

An overview of emerging techniques in virgin olive oil extraction process: strategies in the development of innovative plants

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Abstract

Currently the systems for mechanically extracting virgin oils from olives are basically of two types: discontinuous-type systems (obsolete and dying out) and continuous-type systems. Systems defined as “continuous-type” are generally comprised of a mechanical crusher, a malaxer and a horizontal-axis centrifugal separator (decanter). The “continuous” appellation refers to the fact that two (mechanical crusher and decanter) out of the three machines making up the system operate continuously; the malaxer, which actually is a machine working in batches, is located between these two continuous apparatuses. Consequently the malaxation represents the bottleneck of the continuous extraction process. The entire virgin olive oil (VOO) process has changed very little over the last 20 years. One of the essential challenges of VOO industrial plant manufacturing sector is to design and build advanced machines in order to transform the discontinuous malaxing step in a continuous phase and improve the working capacity of the industrial plants. In recent years, rapid progress in the application of emerging technologies in food processing has been made, also in VOO extraction process. Ultrasounds (US), microwaves (MW), and pulsed electric fields (PEF) are emerging technologies that have already found application in the VOO extraction process on pilot scale plants. This paper aims to describe the basic principles of these technologies as well as the results concerning their impact on VOO yields

and quality. Current and potential applications will be discussed, taking into account the relationship between the processing, the olive paste behavior and the characteristics of the resultant VOO, as well as recent advances in the process development.

Introduction

All operations required in the oil extraction process take aim at to obtaining the highest quality of oil from fruits. Crushing and malaxation are the most important critical points of the oil mechanical extraction process (Amirante *et al.*, 2010a; Clodoveo, 2012; Amirante *et al.*, 2010b; Parenti *et al.*, 2006; Masella *et al.*, 2011; Parenti *et al.*, 2008). Malaxation can largely affect the oil yields and also the healthy properties of virgin olive oil (VOO) (Clodoveo, 2012). In the olive fruit, only the 80% of oil can be easily extracted because it is located in the vacuoles of olive pulp cells, the rest can be found dispersed in the cytoplasm as microgels and thus, is difficult to extract (Aguilera *et al.*, 2010). The effect of traditional malaxing is to disrupt the interfacial films in the olive paste modifying the dispersion degree of oil droplets and promoting the coalescence phenomena, but it requires a long mixing time. Actually, considering the yield as the main economical parameter, oil millers tend to increase malaxing time or temperature with detrimental effect on VOO quality (Clodoveo, 2012). So, it is important to find an innovative technology able to enhance the extraction yields, reducing the process time and preserving the VOO quality.

The VOO plant manufacturers are interested to the searching for new alternative extraction processes able to increase the yield reducing the producing cost of the resulting product (Di Renzo & Colelli, 1997). They have to respond to the changed market needs by offering highly efficient plants for supporting and increasing income of olive millers restricting the plant investment (with a minor number of malaxer) and reducing the working time optimizing the plant working capacity. In order to reach these goals, emerging technologies, such as PEF, US and MW can be employed. This review aims to describe the basic principles of these technologies as well as the state of the art concerning their applications in VOO extraction process. Future trends and potential applications will be discussed, focusing on the relationship between the raw and in-process materials, the processing techniques and the final product quality, as well as recent advances in the process development.

Traditional voo extraction systems

As is well known, currently the systems for mechanically extracting virgin oils from olives are basically of two types: discontinuous-type systems and continuous-type systems. Discontinuous-type systems, generally comprised of a millstone combined with hydraulic presses, generally have a low working capacity and unavoidably require a high amount of labour (Amirante *et al.*, 2010 a). For these reasons they are deemed obso-

