 1.45 MJ/kg for Pa-DM and Po-DM, respectively. As for the EUE it was calculated 28.16, 25.10 and 2.81 for reference, Pa-DM and Po-DM configuration. This apparent worsening of the use of energy resources is due to the fact that Pa-DM and Po-DM introduce an increase in electricity consumption. However, Pa-DM and Po-DM make it possible to completely reduce the heat requirement for conditioning the olive paste. Taking this contribution into account, the SE values become 1.05 MJ/kg and 1.13 MJ/kg, while EUE become 32.80 and 30.62 for Pa-DM and Po-DM, respectively. It is worth noting that the use of olive stone as biofuel introduces a share of production from renewable sources equal to 80 % (GSE source). Regarding operating costs, it was observed that Pa-DM introduces an increase in electricity expenditure of 1,235.30 €/year, while Po-DM involves an increase of 1,844.59 €/year. However, the cost savings for heat production amount to 2,067,89 €/year in both cases. Therefore, using Pa-DM leads to a cost reduction of 832.59 €/year, while Po-DM produces a reduction of 223.30 €/year. Since both technologies can recover on average around 50 % of the stone existing in the starting product, a further income of around 51,000.00 €/year could originate from the sale of the portion of stone not used for combustion in the mill.

The analysis conducted suggests that an adequate management of the process, mainly with an early recovery of the stone in the crushing stage could guarantee both energy and plant operating costs savings.

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