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Towards energy efficient scheduling in the olive oil extraction industry: Comparative assessment of energy consumption in two management models

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ABSTRACT

Although olive oil is one of the most important food products throughout the Mediterranean region, the main consideration in configuring and operating extraction plants is still the quantity of crop that will be brought by the individual growers, who are often of small and medium size. On this basis, the common configuration is the batch processing line (Ba-PL) for small and medium capacities, with malaxers arranged in parallel, or in larger-capacity industrial mills, the arrangement of malaxers in series for simulation of continuous processing (Co-PL). A review of literature to date reveals that there have been no assessments of the energy use and scheduling strategies for these two processes, therefore the current study undertakes such assessment and comparison of the Ba-PL and Co-PL configurations, within a single mill facility. The results show that energy output for Ba-PL was 105,570.00 MJ day^{-1} based on inputs of 3212.76 MJ day^{-1}, while outputs from Co-PL reached 422,280.00 MJ day^{-1} from inputs of 6740.38 MJ day^{-1}. Given that the yield of oil is almost the same in the two processes, the Net Energy (NE) for Ba-Pl then results as 10,2357.24 MJ day^{-1} versus 41,5539.62 MJ day^{-1} for the Co-PL configuration, and moreover the later process is seen to achieve almost double the Energy Use Efficiency, at 62.65 versus 32.86 in Ba-PL. Finally, the Overall Equipment Effectiveness (OEE) analysis of performance for the two processes shows values of 93.1 % for the Co-PL configuration but only 51.2 % for Ba-PL, due mainly to dead times in throughput on the Ba-PL machinery, resulting in a 44.7 % decrease in the values for the Performance parameter. The conclusion is that to meet the needs of small producers, there must be new management approaches and improvement in the energy use for batch processing. Some strategies could be:

- measure the oil content and moisture in input batches using rapid, non-destructive methods, so that homogeneous batches can be pooled before processing;
- reduce dead time by developing automated systems for pumping the olive paste from the malaxers to the separation decanter;
- even in the case that they are non-homogenous, consider pooling undersized batches so as to avoid mass flows far below the malaxer capacities.

Throughout the Mediterranean, olive oil production using batch processing remains very substantial, therefore further studies are required for the identification and evaluation of solutions for optimising this process.

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Introduction

The world population continues to grow: from an estimated 7.8 billion people in 2020, the medium-variant projection indicates that this could grow to around 8.5 billion in 2030, 9.7 billion in 2050, and 10.9 billion in 2100 (United Nations, 2019) [1]. Compared to the global trend, demographic growth in Europe will be smaller. The EU-27 population is projected to increase from 448 million in 2020 to 449.3 million in 2026, then decrease gradually to 441.2 million in 2050 and 416.1 million in 2100, thus resulting in an overall decrease of 30.8 million (−6.9 %) from 2019 to 2100 (Eurostat Europe in Figures: Eurostat yearbook, 2012) [2].

The global trend towards greater population will give rise to substantial increases in world demand for food. At the same time, the standards of living and incomes of the developing countries are expected to improve, with this involving greater per capita consumption of animal protein (meat, milk and dairy products), vegetable oils and processed foods.

The combination of increasing world population with improved standards of living will have strong impacts on energy demand. According to the UN Food and Agriculture Organization [3], the agri-food sector currently accounts for around 30 % of world total end-use energy consumption. This ratio accounts for both direct and indirect consumption, where “direct energy” refers to inputs at the industrial level to power machines and service installations, and “indirect energy” refers to the cumulative energy required for production and transport of the energy to industry Pelletier et al. [4].

Looking at the EU-27 alone, the agri-food sector is once again a major consumer of energy, with about 26 % of regional total final energy consumption, of which one third for the agricultural sector (including crop cultivation and animal rearing), 28 % for industrial food processing, and the remaining part for logistics, packaging and end-of-life phase (including final disposal of food waste) [5].

In recent years at the global level, there has been a remarkable increase in sensitivity to the paradigm of sustainability and sustainable resource use. At the levels of the EU as a whole and for each member state, the European Green Deal is centred on sustainability, and the same holds true for the National Recovery and Resilience Plans. These respond to the urgent needs for fostering strong recovery, and include growth strategies for transformation of the European Union as a modern and efficient economy in terms of competitiveness, environmental impact and resource use.

In the agri-food sector, the initial transitional efforts in agricultural production have involved both the optimisation of resources use and increases in the use of renewable energy. There have also been important contributions from moves towards more sustainable activities in the food sector, in particular through increased investment in renewable energy and improvements in energy efficiency. The goal is to produce more by using less energy. In this regard, one of the central principles of sustainable manufacturing is to improve the ratio between energy inputs and the desired outputs of a production process i.e., to improve energy efficiency.

Olive oil production is one of the most important food industries of the Mediterranean basin. The typical oil extraction plant is composed of a series of interconnected machines executing a process of five main steps: olive washing; milling or crushing; malaxing; solid–liquid centrifugal separation; liquid–liquid centrifugal separation [6,7].

The organisation and timing of these steps in the extraction process vary from place to place in the world, depending on factors ranging from governmental policies on waste disposal, to hourly mill capacities, and especially in the case of small producers, on the need to carry out the processing in batches. The large vs small-medium producer considerations, in particular, give rise two different solutions in the configuration of oil plants: (i) small/medium-capacity industrial olive mills (500–4000 kg of olives processed per hour), with malaxers arranged in parallel for batch processing of olives; (ii) large-capacity industrial olive mills (over 4000 kg of olives processed per hour), with simulation of continuous processing by malaxers arranged in series.

In batch processing, malaxation is of necessity discontinuous, however this leads to a series of problems in the oil extraction process [8–10], some of which involve energy consumption. In view of the above-stated aims for reduced energy costs in the mill, it is then possible to: change machines to more efficient models; replace electric motors with ones that are more energy efficient; design a new process [10]; optimize operational production planning (scheduling) [11–13]. Of these four methods, the first three require large investments that would be impractical for many small and medium sized companies. Process scheduling, however, can reduce energy costs in the short term, with little investment.

A necessary preliminary step in identifying strategies for optimizing the extraction process is to assess the energy consumed in the process. The literature provides many studies which have examined the energy efficiency of food processing through the assessment of a series of parameters, in particular net energy, specific energy and energy use efficiency. By way of example, the estimation of these parameters has been carried out for the following crop productions: soybean [14], sweet cherry [15], rice [16,17], potato [18], rainfed canola [19], wheat, barley, and sugar beet [20].

It is not easy, however, to find this type of study applied to the olive oil extraction process. Indeed, any studies conducted have mainly involved a life cycle assessment (LCA) of the entire supply chain. Rinaldi et al. [21] performed a cradle to grave carbon footprint (CF) and energy footprint (EF) analysis of extra virgin olive oil (EVOO) produced in the Province of Perugia, Italy, in which the mill production represented only one step of the whole process. The study considered a mill typical of small to medium size farm plants (about 1000 kg/h of olives) with the layout of: defoliation-washing, crushing, horizontal malaxation, three-phase centrifugal extraction, and finally centrifugation. The EF for mill processing was calculated to be 1.27 MJ/L (i.e. l of olive oil), however this was only a small contribution to the EF of the entire supply chain (cultivation, production, packaging, distribution and final disposal), which amounted to 274.27 MJ/L.

The LCA of Tsarouhas et al. [22] instead involved dividing the EVOO supply chain into 14 sub-systems, one of which again consisted of the mill production. These researchers found that 0.93 MJ/L of energy were required to produce one litre of olive oil, and concluded that the main contributors to the energy consumption were: cultivation of olive trees, manufacturing of olive oil, production and transportation of bottles. Secondary demands on energy consumption instead arose from the packaging process and production and transportation of fertilizers. The authors also gave some suggestions on improving efficiency of oil production, such as malaxation in two phases for reduction of production temperature and time, and a complete “just-in-time” strategy for minimisation of storage and processing times. In a recent review of LCA studies on olive oil production, Rapa and Ciano [23] found that the majority of the papers published over last decade have dealt with the full supply chain, or at least more than one stage. Their review found that the highest-impact stage is farming, given its uses of pesticides, fertilizers, water and machine fuels.

