Chapter

Does the Introduction of Ultrasound in Extra-Virgin Olive Oil Extraction Process Improve the Income of the Olive Millers? The First Technology for the Simultaneous Increment of Yield and Quality of the Product

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Abstract

Olive oil is an important product of the European agro-alimentary sector. The current olive oil extraction process can be further improved in order to overcome the weaknesses of the actual system in terms of non-continuity, reduction of oil in waste, sustainability, and improvement of quality both in the healthy and sensory perspective. Many innovative approaches have been developed to improve the olive oil extraction process. However, not all the proposed innovations have the opportunity to effectively reach a technological level of readiness close to "ready for the market." An innovator should simultaneously evaluate the aptitude of its invention to turn into a widely used commercial product both under the technological and the marketing perspectives. Under the technological point of view, an innovation should be effective, so, adequate to accomplish a purpose, and efficient, so, able to perform or functioning in the best possible manner with the least waste of time and effort. Under the marketing point of view, an innovation should be able to develop products that accurately and timely respond to customer needs, offering a valuable experience to the customer, exceeding his expectations. The innovative EVOO process based on ultrasound extraction has several advantages useful to improve olive miller income: higher yield extraction, higher polyphenols, and lower bitter and pungent taste than traditional EVOO samples.

Keywords: olive oil, extraction process, innovative approaches, ultrasound, technological level of readiness

1. Introduction

Oliviculture is one of the most ancient economic activities of the Mediterranean basin; therefore it is usually considered as a traditional sector and not able to positively enhance the economic and social development of European and North African countries where it is diffused.

Today, the olive miller has to directly face the market and all the multiple requirements of society. The growth of the olive miller company is linked to the development of its innovative capacity [1]. Understanding the factors that can determine the potential for innovation means understanding the main levers of intervention for the competitiveness and growth of an entrepreneurial activity [2] threatened by an evolving global context, which leads Italy in particular, among the European contest, to lose its positions of prestige always owned in the international context. In the last 20 years, we have therefore witnessed a "professional metamorphosis" of the role of the olive miller. In the last 20 years a metamorphosis occurred in the role of the olive miller inside his enterprise because the perspective with which the extraction process of extra-virgin olive oil can be considered, under a technological, chemical, biochemical, and sensorial point of view, has changed.

The term "extraction" in the olive oil sector is, in fact, a word to be considered obsolete in the light of the progress of knowledge developed over the last 20 years [3–9]. The word "extraction" is referred to any operation with which one "extracts" something within a specific technical process. Applied to the olive oil sector, the term "extraction" implies the following misunderstanding: the bottled virgin olive oil (product obtained exclusively with the use of mechanical systems), under the chemical and sensory point of view, is the same contained (as small lipid drops) within the elaioplasts (the subcellular organelles specialized in storing lipids inside the cells of the drupe).

This concept is wrong. In fact, during all the operations that start from the crushing, passing, across the malaxation, and the centrifugal separation of oil, a complex mass transfer occurs of those minor components (constitutive of the fruit, phenols, or of neo-formation, volatile compounds) from different tissues (epicarp, pulp, pit and seed) that compose the drupe to triglycerides organized in plastoglobules [8, 9]. Considering the occurrence of these phenomena, of a physical, chemical and biochemical nature, which make virgin olive oils different from the other lipidic plant matrices by composition and sensory and health properties, it is necessary to introduce a new term in the olive sector vocabulary that accurately reflects specificity and uniqueness of the complex transformation to which the process presides. Therefore, the verb "to extract" has to be replaced by the verb "to elaborate," already earlier adopted more than 10 years ago by Carlos Gómez Herrera of the Institute de la Grasa of Sevilla [10]. In fact, the verb "to elaborate" means "to develop a project through careful coordination and transformation of the basic elements to give them an arrangement and a complete form that responds to the desired purpose." In the olive oil world, the elaboration process of virgin olive oil has to allow to the olive miller the obtainment of the planned quantitative and qualitative results. This goal has to be planned at the moment of the raw material evaluation, or even before during the fruit development stage, at the moment in which the choice of the harvesting period occurs, nodal elements for the purposes of defining the characteristics of the product, and the interception of the pre-established market target [11, 12]. The word "extraction" relegates the oil miller of the past to the role of mute spectator who oversees a process whose outcomes are often unknown to him. He is a simple worker assigned to a manual labor only, who is not able to build solid strategy business based on segmentation, target, and product positioning; the verb "to elaborate" innovates the role and skills of the miller. He becomes the craftsman or the artisan, the one who exercises an art intended as an activity that requires a complex of technical knowledge at the service of a particular attitude [13].