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lete and are dying out, superseded by continuous-type systems. The systems defined of continuous type generally are constituted by a mechanical crusher, a malaxer and a horizontal-axis centrifugal separator (decanter). The designation "continuous" relates to the fact that two of the three machines composing the system operate continuously (crusher and decanter), the malaxer, which actually is a machine operating in batches, is placed between these two continuous apparatuses (Clodoveo, 2012). Traditionally, the malaxation phase consists in slow mixing (12-18 revolutions per minute) the olive paste at 27-32°C for a period of time comprised between 30 and 60 minutes depending upon the features of the raw material. The malaxation purpose is to promote the coalescence of the tiny oil drops in drops with greater sizes which can be separated more easily in a centrifugal field on one hand, to reduce the olive paste viscosity value so as to optimize the phase separation inside the decanter (oil/vegetable water / pomace) on the other hand. The malaxation phase actually represents the "bottleneck" of the continuous extraction process. Currently the system used to guarantee continuity to the process, without interrupting the activity of the machines upstream and downstream of the malaxer, consists in placing several malaxing machines in parallel (Figure 1), with the burden of a heavy investment in plant engineering (Amirante *et al.*, 2011). The oil mills which are not equipped with several malaxers actually operate in a discontinuous way and they do not fully exploit the work capacity of crusher and decanter. One of the critical factors determining so long malaxation time is constituted by the period necessary so that the just crushed olive paste reaches the process temperature (27-32°C) (Clodoveo, 2013a). Such period on the average lasts at least one third of the total malaxation time. The malaxer usually is a semi-cylindrical tank equipped with a rotating arms shaft and stainless steel blades. The walls of the malaxing tank are hollowed so that warm water flows through the jacket heating the olive paste (Clodoveo, 2012). The malaxer is a heat exchanger characterized by a low overall heat transfer coefficient because the ratio (r) of surface area (S) to volume (V) is disadvantageous ($r = S/V$), so it is important to find an innovative technology able to improve heat-exchange (Amirante *et al.*, 2006). In this sense, pulsed electric field (PEF), power ultrasound (US) and microwave (MV) are considered to be emerging and promising technologies for VOO industry.

Principles and mechanism of PEF

PEF treatment involves the application of short pulses of high voltage in order to disrupt biological cells in the food material. The concept was established and reported for the first time more than 50 years ago (Toepfl *et al.*, 2006). However, besides some sporadic industrial applications conducted in the following decades it was just recently, that the technology was introduced at an increasing number as large scale commercial application. Depending on the treatment intensity (electric field strength, number and duration of the electric pulses) and cell properties (size, shape, orientation, conductivity) the pore formation may be permanent or temporary (Zimmermann *et al.*, 1974; Zimmermann *et al.*, 1976; Angersbach *et al.*, 2000). The treatment consists of the application of very short electric pulses (1 – 100 s) at electric field intensities in the range of 0.1 – 1 kV/cm (reversible permeabilization for stress induction in plant cells), 0.5 – 3 kV/cm (irreversible permeabilization of plant and animal tissue) and 15 – 40 kV/cm for the irreversible permeabilization of microbial cells. The aforementioned field intensities lead to the formation of a critical transmembrane potential, which is regarded to be the precondition for cell membrane breakdown and electroporation (Tsong, 1990) (Figure 2). The irreversible electroporation results in a loss of turgor, the leakage of cytoplasmic content and lysis (Rubinsky, 2010). Reversible permeabiliza-

tion leads to the formation of conductive channels across the cell membrane but electrically insulating properties will recover within seconds (Angersbach *et al.*, 2000).

PEF mechanical effect

Cell membrane acts as a physical barrier in removing the intracellular substances (water, oil, and antioxidants) from plant tissues in solid-liquid extraction (Puértolas *et al.*, 2012).

The disintegration or permeabilization of the cell membrane in a plant food tissue can allow the release of intracellular water, oil and solutes (secondary metabolites) to migrate in an external medium (Ade-Omowaye *et al.*, 2001). Application of PEF of high intensity, due to its mechanical effect, can cause temporary or permanent rupture of cell membranes (Barbosa-Cánovas *et al.*, 1999). An irreversible perforation of the cell membrane reduces its barrier effect and, applied to fruit and vegetable cells, mass transfer processes like pressing or extraction are more effective (Jaeger *et al.*, 2009). Its ability to permeabilize cellular tissue in a short time can be utilized to replace energy- and time-consuming conventional thermal or mechanical techniques (Toepfl *et al.*, 2001).

PEF thermal effect

Although the PEF treatment is defined as a non-thermal food processing technology, there is a significant temperature increase during high intensity PEF treatment due to Joule heating (Sastry & Barach, 2000). Many authors have described the temperature distribution in a PEF treatment chamber and reported the occurrence of high local temperatures due to inhomogeneous field distribution of the electrical



Figure 1. VOO extraction plant equipped with plural malaxing machines in parallel (Photography courtesy Alfa Laval Olive Oil S.p.A.).