It appears from studies such as those cited here, where the extraction process has never emerged as an energy-critical step, that there has never been a study focusing specifically on the optimisation of mill management.

The literature review does yield a very few studies of gate-to-gate LCA which delve into the extraction process. Cappelletti et al. [24] evaluated the net energy of the production chain for virgin olive oil, considering different systems of cultivation and extraction technologies. Concerning mill strategies, the authors analysed four systems: pressure (PS); two-phase (2PS); three-phase (3PS); a finally a system with depitting prior to oil extraction from the olive pulp (DPS). The analyses found that the production of 1 l of EVOO required 0.5 MJ/L with PS, 0.7 MJ/L with 2PS and 3PS, and 0.6 MJ/L with DPS. The influence of the extraction step in the overall oil production chain oscillated between 4.4 % and 8.0 %, depending on the choice of cultivation system. Given this finding, however, the study did not proceed to any detailed evaluation for potential optimisation of the milling system. Cini et al. [25] instead carried out a specific LCA on the olive mill, but for purposes of evaluating the energy used in obtaining by-product, in particular olive stones. The authors studied olive mills in the Province of Florence, Italy, representative of the small-size farm typology (500 kg/h capacity). The typical processing sequence was defoliation-washing, crushing, vertical kneading, two stages of centrifugal extraction, and finally filtration with cartridges. The analysis considered 1 kg of olives as the functional unit of processing, and for this found a specific energy consumption of 105.32 kJ/kg, or 169.39 kJ/kg when using a stone separator. As stated, however, the focus here was on the reuse of the olive stones for reduction of environmental impact, not the general optimisation of the milling system.

The review above finds no study that has specifically examined the individual milling stages for identification of possible optimization strategies. Instead, there is a gap in knowledge of this step, essential to the overall supply chain and which should be of great interest in matters of energy efficiency and reduction of energy waste. The analysis of the extraction process could, among others, serve in identifying the main energy problems, the measures for good mill management and for correction of the main weaknesses, with resulting reductions in energy waste.

On the matter of good management in manufacturing processes, Gahm et al. [26] have carried out a literature review with empirical analysis, in particular of the potential benefits of energy-efficient scheduling (EES). The authors assert that EES is a suitable instrument to improve sustainability, both in general and with respect to energy efficiency. AghaAlikhani et al. [16] conclude that, in rice production, appropriate management techniques can substantially influence the energy input-yield relationship. Similar conclusions are seen in Mohammadi et al. [18], for potato production, and Kazemi et al. [19], for rainfed canola production. All of these studies shows that energy use efficiency (EUE) can be increased by changing management practices, and stress the importance of optimizing performance in all steps of the production process towards the final product, for achievement of energy savings and efficiency.

Chikwendu et al. [27] illustrate the measurement of productive system performance using a core quantitative metric known as Overall Equipment Effectiveness (OEE). OEE is an effective way of analysing the performance of the machine or machines engaged in a single manufacturing organisation or process, accounting in particular for three major sources of loss: in performance efficiency; in equipment availability; in rate of quality products (Dal et al., 2000).

At first view, the operation and management of the batch process of olive oil extraction does not appear very rational in terms of energy efficiency, and in fact many olive oil companies now view this matter as a central sustainability concern. For this reason, sustainable scheduling is attracting increasing attention as a potential solution. The current paper therefore addresses the task of evaluating energy consumption in industrial oil extraction plants of two different configurations: one suitable for discontinuous processing in batches, another for continuous processing as typically used by large-capacity producers.

From the descriptions provided above, it is abundantly clear that there has been a lack of research in the aspects of energy consumption, energy efficiency and the relative management strategies of olive mills using the two main extraction processes. No study has analysed the energy consumption resulting from the different management models of olive oil extraction systems, yet such analysis would be essential in identifying technological innovations and management solutions for process optimization. The current study therefore aims to analyse the overall equipment effectiveness and energy consumption in the two main plant configurations for oil extraction, i.e. batch and continuous processing, and so provide mill managers with information that can advance their operational planning towards improved energy efficiency.

Materials and methods

The experimental tests were carried out in an industrial olive oil mill equipped with two production lines: a batch processing line (Ba-PL) of medium hourly capacity, mainly used to process the olives of small producers; a continuous processing line (Co-PL) having large hourly capacity, used to process olives from farms with large groves. The energy consumption of the two production lines was measured continuously over 30 consecutive days, during which the two processing lines simultaneously extracted olive oil from olives (*Olea europaea* L.) of the following sequence of cultivars: Arbequina (first 10 days), Arbosana (7 days), Coratina (6 days), and Peranzana (last 7 days). Processing started at 07:00 h and ended at 22:00 h of each day, for a total of 15 operating hours per day.

Batch processing line (Ba-PL)

Fig. 1 provides a schematic representation of batch processing line Ba-PL, which typically operates on batches of about 700 kg, charged by a forklift in Hopper (H), and can maintain an olive paste flow rate of 3000 $\text{kg} \bullet \text{h}^{-1}$. The line is composed of three sections. In the first section the olives are cleaned by a defoliator (D) and washing machine (W), and then crushed. A cavity pump (CP) feeds the resulting olive paste into the second section, where its rapidly pre-heated to 27 °C by a heat exchanger (HE), and sent to one the five malaxer machines in parallel arrangement (MM), where it is kneaded at constantly maintained temperature of 27 °C. Each MM has a nominal capacity of 700 l, i.e. establishing a batch capacity of 700 kg of olive paste per MM unit. After 40 min of malaxation at 27 °C, the paste batch is fed into the third section by another CP, where it is subject to solid–liquid separation in a three-phase horizontal centrifuge (3P-DC) operating at bowl speed of 3600 *rpm*, screw speed of 3588 *rpm*, with addition of 10 % processing water, and finally liquid–liquid separation in a vertical centrifuge (VC) operating at bowl speed of 6500 *rpm*.

The batch extraction machines are exclusively electrically powered, except for the HE and MM of section two, which also require thermal energy for heating the service fluid. This is provided by a biomass burner fuelled with olive stone, which is a by-product of the extraction process.

The processing of each batch of olives is entrusted to the experience of the miller operating on a control panel, who sends the paste to the array of parallel malaxers, and in sequence from there to the decanter for oil extraction, all in a manner that avoids mixing between the crop processing of the different producers.

Continuous processing line (Co-PL)

The Co-PL line (Fig. 2) is capable of continuous operation at olive paste flow rate of 6000 $\text{kg} \bullet \text{h}^{-1}$. The first section is of composed identically to that of Ba-PL and ends in a CP, which pumps the resulting olive paste into the second section. The second section consists of the heat-exchanger for rapid pre-heating of the paste to 27 °C, then two malaxer machines of capacity 6000 l, connected in vertical series. Here, the olive paste is continuously conditioned at 27 °C before transferring by means of another CP to the third section. This section executes the separation, in this case without addition of processing water, by means of a two-phase horizontal centrifuge operating at bowl speed of 3000 *rpm* and screw speed at 2970 *rpm*, then and liquid–liquid separation in a vertical centrifuge (VC) at bowl speed of 6500 *rpm*.

As in Ba-PL, all machines of the Co-PL are exclusively electrically powered except for the heat exchanger and malaxer, which receive heat from the same boiler as for the Ba-PL, operating on olive stone fuel.