The modern miller masters the technology and the technological innovations. He is able to use the machines, regulating the macroscopic parameters of processing (specific energy, times, temperatures, atmosphere in contact with the product, and quantity of process water), with the aim to "modulate" the enzymatic activities that take place at the microscope level in the olive paste, consciously modifying the chemical, organoleptic, and health characteristics of the resulting virgin oil [9]. The word "modular" is a term borrowed from the world of music that refers to the ability to vary a sound or a tone, to achieve a harmonious effect. It is an indispensable term to describe the activity of the miller that, in a very short period of time, must make a series of decisive choices to obtain an extra-virgin olive oil, with a pleasant overall sensation, due to the perception of its components, phenolics and volatiles, which act as olfactory-gustatory, tactile, and kinesthetic stimuli balance between them.

However, the relationship of the olive oil sector with technological innovation is controversial. The olive and olive oil sector can be considered a technologically conservative productive system, that is, with a limited introduction of innovations compared to other sectors of agro-food [14]. This approach is apparently consistent with the behavior of the typical consumer. Consumers are linked to a model of consumption of extra-virgin olive oil based on habit and bound to a taste that has consolidated over time. People are reluctant to change, despite the pressure of a communication and training activities aimed to increase in the culture of olive oil for the improvement of the competitiveness of high-quality products [15, 16].

On the contrary, the global agri-food system seems to be constantly encouraged to develop innovations in products, processes, or services able to face an increasingly pressing demand for healthy, quality food, able to satisfy, at the same time, healthy and hedonistic needs, with certain origin, and that they can offer a strong experiential dimension. In the agri-food sector, therefore, the tendency of the market is the creation of a growing demand for an increasingly differentiated and segmented product, in countercurrent with the world of olive oil.

Technological innovation, and the product segmentation that derives from it, is the only path that can be followed by the olive oil sector, which must increase competitiveness. The exploitation of technological innovations is the only useful tool to increase production efficiency, product quality, process sustainability, and ultimately the profitability of the sector.

2. The first technology for the simultaneous increment of yield and quality of the extra-virgin olive oil

Public and private research bodies are constantly working on innovative approaches to develop new products, processes or organizational models in the olive oil sector. However, the conversion of these research results to industrial innovations considerably more complex than generally believed. In practice, not all inventions, that is, new solutions developed in laboratories in response to a technical problem, can be transformed into innovations, then into new products or processes suitable for commercial exploitation for a competitive supply chain advantage.

In the olive oil sector, the levers that guide research and development of innovations are constituted by the need to favor, during the extraction process, the separation of the highest quantity of oil, and of the best quality, modulating appropriately the complex series of physical transformations, chemical-physical, chemical, and biochemical within the olive paste. The increase in yield and product quality is an antithetical objective, which cannot be achieved simultaneously with the currently widespread technologies but which must be pursued to guarantee fair profitability for the operators of the sector.

Innovations can be distinguished by the degree of novelty with respect to existing technology, organization, and demand, in two different types: incremental innovations and radical innovations. Incremental innovations involve the improvement of a process, of a product or service with respect to a specific existing model or process. Radical innovations represent a break with existing products or processes. From these innovations, in some cases, new industries or market segments can arise. Incremental innovations are very numerous, while radical ones are rarer.

Considering the machinery for the oil sector, the last radical innovation is represented by the introduction of centrifugal separation of oils and the transformation of the obsolete pressure extraction system, characterized by low working capacity, high labor demand, and poor hygienic standards, in the modern "continuous" system, highly effective and efficient. This innovation dates back to the 1970s. It involved the need to combine the decanter, the centrifuge with horizontal axis that continuously separates the oil from the olive paste, with the malaxers. The malaxer is a machine that operates in batch and that is necessary to favor, thanks to the heat exchange and agitation, the coalescence of minute droplets of oil into larger diameter drops, able to be separated in a centrifugal field and to guarantee satisfactory yields [8, 9].

Most of the incremental innovations developed in the last 30 years have had the purpose to improve the performance of the malaxers. The aim of these innovation was optimizing the machine geometry and the heat exchange (also by means the introduction of heat exchangers), improving the ratio between volumes of olive paste and exchange surface, to reduce treatment times and the number of malaxers necessary to guarantee continuity to the process. Observing the principles on which the incremental innovations were based, it is possible to state that the levers experimented to design new machines, able to improve the extraction yields and reduce the residual fat present in the by-products, are, on the physical point of view, the same principles on which traditionally the olive oil technology has always been based: heating and stirring to reduce the viscosity of the olive paste. We can consider, with good margins of certainty, that every technological effort based on the optimization of these three factors has reached the apex of applicability and that the machines currently on the market are the best performing. The perspectives for improvement are technically feasible if we persevere with the already consolidated approaches.