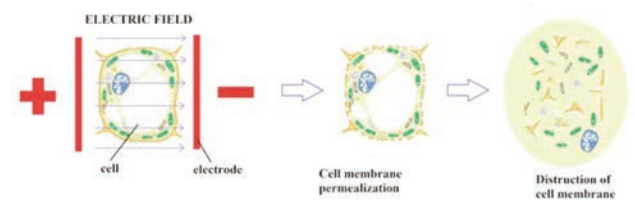


Figure 2. When external applied electric field reaches to the threshold values of the cell membrane, then cell membrane can permeabilize to deliver cytoplasmic content. Applying an intense electric field, which exceeds certain critical value, irreversible electroporation can occur resulting cell membrane rupture.

field, limited flow velocity and recirculation of the liquid (Fiala *et al.*, 2001; Lindgren *et al.*, 2002; van den Bosch *et al.*, 2002; Gerlach *et al.*, 2008; Jaeger *et al.*, 2009). The increase in product temperature dependent on the energy input (Toepfl, *et al.*, 2003) in comparison to conventional thermal processing is quite low (from 30 to 80°C) and in general do not affect the functional and nutritional value (e.g. vitamin content) of the food in contrast to traditional heating methods (Olsen *et al.*, 2010). Traditional heating methods always include a temperature gradient, which causes areas of high temperature at the surface resulting in an overtreatment. Using PEF, the applied energy causes a temperature increase, which is a volumetric heating. The PEF process can be used for liquids, also containing particles. Field strength of about 20 kV/cm, depending on the product, and 3.000 to 6.000, very short pulses (microseconds), results in a slight increase of temperature and a decrease of processing time.

Applications of PEF technology in VOO extraction process

PEF has been already used in food processing for sterilization and preservation and has been shown to increase yields in the extraction of fruit juices, such as from oranges (Rivas *et al.*, 2006). Recent research reveals its potential for making olive oil (Figure 3).

Abenoza *et al.* in 2012 studied the effect of the application of PEF treatments of different intensities (0–2 kV/cm) on Arbequina olive paste in reference to olive oil extraction at different malaxation times (0, 15, and 30 min) and temperatures (15 and 26 °C). They observed that when the olive paste was treated with PEF (2 kV/cm) without malaxation the extraction yield improved by 54 %. At 15 °C, a PEF treatment of 2 kV/cm improved the extraction yield by 14.1 %, which corresponded with an enhancement of 1.7 kg of oil per 100 kg of olive fruits. So, they suggested the application of a PEF treatment could permit reduction of the malaxation temperature from 26 to 15°C without impairing the extraction yield. These data confirm that Therefore, the treatment of the olive paste with PEF has the potential to induce cell disintegration and to facilitate the release of the small oil droplets. The facilitated release of oil from the cell provides the potential to perform the malaxation at lower temperature with beneficial effects on the oil quality (Kalua *et al.*, 2007): regard to the parameters legally established (acidity, peroxide value, K232, and K270), VOO were not affected by the PEF treatments like the sensory analysis. Moreover, PEF also has potential to increase VOO phytonutrient content and to improve consumer health benefits and olive oil shelf life. PEF treatment also provides energy and time savings – compared to thermal or enzyme treatment – and improving oil quality. These preliminary results stimulated the scaling up of this technology and a commercial product was developed (Figure 4).

PEF equipment

The PEF process is based on pulsed electrical currents delivered to a product placed between a set of electrodes. The electric field may be applied in the form of exponentially decaying, square wave, bipolar, or oscillatory pulses and at ambient, sub-ambient, or slightly above-ambient temperature. The high intensity PEF processing system is a simple electrical system (Figure 4). Generation of pulsed electric fields requires a fast discharge of electrical energy within a short period of time. This is accomplished by the pulse-forming network, an electrical circuit consisting of one or more power supplies with the ability to charge voltages (up to 60 kV), switches (ignitron, thyatron, tetrode, spark gap, semiconductors), capacitors (0.1-10 F), inductors (30 H), resistors (2 Ω – 10 MΩ), and treatment chambers (Gongora-Nieto *et al.*, 2002). A PEF treatment chamber can consist of at least two electrodes and insulation zone, where the foods receive pulses. The electrodes are made of inert materials, such as titanium (Figure 5).



Figure 3. Setup for a pilot plant to study the PEF assisted VOO extraction process. A) pulse generator; B) Crusher feed hopper and screw; C) Crusher; D) PEF treatment chamber; E) malaxer; F) decanter.

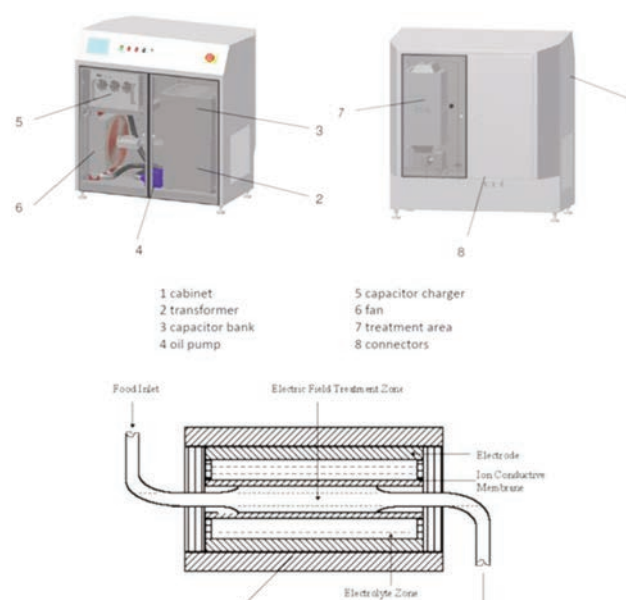


Figure 4 PEF industrial device available for VOO extraction process (Image courtesy Diversified Technologies, Inc.)