In the Co-PL line, the miller continues feeding the hopper of the first section without separation of the olives into batches, thereby operating

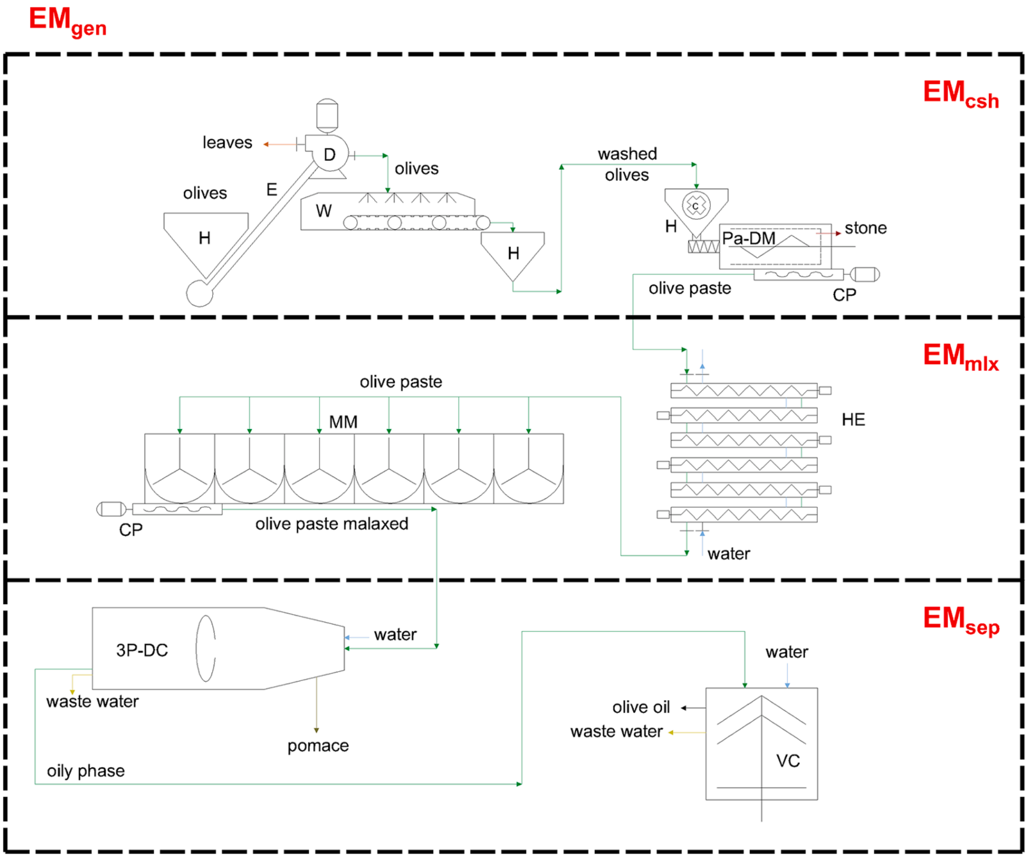

Fig. 1. Batch processing line (Ba-PL) with location of four energy meters (EM).

the machines in constant production. Once the line is in operation, the miller has only to monitor, without need of intervention in the separate processes.

Quantitative and qualitative performance of the plant

The quantitative performance of the two lines is compared by measurement of their olive oil extractability (E), defined as the ratio of the percentage of oil extracted from the olives (Oe) to the percentage of the oil content in the olives (Oo), and calculated using the following equation:

$$E = \frac{O_e}{O_o} \bullet 100 \tag{1}$$

For each of the 30 days and for each line, measurement was conducted of the quantity of incoming olives and outgoing olive oil. Also on each day, every-three operating hours and for both lines, samples were taken of the input olives, the pomace and wastewater.

Finally, the qualitative performance of the two lines was compared in terms of the quality parameters laid down in Regulation (EU) 2015/1830 [5]: in particular by measuring the free acidity, peroxide value, and extinction coefficients (K232, K270 and ΔK) of the product oil.

Extractability and oil content in olives, pomace and wastewater

As noted above, the quantitative performance of the oil extraction lines is assessed by measuring the parameters of olive oil extractability and oil content in the pomace and wastewater, according to Servili et al. [28]. The sampling of olives, pomace and wastewater, and quantity measurements of incoming olives and outgoing oil are as described above.

Measurement of electrical and thermal energy consumed on processing lines

The energy consumed by the machines in the transformation (production) processes is measured. The energy consumption unrelated to production processes or with little or no influence from scheduling (e.g. mill interior climate control, lighting, information technologies) is not considered.

Data on electricity consumption are acquired on the first, second and third sections of the two lines, as described above, i.e.: crushing (csh), malaxing (mix) and separation (sep) sections. For this purpose, for each oil extraction line, four energy meters (EM) were installed, for measurement of active power (*P*) and active energy (*E*). Figs. 1 and 2 provide schemas of the Ba-PL and Co-PL lines, showing the locations of each energy meter (EM).

The EM_{csh} acquired the electric data of the crushing section, the EM_{mlx} of the malaxing section, and EM_{sep} of the separation one. Finally, an energy meter was installed on the general switch of each line (EM_{gen}). All the EMs were connected to a local monitoring system for data collection over all 30 working days, at sampling time of 30 s. The reactive components were also measured, however since both extraction lines were equipped with devices for power factor correction, the power factor is almost equal to 1, i.e. the values are negligible.

Both lines, in the second section, supply heat for conditioning of the olive paste. To compute the use of thermal energy a meter was installed for measurement of the mass flow rate of the service fluid, and two thermocouples were installed on the inlet and outlet pipes of the external jacket of the malaxers; on the heat exchangers, probes were installed for measurement of temperature at the inlet and the outlet of the olive paste pipe.

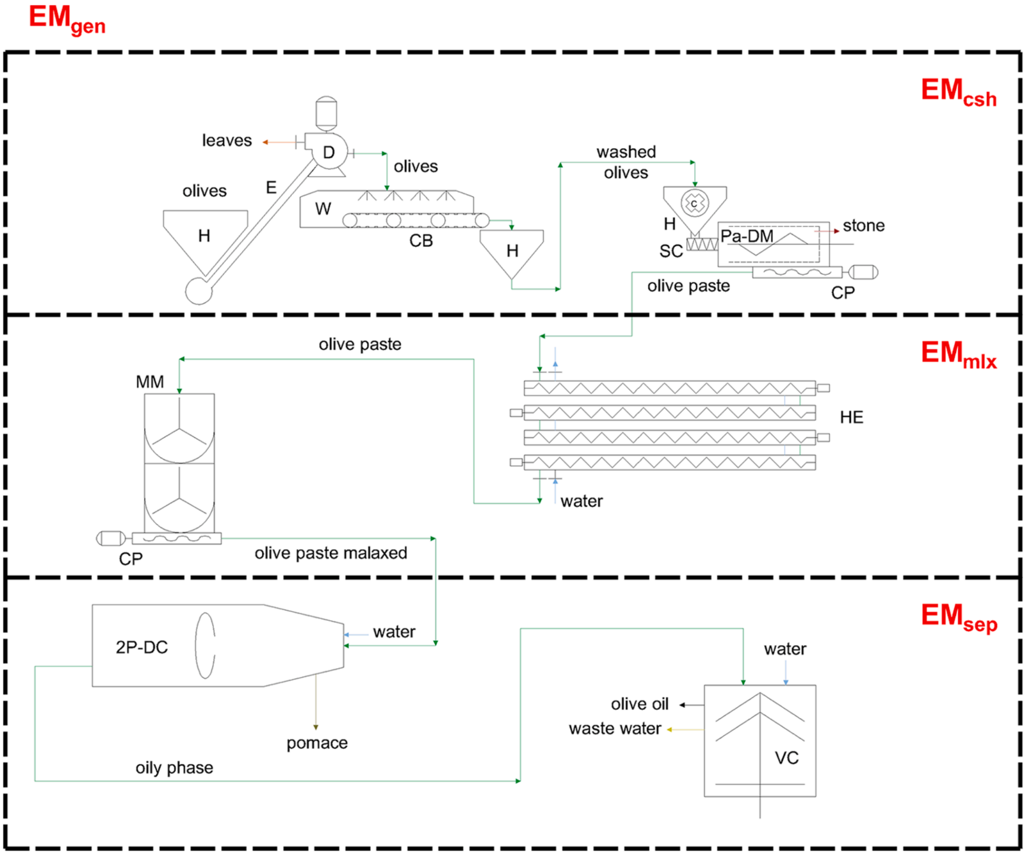

Fig. 2. Continuous processing line (Co-PL) with location of four energy meters (EM).

Overall Equipment Effectiveness (OEE) analysis

The standard for measurement of manufacturing productivity is a core quantitative metric called overall equipment effectiveness, or OEE [29], which accounts for the six main losses by grouping them into three areas of macro-loss: availability, performance and quality (Dal et al., 2000). OEE is thus defined as the product of equipment availability, process performance and product quality, per the following equation:

$$OEE = Availability\ (A)\ x\ Performance\ (P)\ x\ Quality\ (Q) \tag{2}$$

Availability: considers availability loss, including unplanned stops (equipment failure/breakdown losses) and planned stops (setup/adjustment losses).

$$Availability:\ A = \frac{planned\ production\ time - downtime}{planned\ production\ time} \tag{3}$$

Performance: considers performance loss, i.e. losses due to idling, minor stops and operation of the manufacturing process at less than maximum possible speed. The parameter was measured considering only the horizontal axis centrifuge, known as the decanter, which separates solids (pomace) from liquids (water and olive oil). The decanter is considered the fulcrum of an olive oil extraction plant, since it dictates the working times of all other component machines. The working flow rate of the decanter coincides with the working flow rate of the olive oil extraction plant.

$$Performance:\ P = \frac{total\ amount\ of\ olives\ processed}{actual\ production\ time \times theoretical\ mass\ flow\ processing\ rate} \tag{4}$$

Quality: considers the reduced quality occurring during the first stages of production from machine start up to stabilization, and from other production of olive oil not meeting the legal quality parameters previously described.

$$Quality:\ Q = \frac{total\ amount\ of\ olive\ oil - total\ amount\ of\ defective\ olive\ oil}{total\ amount\ of\ olive\ oil} \tag{5}$$

The observations were made for 30 consecutive working days.

In simpler terms, OEE may also be understood as the ratio of fully productive time (FPT) to planned production time (PPT), where PPT is the total production time scheduled for the asset, and FPT is planned production time less overall downtime. Table 1 summaries the world-class OEE goals as presented by Okpala et al. [30,31], as greater than: 90 % for Availability, 95 % for Performance, 99 % for Quality and 85 % for OEE. Such benchmark standards serve for evaluation of performance for manufacturing companies, and for continuous improvement in manufacturing systems. If the OEE of a manufacturing company is measured below these global references, then urgent measures are suggested for improvement of the policies, management and maintenance of the plant.

Table 1
World-Class OEE.

OEE factor	Value (%)
Availability	90
Performance	95
Quality	99
OEE	85

Energy analysis

To compare the energy efficiency of the two processing lines, the net energy (NE), energy productivity (EP), energy use efficiency (EUE), and specific energy (SE) were calculated as reported in [16,18,19], with adjustment of the defining equations so as to consider only the electric and thermal energy inputs and oil yields for each typical day of processing, given that the extraction season is on average only about three months per year:

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

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

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

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

The primary energy was calculated using the national energy efficiency for electricity (GSE) and the overall heat efficiency (including generation and distribution losses) for thermal energy.

Results and discussions

Quantitative and qualitative performance of the two processing lines

Table 2 reports the extractability for the four varieties of tested olives, as observed for the two different process lines.

It can be observed that the extractability varies depending on the variety processed, from a minimum of 83.41 % for the Arbosana variety using the Ba-PL line, to a maximum of 87.81 % for the Peranzana variety using the Co-PL line. For all four olive varieties, however, there are no significant differences in extractability ($p < 0.05$) between the two lines.

Moreover, for all four varieties, the choice between the two different processing lines had no significant effect on the values of the main legislated quality parameters for VOOs. The measurements (not shown here) on free acidity, peroxide value and UV spectrophotometric indices (K232, K270 and ΔK) showed no significant differences, and were well within the legal limits for extra virgin olive oil.

Table 2
Quantitative results and process parameters.

Cultivar	process Line	Extractability (E) (%)
Arbequina	Ba-PL Co-PL	84.32 ± 1.20 *a* 85.19 ± 1.16 *a*
Arbosana	Ba-PL Co-PL	83.41 ± 0.85 *a* 83.72 ± 0.94 *a*
Coratina	Ba-PL Co-PL	86.45 ± 1.60 *a* 87.22 ± 1.41 *a*
Peranzana	Ba-PL Co-PL	87.51 ± 1.10 *a* 87.81 ± 1.19 *a*

Different letters in columns for each variety denote significant statistical differences at $p < 0.05$.

Overall equipment effectiveness

Table 3 reports the measurements of the Availability, Performance and Quality parameters and the resulting calculation of OEE for the two processing lines operating on each olive variety.

In all tests, regardless of variety, the oil produced always met the legislated standards for quality parameters of extra virgin olive oil, and as reported in the above Table 2, there were no significant differences in extractability between the two processing lines. Therefore, in all tests the Quality parameter was attributed a value of 100 %. From the table, it can also be seen that in both plant configurations, there is no variation in performance in relation to the variety of processed olive. With all three varieties, in fact, there are no significant differences in Availability, Performance or OEE in the operation of the individual lines.

As explained in section 2.6, Performance is measured taking account of the actual operating time with respect to planned operating time, and the actual mass flow rate of the decanter with respect to its theoretical mass flow processing rate (3000 kg h^{-1}).

While for the Co-PL configuration the decanter was fed continuously, except for a negligible loss of time due to misunderstandings between plant operators, the management of olive batches on the Ba-PL line required discontinuous feeding of the decanter, resulting in substantial losses of operating time. Once the paste from one malaxer was pumped out of the decanter, the operator waited for the oil to completely drain before feeding in paste from the next malaxer, so as to prevent intermixing of the subsequent batch with any oil residue from the first one. These non-operational times for the decanter result as performance losses. Furthermore, not all olive batches amounted to the 700 kg of malaxer capacity, some even measuring less than 100 kg, meaning that some malaxers would then be filled below nominal capacity while all still operated at uniform total time. This resulted in further Performance losses.

Figs. 3 and 4 present the response surface plot of Performance vs Availability vs OEE are shown.

In both the batch and continuous configurations, as would be expected, the OEE value increases with increasing Availability and Performance of the plant. The OEE values, however, are much lower in the Ba-PL configuration compared to the Co-PL, for the former ranging over about 46–55 %, compared to about 85–97 % for the latter. The shape of the response surfaces therefore demonstrates the influence of the higher values of A and P parameters on OEE, for the continuous vs batch plant configuration.

Moreover, comparing the three metrics of OEE with the global reference values presented in Table 1, it is readily apparent that the values detected for Co-PL are all higher than reference, while for the Ba-PL plant the Performance values, and consequently OEE values, fall far below reference.

These analytical results clearly demonstrate that the system of parallel batch processing results in underutilisation of the plant, meaning unacceptable losses in productivity: the handling of the olive crop in batches requires long pauses in operation, but also reductions in operational speed (mass flow).

To avoid such ineffectiveness, the plant operators could direct crop to continuous processing, rather than batch processing. Such a strategy could be accomplished, without economic harm from mixing of olive crop batches, by measuring the oil content and humidity in input batches using rapid non-destructive systems and then uniting batches of similar value, for entry of the pooled batches in continuous processing. Giovenzana et al. [32], for example, illustrate the promising applicability of vis/NIR spectroscopy as a rapid method of predicting oil content at different points in the extraction process. Such predictive models could then be applied in an on-line system for monitoring and feed-forward control.

Another improvement strategy could be to automate the system of pumping the olive paste from malaxers to decanter, thereby reducing operator-dependant downtime in transition from one malaxer to

Table 3
OEE parameters.