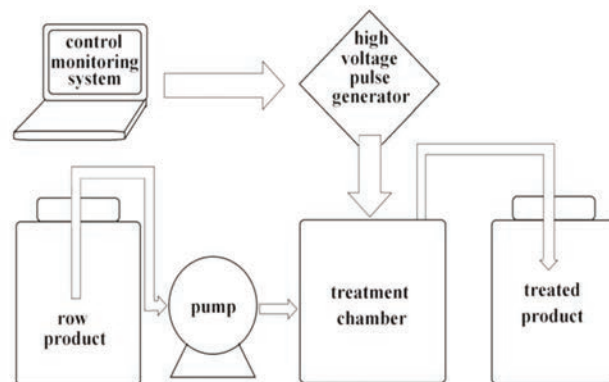


Figure 5. Flow chart of a PEF food processing system with basic components.

Economic aspects of PEF technology

PEF equipment uses ordinary electricity. The facility meets electrical safety standards and no harmful environmental by-products are produced (Ramaswamy *et al.*, 2005). PEF is an energy efficient process compared to thermal processes (Vega-Mercado *et al.*, 1997). A commercial-scale PEF system can process between 1,000 and 5,000 liters of liquid foods per hour and this technology is easy scalable (Sampedro & Zhang, 2012). Generation of high voltage pulses having sufficient peak power (typically megawatts) is the limitation in processing large quantities of fluid economically (Gaudreau *et al.*, 1998). The emergence of solid-state pulsed power systems, which can be arbitrarily sized by combining switch modules in series and parallel, removes this limitation (Gaudreau *et al.*, 2001).

Principles and mechanism of us

US are a form of energy generated by sound waves of frequencies above 16 kHz (Jayasooriya *et al.*, 2004). Two main mechanisms of US could be useful to optimize the VOO extraction process: the mechanical and the thermal effects (Clodoveo, 2012). Mechanical action is due to the cavitation phenomena (Luque Garcia & Luque de Castro, 2003) which disrupt the biological cell walls (Cravotto, *et al.*, 2008). Heating occurs as the ultrasonic energy is absorbed in a medium (Jayasooriya *et al.*, 2004; Zheng & Sun, 2006).

US mechanical effect

During the sonication process, longitudinal waves are created when a sonic wave meets a liquid medium, thereby creating regions of alternating compression and expansion (Piyasena *et al.*, 2003) (Figure 6).

These regions of pressure change cause the phenomena of cavitation (Bove *et al.*, 1969). Cavitation can be defined as the formation, growth and subsequent collapse of vapor and/or gas-vapor filled bubbles in the liquid (Zhou *et al.*, 2009). The energy which the cavity gains during its growth over terms of microseconds is released during its subsequent implosive collapse in a time-duration of few microseconds. The implosion of cavitation bubbles generates macro-turbulence, high-velocity inter-particle collisions and perturbation in micro-porous particles of the biomass which accelerates the diffusion of cellular content (Vilkhu *et al.*, 2011). Moreover, the cavitation near the liquid–solid interface sends a fast moving stream of liquid through the cavity at the surface. Cavitation on the product surface causes impingement by micro-jets that result in surface peeling, erosion and particle breakdown. This effect provides exposure of new surfaces further increasing mass transfer (Vilkhu *et al.*, 2008).

US thermal effect

The thermal effect occurs as kinetic energy from the ultrasound waves is absorbed by a medium (Wu & Nyborg, 2008). Ultrasound kinetic energy when absorbed by tissues can also be converted into heat (Nussbaum, 1997). This phenomena is called attenuation. Whenever ultrasonic energy is propagated into an attenuating material, such as a vegetal tissue, the amplitude of the wave decreases with distance (Ma *et al.*, 2008). This attenuation is due to either absorption or scattering. Absorption is a mechanism that represents that portion of ultrasonic wave that is converted into heat, and scattering can be thought of as that portion of the wave, which changes direction (O'Brien Jr, 2007). Because the medium can absorb energy to produce heat, a temperature rise may occur as long as the rate of heat production is greater than the rate of heat removal. Attenuation increases if frequency increases (Gammell *et al.*, 1979).