		Ba-PL				Co-PL			
Cultivar	Day	A (%)	P (%)	Q (%)	OEE (%)	A (%)	P (%)	Q (%)	OEE (%)
Arbequina	1	96.7	54.3	100.0	52.5	96.3	98.3	100.0	94.7
Arbequina	2	96.2	54.6	100.0	52.5	96.5	98.6	100.0	95.1
Arbequina	3	96.1	55.5	100.0	53.3	96.7	99.2	100.0	95.9
Arbequina	4	95.1	55.2	100.0	52.5	96.7	100.0	100.0	96.7
Arbequina	5	92.3	56.1	100.0	51.8	96.1	99.1	100.0	95.2
Arbequina	6	90.2	53.5	100.0	48.3	91.2	99.7	100.0	90.9
Arbequina	7	96.7	52.6	100.0	50.9	90.2	99.6	100.0	89.8
Arbequina	8	95.5	54.7	100.0	52.2	95.7	98.2	100.0	94.0
Arbequina	9	94.3	54.3	100.0	51.2	93.1	97.5	100.0	90.8
Arbequina	10	93.7	53.5	100.0	50.1	90.2	97.2	100.0	87.7
		94.7 ± 2.1 a	**54.4 ± 1.0 a**	**100.0 ± 0.0 a**	**51.5 ± 1.5 a**	**94.3 ± 2.8 a**	**98.7 ± 0.9 a**	**100.0 ± 0.0 a**	**93.1 ± 2.1 a**
Arbosana	11	92.5	55.6	100.0	51.4	93.5	96.3	100.0	90.0
Arbosana	12	94.5	54.6	100.0	51.6	96.7	100.0	100.0	96.7
Arbosana	13	94.2	52.9	100.0	49.8	92.1	100.0	100.0	92.1
Arbosana	14	91.4	54.8	100.0	50.1	95.8	100.0	100.0	95.8
Arbosana	15	90.2	51.2	100.0	46.2	91.9	100.0	100.0	91.9
Arbosana	16	92.5	56.9	100.0	52.6	90.3	99.2	100.0	89.6
Arbosana	17	94.3	58.9	100.0	55.5	91.2	98.5	100.0	89.8
		92.8 ± 1.6 a	**55.0 ± 2.5 a**	**100.0 a**	**51.0 ± 2.9 a**	**93.1 ± 2.4 a**	**99.1 ± 1.4 a**	**100.0 ± 0.0 a**	**92.3 ± 2.9 a**
Coratina	18	94.3	54.1	100.0	51.0	92.7	97.6	100.0	90.5
Coratina	19	96.7	54.6	100.0	52.8	94.6	98.6	100.0	93.3
Coratina	20	90.7	58.3	100.0	52.9	95.6	100.0	100.0	95.6
Coratina	21	95.1	53.5	100.0	50.9	95.4	99.6	100.0	95.0
Coratina	22	94.3	53.9	100.0	50.8	93.5	98.5	100.0	92.1
Coratina	23	93.4	54.9	100.0	51.3	95.4	97.6	100.0	93.1
		94.1 ± 2.0 a	**54.9 ± 1.7 a**	**100.0 a**	**51.6 ± 1.0 a**	**94.5 ± 1.2 a**	**98.7 ± 1.0 a**	**100.0 ± 0.0 a**	**93.3 ± 1.9 a**
Peranzana	24	90.7	55.1	100.0	50.0	96.3	99.3	100.0	95.6
Peranzana	25	91.6	54.2	100.0	49.6	92.1	99.5	100.0	91.6
Peranzana	26	95.1	51.6	100.0	49.1	90.3	99.6	100.0	89.9
Peranzana	27	93.1	53.6	100.0	49.9	93.6	99.7	100.0	93.3
Peranzana	28	94.1	54.8	100.0	51.6	94.5	100.0	100.0	94.5
Peranzana	29	92.1	54.8	100.0	50.5	96.7	100.0	100.0	96.7
Peranzana	30	90.4	58.5	100.0	52.9	96.8	98.5	100.0	95.3
		92.4 ± 1.7 a	**54.7 ± 2.1 a**	**100.0 a**	**50.5 ± 1.3 a**	**94.3 ± 2.5 a**	**99.5 ± 0.5 a**	**100.0 ± 0.0 a**	**93.9 ± 2.4 a**

Different letters in columns denote significant statistical differences ($p < 0.05$), one-Way ANOVA including Tukey HSD.

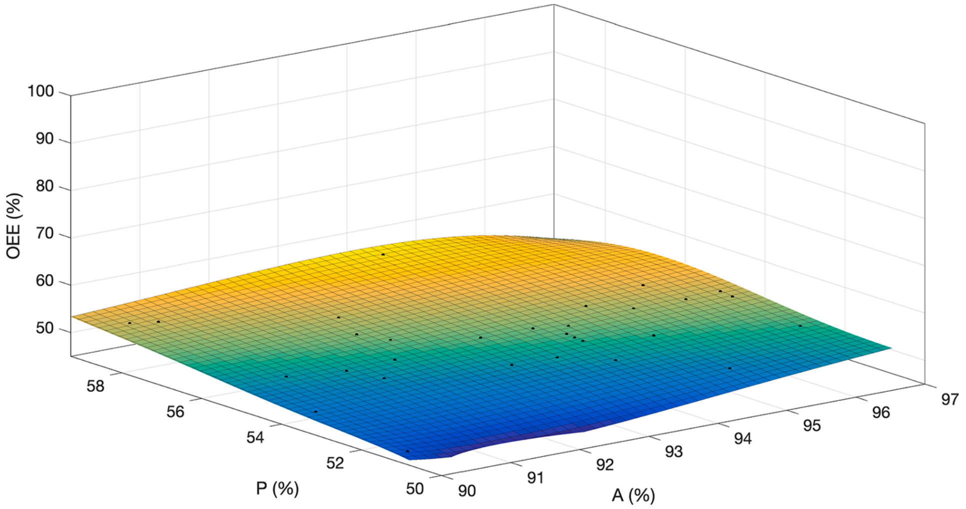

Fig. 3. Response surface, OEE vs Performance and Availability for the batch plant configuration (Ba-PL).

another.

Ultimately it may be desirable to join undersized crop batches, even of dissimilar qualities, thereby avoiding masses far below malaxer capacity and the detrimental low flow rates of the decanter. Alternatively, it could be necessary to operate the malaxers at reduced times on smaller batches, at intervals during the working day, accepting that this could have negative effects on the Quality parameter [33].

Electrical and thermal energy consumed

Within the energy data acquired over 30 days of processing, it could be observed that on both production lines, the consumption trends of the production phases repeated cyclically over the course each day. For this reason, only a five-hour portion of data acquisition is reported, as suitably representative of the consumption over the course of processing.

Fig. 5 shows, by way of example, the trend of power over five hours of Planned Production Time (PPT) for Ba-PL, corresponding to the

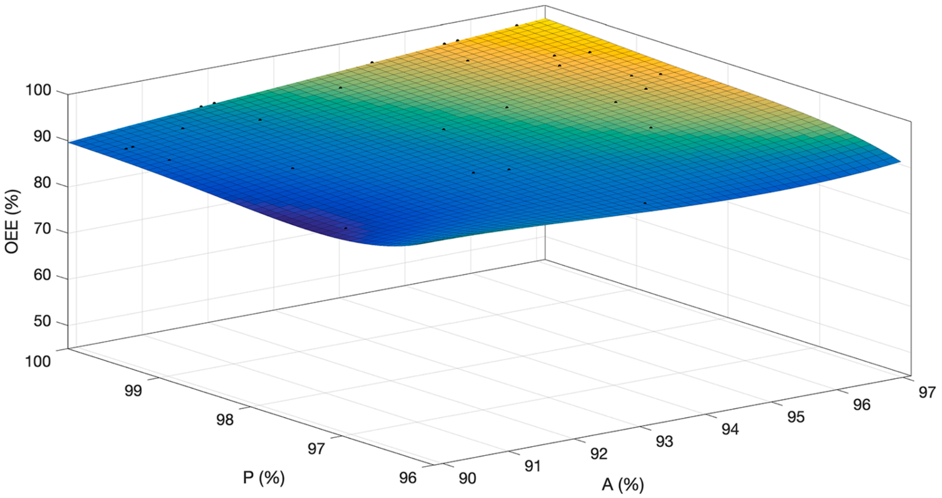

Fig. 4. Response surface, OEE vs Performance and Availability for the continuous plant configuration (Co-PL).