Applications of US technology in VOO extraction process

One of the latest challenges for the VOO industrial plant manufacturing sector is the conversion of the traditional malaxing batch process into a continuous operation (Clodoveo, 2012). The first step towards the continuous process consists in reducing the duration of malaxation. In order to reduce the malaxing time enhancing the quality of the product, Clodoveo *et al.* (2013a & b) tested an ultrasound assisted VOO extraction processes against the traditional method (Figure 7).

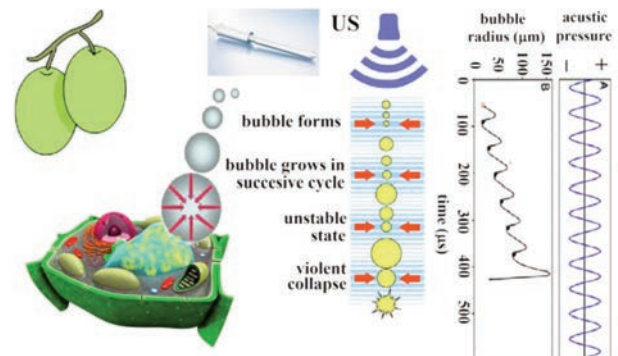


Figure 6. Cavitation phenomena.

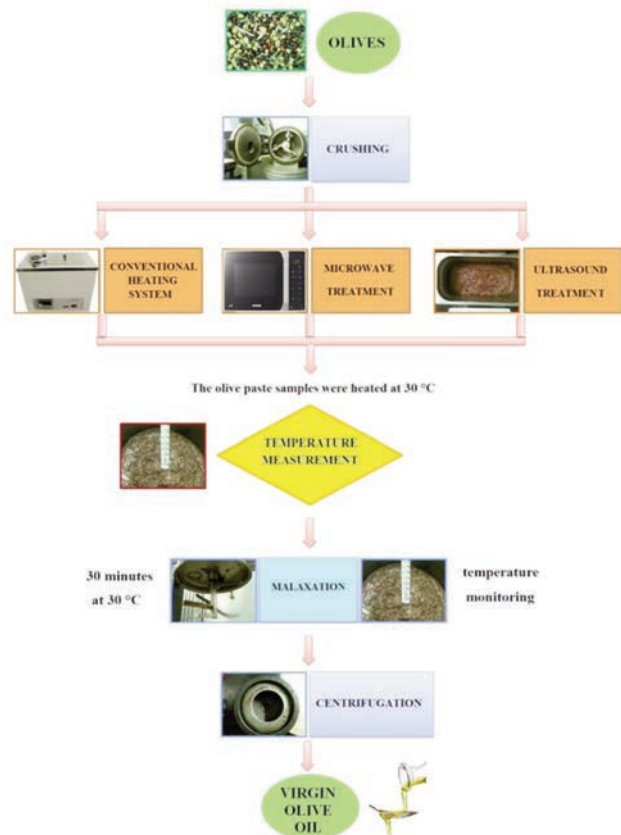


Figure 7. The flow chart of the method used to evaluate the thermal effect of US and MW on olive paste and its influence on the length of malaxation in a pilot scale plant.

The sonication treatment was applied on olive paste after the crushing. As mentioned, the malaxing phase can theoretically be divided into two different stages. The first stage is definable as “pre-heating”, i.e. the time required to the olive paste to achieve the process temperature (30 °C). The second stage is definable as the “effective malaxation”. The duration of the pre-heating stage is about 50% of the total process time and is also influenced by the room temperature (the oil mill temperature depends on whether condition and is about 10–20°C during the olive harvesting season, from September to January). In this experimental plan (Figure 7), malaxation time was established as a function of two factors: a) the time required to reach 30°C (pre-heating) b) the fixed time of 30 min needed to complete the oil coalescence. When the US treatment to the olive paste (cv. Coratina) was applied instead of the conventional heating system (Clodoveo *et al.*, 2013 b & c), a quick heating of the product occurs. Applying the conventional heating method of the olive paste, the length of the pre-heating stage was about 45% of the total process time (Figure 8A), taking 25 minutes to carry the olive paste up 30°C before the “effective malaxation” stage. Applying the US treatment (35 kHz – 150 W) on the olive paste (2.5 kg) the pre-heating length was about 10 minutes (Figure 8B), corresponding to a 60% reduction in respect to the conventional system.

Parameters legally established (acidity, peroxide value, K_{232} , and K_{270}) to measure the level of quality of the virgin olive oil were not affected by the US treatments.

A sensory analysis revealed that the application of a US treatment did not generate any bad flavor or taste in the oil. The ultrasound technique improved antioxidant content in VVOs, and in Coratina VVO improved its taste by reducing the bitter and pungent notes, which are not always accepted by consumers. Ultrasound treatment of olive paste before malaxation increases the process efficiency by reducing the malaxation step, so it represents a useful strategy to reduce the number of malaxers thus reducing the plant costs. Moreover, US treatment significantly improves the extractability of “Coratina” VVO (Clodoveo 2013 a). These results are in agreement with a previous study made by Jiménez *et al.* (2007). In the considered experimental conditions, at pilot plant scale, the average increase of extracted VVO after sonication treatment was about 8 g/kg of olives. In an industrial full scale plant with a 2000 kg of olives/h working capacity, if the plant works 8 h/day, with an average extraction yield of 16%, it produces about 2500 kg of VVO per day. Employing the ultrasound technology for 10 min (ultrasonic frequency – 35 kHz; effective ultrasonic power – 150 W), assuming at least an increase of about 5 g of extracted VVO per kilogram of olives, the quantity of extracted VVO per day could increase of about 80 kg with an increment of 3% of the total VVO production. Moreover, this calculation does not take into account that the ultrasound treatment determines a 70% reduction of the duration of the pre-heating ; this could also contribute to increase the quantity of extracted VVO per day because of the higher working capacity of the innovative plant in comparison with the traditional system. Other results obtained excluding the malaxation are even more interesting: at laboratory scale, Clodoveo *et al.* (2013 c) observed that when the VVOs were extracted without malaxing, the extraction yield of untreated sample was 1.0 % (± 0.1), while US treatment of olive paste produced a significant increase in extraction yields equal to 5.4 % (± 0.3). The results, obtained without malaxation in the laboratory procedure, open up new prospects for developing innovative continuous extraction system to overcome the actual obsolete malaxing batch technology. Moreover, reducing the length of the pre-heating malaxation stage could present energy savings for the olive oil extraction industry.

US equipment

In order to develop an industrial ultrasonic plant feasible for VVO

extraction plant (Clodoveo 2013 a) (Figure 9) it is possible retrofitting the existing devices collocating a rod-style piezoelectric transducer into the malaxer with the aim to sonicate the olive paste. Moreover, as an alternative, a new device, an ultrasonic reactor, placeable between the crusher and the malaxer can be developed. An ultrasonic reactor consists of a holding tank and an ultrasonic sonotrode.

After the crushing, olive paste can fall into the closed ultrasonic reactor, and at the end of sonication treatment, a pump can be used to move the sonicated and preheated olive paste into the malaxer.

In order to reduce the duration of sonication treatment it is also possible to combine a heat exchanger with the ultrasonic reactor (Amirante *et al.*, 2006).

Economic aspects of US technology

Ultrasonic processing is a technology with good payback on capital investment (Ashokkumar *et al.*, 2009). Significant improvements process enhancement and cost reduction are achievable on a commercial scale (Patist & Bates, 2011). The efficiency of ultrasonic generators and transducers has been improved: current systems have an energy efficiency around 85% which simply means that most of the power sent to the transducer is transferred into the medium. The transducers are easily installed into an existing facility. The amount of energy required per liter material treated (often defined as kWh/L) is comparable to any other unit operation in the industry and the maintenance cost are low. The payback (defined here as investment cost over the benefit) is in general less than 1 year (Patist & Bates, 2008).

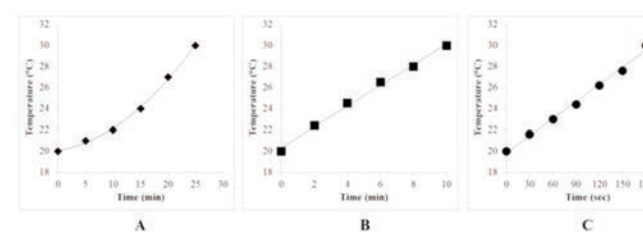


Figure 8. Influence of the olive paste heating system on the duration of the pre-heating stage: conventional heating method (A), US treatment(B) MW treatment(C).