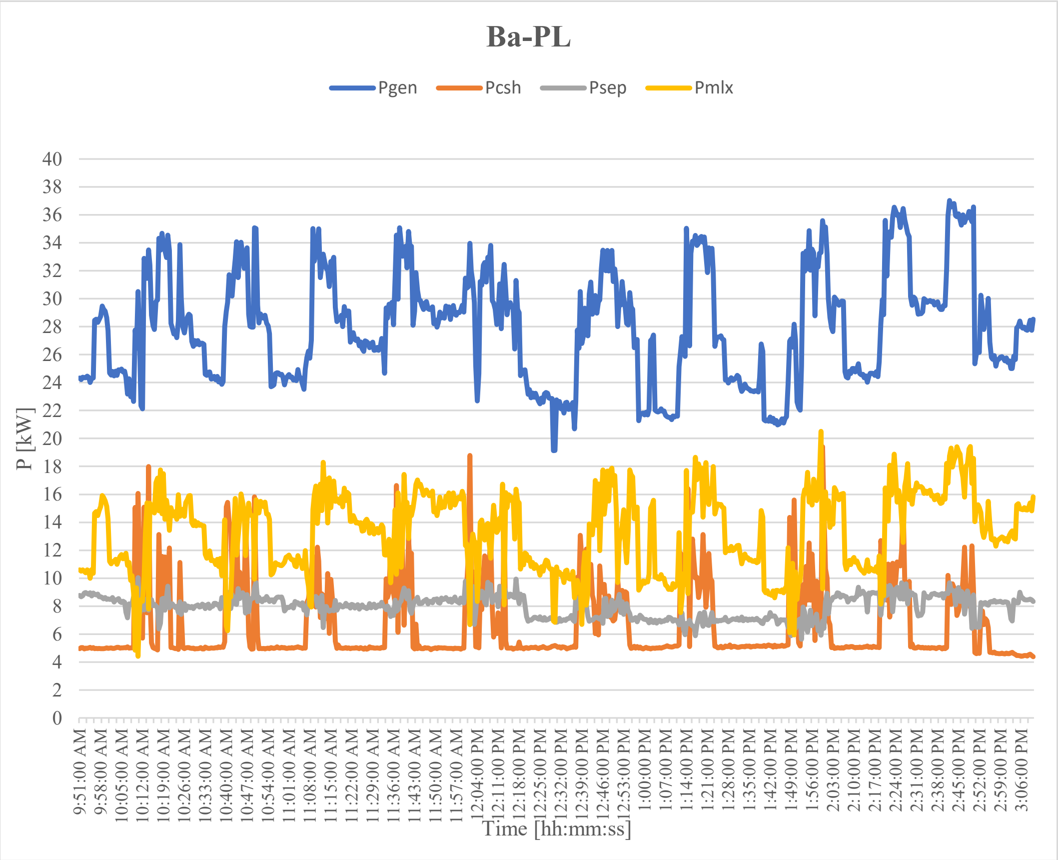

Fig. 5. Ba-PL power trend over 5 operating hours.

processing of 10 batches of olives of 700 kg, while Fig. 6 shows the cumulative energy consumed over an equal period of time and under the same conditions.

From Fig. 5, it can be seen that although the machines are in constant operation, the electric power alternately rises and falls in relation to the load on the plant. As a batch of olives is processed the power rises: the average electric power employed by the crushing machine (orange line) is 5.04 ± 0.37 kW when electric motor is working but the machine is not engaged in crushing; substantial oscillations in power consumption are then observed as olives enter into crushing, due to discontinuities in the feed of olives from the auger elevator. Fig. 6 instead permits assessment of total electrical consumption of the crusher over time (300 min): consumption for this machine amounts to 29.00 kWh, representing 19.6 % of total plant consumption for the given period. The fully productive working time (FPT) of the crusher, however, totalled only 103 min out of a planned time (PPT) of 300 min. The time lost (193 min) was due to discontinuous plant feeding as batches of olive crop arrived in the mill, and then following the washing step, the bottleneck of a sole hopper and conveyor belt leading to the crushing machines. The combination of these factors resulted in an average waiting time of 13 min between

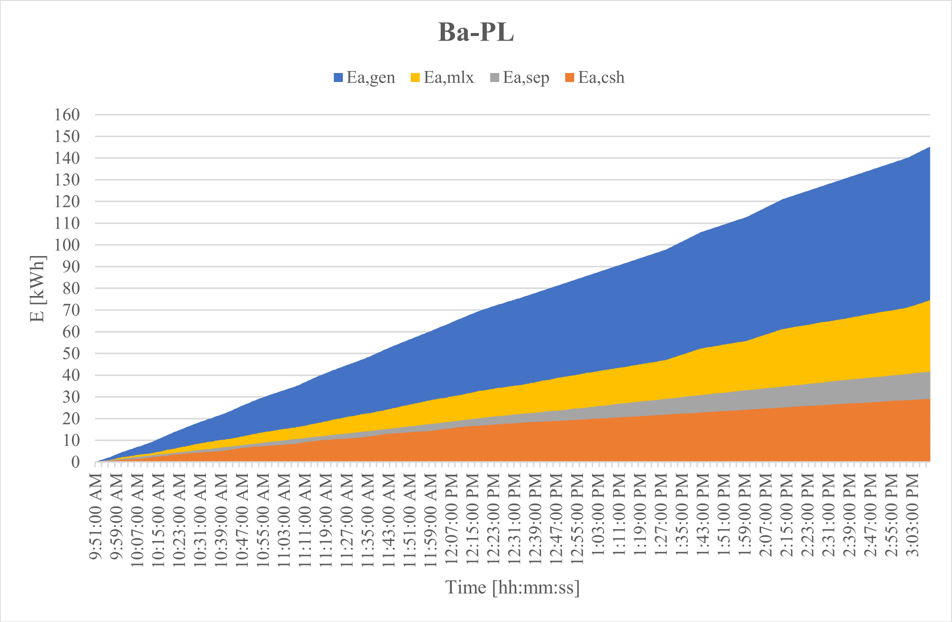

Fig. 6. Ba-PL energy trend over 5 operating hours.

crushing of consecutive batches.

The malaxers section, composed of five machines, shows an average energy consumption of 13.29 ± 2.84 kW, and a less fluctuating trend than that of the crusher, given the relatively constant operation of these machines: at any given time over the five hours (300 min, three of the five malaxers would be fully operational, while the other two were respectively engaged in loading and unloading. The total energy consumption of the malaxers section was 74.6 kWh, representing 51.34 % of total plant consumption over the period.

The separation phase, carried out by horizontal and vertical centrifuges in serial connection, shows an average energy consumption of 7.97 ± 0.80 kW, however with fluctuating value of P due to the discontinuity

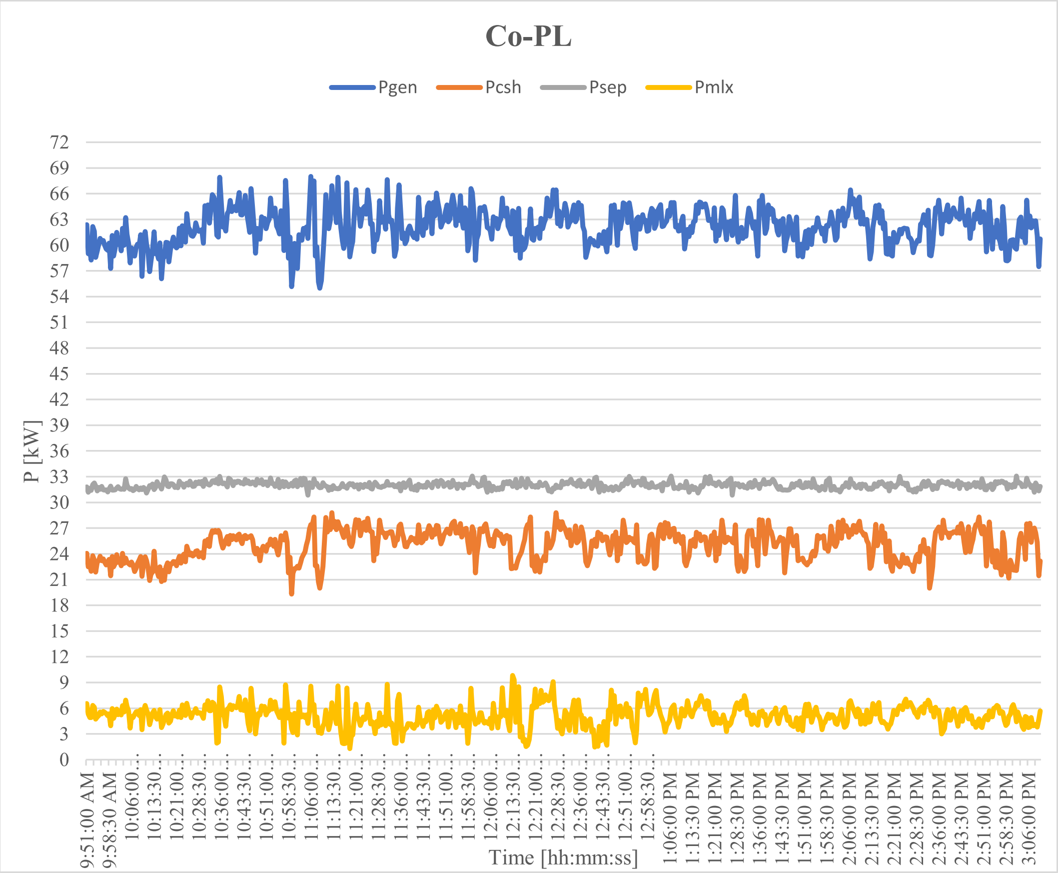

Fig. 7. Co-PL power trend over 5 operating hours.

of operation in batch processing. As noted, to avoid batch mixing, the operator withholds the feed of the next batch until the horizontal centrifuge is completely drained from the previous batch. The resulting waiting time is determined to be 13 min. The energy consumption recorded for the two centrifuges over the period is 41.7 kWh, representing 28.70 % of total plant consumption (Fig. 6).

Out of the total 300 min. PPT for the batch system, the *FPT* of the two centrifuges was recorded as 155 min. Given the mass flow rate of 3000 kg h^{-1} for the centrifuge series, the time necessary for processing a 700 kg batch averaged 14 min, followed by the average 13 min of wait time between batches. As with the crusher, the time losses encountered were also due to the discontinuity in feeding the entire system and the bottleneck of the single hopper and conveyor between washing machine and crusher.

In contrast to the discontinuous plant, the continuous plant showed almost constant trends in use of electrical power (Fig. 7), with only very slight variations, probably due to momentary fluctuations in the rate of olive supply to the overall system. As can be seen, for each machine, the trend in consumption of electrical power is clearly defined: the crusher draws average electrical power of 25.06 ± 0.68 kW, the malaxer 5.14 ± 1.30 kW, and the centrifugal separators 32.01 ± 0.39 kW. Overall power consumption is 62.21 ± 2.12 kW. Moreover, from Fig. 8, it is apparent that the trend in cumulative consumption is entirely constant over time, unlike the discontinuous process (Fig. 6). The explanations for this would include the absence of stops and starts of the electric motors, and so freedom from peak energy demands for restarting torque, and incidentally lesser stress on the motors.

The heat estimation considers the parameters reported in Table 4. In both lines, on average, the heat exchanger Q_{HE} provides heat sufficient to raise the olive paste temperature by 10 °C, estimated as follows:

$$Q_{HE} = \dot{m}_p c_{p_p} \Delta T_p \Delta t_{HE} \tag{10}$$

where $\dot{m}_p$ is the paste mass flow rate, c_{p_p} is the specific heat of the paste at constant pressure, ΔT_p is the temperature difference of the paste from inlet to outlet, and Δt_{HE} is the heat exchanger activation time. Calculation of total heat used in the production lines requires inclusion of the heat supplied to the malaxers by the service fluid, as follows:

$$Q_{mlx} = \dot{m}_w c_{p_w} \Delta T_w \Delta t_{mlx} \tag{11}$$

where $\dot{m}_w$ is the water mass flow rate, c_w is the specific heat of the water at constant pressure, ΔT_w is the temperature difference of the water from jacket inlet to outlet, and Δt_{mlx} is the water heating activation time.

Table 4
Thermal energy calculation for the two plant configurations.

	Ba-PL	*Co-PL*
Paste flow rate $\dot{m}_p$ (kg h^{-1})	3000.00	6000.00
Water flow rate $\dot{m}_w$ (kg s^{-1})	0.50	1.00
Paste specific heat capacity c_{p_p} (J kg^{-1}K^{-1})	3227.00	3227.00
Water specific heat capacity c_{p_w} (Jkg^{-1}K^{-1})	4186.00	4186.00
Paste temperature difference ΔT_p (°C)	10.00	10.00
Water temperature difference ΔT_w (°C)	3.00	3.00
Heat exchanger activation time Δt_{HE} (h/day)	6.00	12.00
Water heating activation time Δt_{mlx} (h/day)	8.00	3.00
Heat exchanger heat Q_{HE} (kWh/day)	161.35	645.40
Malaxers heat Q_{mlx} (kWh/day)	50.23	37.67
Total heat Q (kWh/day)	211.58	638.07

From Table 4, it can be observed that the heat exchanger supply in the Ba-PL line was 75 % less than the supply to the Co-PL line, since in the latter case the demand from operation is continuous (12 h operating day), and must serve double the mass flow rate. Contrarily, in the case of the malaxers, it is the heat exchanger supply to Co-PL line that is about 25 % less, due mainly to losses in the batch line as the malaxers stood cyclically empty. In these cases, the hot service fluid cannot be maintained in circulation in the jacket, but must be repeatedly heated for new batches, resulting in greater total heating times.

Table 5 reports the energy balance of the two plant configurations for a typical working day, limited to the input energy used exclusively for the machines of the two overall extraction processes. It can be seen that for the Ba-PL configuration the highest input is electric energy, requiring 1022.83 MJ/day, or 57.32 % of total input energy. In Co-PL, it is instead the heat requirement that dominates, at 2459.07 MJ day^{-1}, or 60.12 % of total. These dominant demands are completed, respectively, by the heat requirement in Ba-PL of 761.70 MJ day^{-1} (42.68 %), and electric energy demand in Co-PL of 1631.52 MJ day^{-1} (38.88 %). Overall, the total energy input in Ba-PL was then 1784.53 MJ day^{-1}, while in Co-PL it

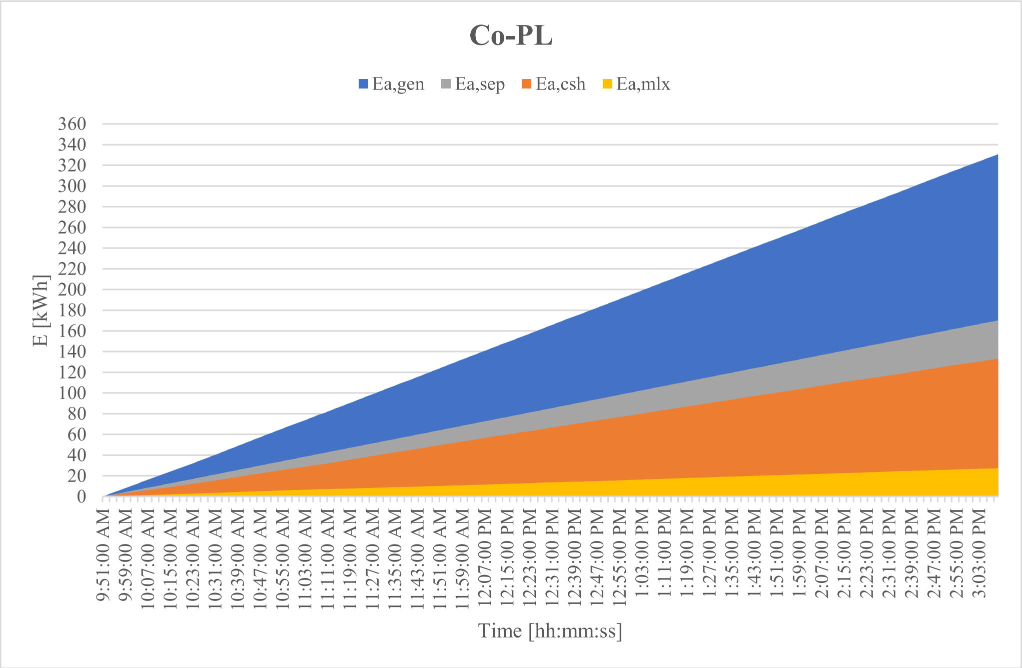

Fig. 8. Co-PL energy trend over 5 operating hours.

Table 5
Energy balance for the two plant configurations.