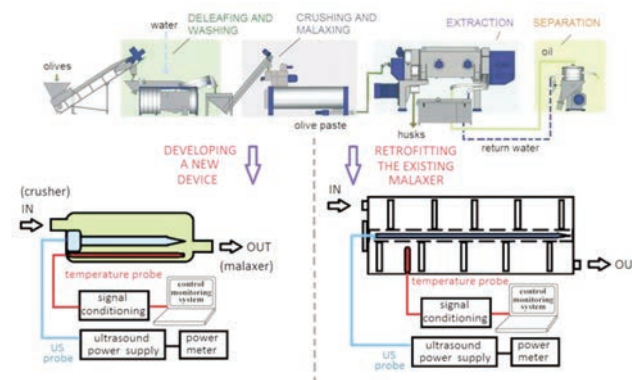


Figure 9. Scaling up of ultrasounds application in VVO industry.

Principles and mechanism of mw

MW are non-ionizing electromagnetic waves of frequency between 300 MHz to 300 GHz (Banik, 2003). MW is a technology applied in many food processes enables to reduce processing times (Mullin, 1995). MW operations have extensive applications in food technologies such as solvent lipid extraction from seed, pasteurization, sterilization, baking, blanching, cooking, drying, and thawing of different food products (Ramaswamy, & Marcotte, 2005). But, before the olive harvesting seasons 2011-2012 and 2012-2013, the MW treatment of olive paste has never been applied (Clodoveo 2013 c). The MW treatment of olive paste presented many advantages due to its mechanical and thermal effects.

MW thermal effect

Microwave heating is a process in which the materials couple with microwaves, absorb the electromagnetic energy volumetrically, and transform into heat (Zhao *et al.*, 2000). This is different from conventional methods where heat is transferred by the mechanisms of conduction, radiation and convection (Oghbaei & Mirzaee, 2010). In conventional heating, the material's surface is first heated followed by the heat moving inward. This means that there is a temperature gradient from the surface to the inside. However, microwave heating generates heat within the material first and then heats the entire volume (Yadoji *et al.*, 2003). This heating mechanism is advantageous due to the following facts: enhanced diffusion processes, reduced energy consumption, very rapid heating rates and considerably reduced processing times, improved physical and mechanical properties, simplicity and lower environmental hazards. These are features that have not been observed in conventional processes (Yadoji *et al.*, 2003; Leonelli, *et al.*, 2008).

MW mechanical effect

MW technology presents also a mechanical effect due to the heating which determines an increasing of the vegetal tissue volume and, in this way, cells explode releasing their content into the liquid phase. Moreover, when the liquid phase absorbs the MW, the kinetic energy of its molecules increases, and consequently, the diffusion rate increases too (Kratchanova *et al.*, 2004; Mandal *et al.*, 2007).

Applications of MW technology in VOO extraction process

Considering the thermal and mechanical effects of this emerging technology, it is reasonable to hypothesize that the MW can reduce the length of malaxation improving the oil releasing. Experimental trials were carried out in a pilot scale plant applying MW treatments on olive paste (Figure 7). Applying the MW treatment (800W) on the olive paste (2.5 kg) the pre-heating length was about 3 minutes (Figure 8C), corresponding to an 88% reduction in respect to the conventional system. Table 1 summarizes data relative to the qualitative parameters of extracted VOOs using the conventional and MW heating employing a pilot scale plant. All the examined VOOs, regard the considered parameters, belong to the extra VOO commercial class. In fact, all the samples showed very low percentages of free fatty acids and peroxide value (index of primary oxidation), and all the samples were always below the legal limit. No differences attributable to this innovative technologies were highlighted confirming that MW, in these experimental conditions (temperature treatment: 30°C), did not affect oil acidity and peroxide value. Also the values of K_{232} (another index of primary oxidation) and K_{270} (an index of hydroperoxides degradation) were not influenced by the MW treatment. All the oils were free of defects. The oils obtained by applying the MW treatment on olive paste were more pig-

mented than the conventional ones. This result was due to the MWs which cause the increase of vegetal tissue volume disrupting the cells and releasing the pigments. This visual observation was confirmed by the analytical data. Considering the total chlorophylls and carotenoids content, the lower values were obtained from olive paste untreated with 164 ± 17 and 33 ± 6 (mg/kg), respectively. The highest values were obtained when the MW treatment was applied with 219 ± 23 for the total chlorophyll and 81 ± 6 (mg/kg) for the total carotenoid contents. Aware that these compounds act as prooxidants in the light, these olive oils should be stored in the dark and in adequate bottles (Malheiro *et al.*, 2013) to more preserve the VOO quality and shelf-life. Considering the effect of MW treatment on extraction yields, employing the pilot scale plant, the extraction yield was 16.7 % (± 0.2), and 17.1 % (± 0.1) for the conventional and MW treatment respectively. When the VOOs were extracted without malaxing, the extraction yield of untreated sample was 1.0 % (± 0.1) while the MW treatment produced a significant increase in extraction yields equal to 5.4 % (± 0.3). These results demonstrate that this innovative treatment has a mechanical effect on olive paste causing the rupture of cell walls and recovering the oil trapped in the uncrushed olive tissue (Li *et al.*, 2004; Cravotto *et al.*, 2008). This data open up new prospects for developing innovative continuous extraction system to overcome the actual obsolete malaxing batch technology. In fact, a secondary effect should be considered: the crushing step may create an emulsion that impedes the complete separation between the oil and water; the emerging MW can facilitate the emulsion phases' separation determining the coalescence phenomena in a shorter time compatible with the development of a continuous system (Nour *et al.*, 2010)

MW equipment

There are many options to develop a continuous MW system placeable between the crusher and the malaxer. The easier apparatus could be constituted by a MW tunnel: A modular microwave tunnel oven can be easily developed projecting equipment with multiple microwave sources and the possibility to control the atmosphere for the continuous processing of olive paste. A conveyor belt can run for carrying olive past from the crusher outlet through the oven cavity, to the malaxer. Microwave energy can be launched into the cavity above and below the conveyor belt. A more complex system could be represented by a continuous a rotating tube system: this system can be consisted of a screen and reverberant cavity inside which there is a slightly inclined pipe in which the olive paste is irradiated. The rotating tube, in addition can transferring the olive paste from loading to unloading, favors its constant mixing and reduces the risk that an uneven heating occurs. It could be easily monitored the temperature, the microwave power, and the speed, with a management system based on electronic logic PLC.

Economic aspects of US technology

Conventional industrial heating method using steam or electric heaters may be more efficient compared to microwave heating in terms of converting the energy into a useful heat. It is difficult to estimate the total economic value for microwave technology when considering the complete extraction process, because, even if this technology has the lower energetic efficiency (42%) (defined as the ratio, expressed as a percent, between the transferred heating power necessary to warm up the olive paste and the input electric power) if compared to the conventional (49,5%) and the US heating treatment, the higher speed in reach the process temperature can allow a high increase in plant working capacity and a high reduction of investment costs. Moreover, other new values are added by using versatile novel technology that offers advantages over traditional processing such as: more rapid heating, preservation of sensory and nutritional quality, high throughput of processed

foods, and possibility of incorporation of microwave processing equipment in the existing processing lines.

Conclusion

The application of new emerging technologies, such as PEF, US and MW, in the VOO extraction process offers a number of advantages due to their mechanical and thermal effects. In contrast with the existing technology, the considered emerging ones are able to cause the rupture of cell walls and recovering the oil and minor compounds trapped in the uncrushed olive tissue, increasing the work capacity of the extraction plant and reducing the process time. PEF, US and MW can be retrofitted to existing VOO extraction plants or be engineering into new systems. The industrial application of these technologies could represent the first step toward a continuous malaxing phase. A continuous process presents potential advantages such as minor operating costs, minor capacity limitations, faster return on investments, lower cost of production, reduced energy demands, reduced work-in-progress, faster and easier cleaning, real-time quality control and significantly reduced footprint facility (Clodoveo *et al.*, 2013 a). In recent years many efforts were spent to increase the overall heat transfer coefficient of the malaxer improving the ratio between the surface area of the malaxing tank and the volume of olive paste. Moreover, sophisticated system for the real time monitoring of the malaxing condition (temperature, atmosphere composition, viscosity, etc.) were tested in order to design the most innovative malaxer without resolving the question of the batch process (Amirante *et al.*, 2008 a & b) (Figure 10).

The relative increment of the plant costs discourages the VOO plant manufacturers to continue towards this direction, also considering the negative trends of virgin olive oil prices in the worldwide market, which is a real impediment for the olive millers to invest money in new expensive machines. The actual trend is developing new apparatus to reduce plant investments increasing the extraction yields. If it is possible to apply a thermal and mechanical action on the olive paste before the inlet in to the malaxer, a high constructive simplification of this machine can be realized reducing its cost: in fact, the malaxer can be



Figure 10 Malaxer equipped with sensors in order to control the oxygen concentration in the head space of the tank and in the olive paste. Besides, a system to inject oxygen was introduced on this machine.

transformed in a thermally isolated tank equipped with a rotating arms shaft and stainless steel blades, excluding the jacket for heating the olive paste. Future researches should be developed to evaluate the significance of these technologies assessing their potential using the following criteria: energy savings, first costs, and other benefits, all being compared to existing technologies.

ABBREVIATIONS

VOO: Virgin Olive Oil

PEF: Pulsed Electric field

US: Ultrasound

MW: Microwave

r: ratio of surface area to volume

S: surface area of the malaxer

V: volume of the malaxer

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