Input	*Unit*	*Energy equivalent ($MJ\ unit^{-1}$)*	*Ba-PL* *Input per day ($unit\ day^{-1}$)*	*Ba-PL* *Energy value (MJ/day)*	*Ba-PL* *Ratio (%)*	*Co-PL* *Input per day ($unit\ day^{-1}$)*	*Co-PL* *Energy value (MJ/day)*	*Co-PL* *Ratio (%)*
Electricity	kWh	3.6	284.12	1022.83	57.32	453.20	1631.52	39.88
Heat	kWh	3.6	211.58	761.70	42.68	683.07	2459.07	60.12
Total	–	–	495.70	1784.53	100.00	1136.27	4090.59	100.00
Output	*Unit*	*Energy equivalent ($MJ\ unit^{-1}$)*	*Input per day ($unit\ day^{-1}$)*	*Energy value (MJ/day)*	*Ratio (%)*	*Input per day ($unit\ day^{-1}$)*	*Energy value (MJ/day)*	*Ratio (%)*
Yield	kg	34.5	3060.00	105570.00	100.00	12240.00	422280.00	100.00
Total	–	–	3060.00	105570.00	100.00	12240.00	422280.00	100.00

was 4090.59 MJ day^{-1}, meaning about 56 % higher. On the other hand, the output of the Co-PL was estimated to be about 75 % higher, at respectively 12,240.00 kg vs 3060.00 kg of olive oil for the Ba-PL line.

Table 6 show the main energy indices serving to compare performance of the two plant configurations. Primary electrical energy input is calculated assuming the national energy efficiency of 0.46, as reported by the responsible sectoral agency, while primary thermal energy is calculated assuming efficiency of 0.77, considering the overall combination of both generation and distribution efficiency. The extraction yield of both plant configurations was estimated to be about 17 %, considering that the two lines both achieve equal overall efficiency.

The net energy (NE) of the continuous plant configuration was about 75 % higher than that of Ba-PL, which is consistent with the difference in magnitude for oil production from the two lines (Table 6). From the table, it can also be readily seen that for Co-PL, the energy content of the final product (34.5 MJ kg^{-1}) resulted in an energy output that was two orders of magnitude greater than input. Comparing the two configurations, the energy production (EP) in the Co-PL line (1.82 kg MJ^{-1}) was about twice that of Ba-PL (0.95 kg MJ^{-1}), while the specific energy for the Co-PL line was about half that of the other line (0.55 MJ kg^{-1} vs 1.05 MJ/kg). Finally, the energy use efficiency (EUE) was about 48 % higher in Co-PL (62.65 vs 32.86 for Ba-PL) confirming that the continuous extraction process achieves more effective use of energy inputs. As already mentioned, the shortcomings of the Ba-PL system consist mainly in the dead times of crushing and separation stages, since the machines continue to consume energy even when not engaged in processing.

EUE is an important parameter for evaluating the efficiency of realising a final product. Mandal et al. [14] found that the EUE for soybean-based crop production systems (excluding energy contained in by-products) was 2.03 for soybean–wheat systems, 2.13 for soybean–mustard, and 1.77 for soybean–chickpea. An analysis of the production process of sweet cherry in Turkey found an EUE of 1.23 [15]. AghaAlikhani et al. [16] assessed the EUE in rice production and found values equal to 1.72 for traditional systems and 1.63 for mechanised systems, while Mohammadi et al. [18] calculated an EUE of 1.25 for potato production. These studies on important food products give an idea of the relationship between the energy production versus expenditures, however these calculations of EUE consider all stages of the process, from field to final product. Comparing such results reported in the literature to those of the current study could be accomplished by reference to Cappelletti et al. [24], who studied the net energy of the production chain for virgin olive oil under different systems of cultivation and extraction. In this, they found that the extraction process counted for an average of about 6.2 % of NE for the entire supply chain. Extrapolating, the EUE of the batch and continuous production lines considered in the current study would be 2.04 and 3.88 respectively. A fundamental implication would be that EVOO, thanks to its high energy content, is a product that achieves efficiencies comparable and indeed superior to those of other important foods. This is true even with the less efficient batch plant configuration examined in the current study, but the efficiencies could truly be optimised for these processes by reducing downtimes of critical machines, thereby approaching the achievements of the continuous plant configuration.

Table 6
Energy indices for the two plant configurations.

Index	*Unit*	*Ba-PL*	*Co-PL*
Extraction Yield	%	17	17
$E_{in,el}$	MJ/day	2223.55	3546.78
$E_{in,th}$	MJ/day	989.21	3193.59
E_{in}	MJ/day	3212.76	6740.38
E_{out}	MJ/day	105570.00	422280.00
NE	MJ/day	102357.24	415539.62
EP	$Kg_{oil}\ (MJ)^{-1}$	0.95	1.82
SE	$MJ\ (Kg_{oil})^{-1}$	1.05	0.55
EUE	–	32.86	62.65

Conclusions

The production of olives by small and medium-sized growers is still widespread in the Mediterranean basin. For this reason, batch processing through parallel installations of malaxers is common, although continuous processing for large quantities through malaxers arranged in series is becoming more popular. The current study has examined and compared the energy requirements of the two different processes of batch (Ba-PL) and continuous (Co-PL) extraction operating in the same olive mill. Energy meters were installed on the general switch and on each the main sections (crushing, malaxing, separation) of the two production lines, for recording of both power and energy consumed. Measurements were also made of the heat supplied by a biomass boiler for the preheating and kneading of the olive paste. Based on the data collected, it was then possible to calculate the Overall Equipment Effectiveness (OEE) of each plant configuration, and gain useful indications for improved management strategies in regards to energy consumption.

The main results from the analysis of this specific mill are that:

- Ba-PL production is subject to great discontinuities, due mainly to the bottleneck of a single hopper and conveyor between the washing and crushing sections;
- In Ba-Pl, the centrifugal separation stage also results in dead times, since to avoid mixing, management practice has been to completely drain the decanter following each batch, before introduction of the next one.
- The discontinuities in the Ba-PL process result in a value of Performance (P) parameter that is sharply lower (44.7 %) than what is observed in Co-PL.

Given these data, the Overall Equipment Effectiveness (OEE) analysis revealed values of 93.1 % for the Co-PL configuration, versus 51.2 % for Ba-PL. Neither the Performance nor OEE values for Ba-PL reached the world benchmarks, recognised as 95 % for P and 85 % for OEE.

The discontinuity of the Ba-PL resulted in poor management of energy resources compared to Co-PL. Energy input and output for Ba-PL were calculated as 3212.76 MJ day^{-1} and 105,570.00 MJ day^{-1}, respectively, meaning that Net Energy (NE) was 102,357.24 MJ day^{-1}, with a Specific Energy (SP) of 1.05 MJ $(kg_{oil})^{-1}$, and finally Energy Use Efficiency (EUE) of 32.86. On the other hand, the calculations for the continuous extraction process revealed energy inputs of 6740.38 MJ day^{-1} but output reaching 422,280.00 MJ day^{-1}, with an NE of 415,539.62 MJ day^{-1} and SE of 0.55 MJ $(kg_{oil})^{-1}$. From this, the EUE value of the continuous plant configuration reached 62.65, or double that of the 32.86 value obtained using the batch configuration.

These research results reveal the strong need of strategies for improving the energy efficiency of batch processing lines in olive oil production. Some solutions would be:

- Measure the oil content and humidity of incoming crop batches using rapid non-destructive measuring systems, such as vis/NIR spectroscopy, so as to document the real economic value of each batch, thus enabling the combination of batches for feed into continuous processing.
- In the case of parallel malaxers, automate the system for transitioning from one to another during pumping of the olive paste into the decanter, so as to reduce downtime in this stage.
- Even in the case of varying qualities of undersized batches, join these for complete filling of the malaxers and operation at full capacity flow rate of the decanter.

Further studies would be necessary to measure the improvements in energy efficiency achieved by implementation of the above strategies.

CRediT authorship contribution statement

Claudio Perone: Data curation, Investigation, Writing – original draft, Writing – review & editing. **Roberto Romaniello:** Conceptualization, Methodology, Data curation, Software. **Alessandro Leone:** Conceptualization, Methodology, Supervision. **Antonio Berardi:** Visualization, Investigation, Validation, Writing – review & editing. **Antonia Tamborrino:** Conceptualization, Methodology, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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