Looking at the characteristics of the oil by-products, it is clear that there is still room to increase the efficacy and efficiency of the machines destined for olive oil extraction. And here it is perhaps the case to dwell on the terms "effectiveness" and "efficiency," often used indistinctly as synonyms but which actually reflect two distinct concepts. Effectiveness, in fact, indicates the ability to achieve the set objective, while efficiency evaluates the ability to do so using the minimum necessary resources. In the case of olive plant engineering, we can say that a technology is effective if it is able to increase yields and antioxidant content by reducing the losses in by-products and is effective if it achieves these goals in a sustainable manner, reducing energy costs for the benefit of business economies and the impact on the environment.

Effectiveness and efficiency can be achievable goals also thanks to the use of emerging technologies [17–19]. Emerging technologies are technologies available at the experimental level, which have already shown advantages in other fields of application and whose developments are now considered extremely promising in the coming decades. In the case of the extraction of extra-virgin olive oil, emerging technologies must ensure the simultaneous achievement of two different effects: a mechanical and a thermal effect. The mechanical effect comprises the breakage of the cells passed intact to the crusher and the release of further oil and minor compounds. The mild thermal effect is useful to accelerate, by means of the hydrophobic effect, the coalescence of minute lipid droplets. Among the emerging technologies that are spreading in the food industry, candidates to become real-scale plants in the oil sector in the near future, there are microwaves and ultrasounds [20–25].

Microwaves are electromagnetic radiations with frequencies between 300 MHz and 300 GHz [21]. They determine powerful and macroscopic thermal effects in the matrix due to the effect that the electromagnetic radiation exerts on the polar molecules, such as water. The polar molecules rotate with high frequency to align their dipole to the electromagnetic field, generating frictions with the adjacent molecules that induce a rapid and inhomogeneous heating. Because of thermal spots, areas where there is concentration, due to the inhomogeneity of the radiation and a high thermal increase, the dilatation of the aqueous phase of the cytoplasm induces a mild mechanical action of breaking of the cell walls.

Ultrasounds are sound waves with frequencies from 20 kHz to some GHz, higher than the audible limit of the human ear. At low frequencies, between 20 and 40 kHz, they determine an evident mechanical effect, due to the phenomenon of cavitation, which contributes significantly to the breakage of the intact past cells to the crusher, freeing the lipid content (**Figure 1**); the thermal effect is mild and negligible [20].

Tests aimed at measuring the ability of the two technologies to be transferred in the design of real-scale plants and implemented in modern full-scale mills have been realized, and the performances in terms of effectiveness and efficiency have been measured.

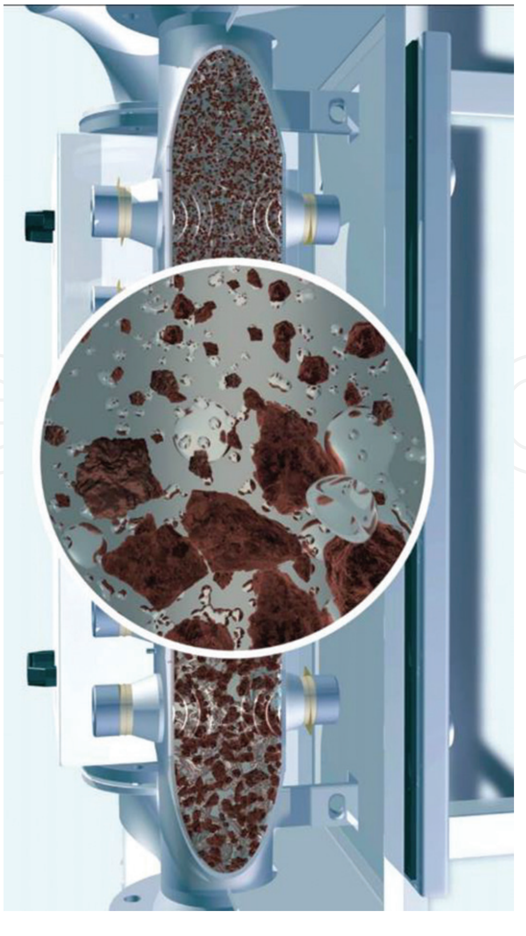

Figure 1.
Cavitation breaks the intact past cells to the crusher freeing the lipid content. Picture by courtesy of Weber Ultrasonics AG.

From the point of view of effectiveness, and therefore of the capacity to increase extraction yields, the theoretical premises based on the intrinsic characteristics of the two technologies have been confirmed by the experimental evidence. In relation to the heating times, the microwaves showed the ability to significantly reduce the duration of the malaxation with the same extraction yields. On the contrary, the mechanical action of the ultrasounds, clearly superior to the mechanical action of the microwaves, combined a noticeable increase in extraction yields with a time reduction.

Two technologies compared with two antithetical effects. What strategies can be applied to design the plant that will most likely contribute to the improvement of the process?

Alongside the efficacy observations summarized in terms of contraction of the malaxation times (one-tenth for the microwaves and one third for the ultrasounds), the considerations in terms of efficiency were decisive. The tests carried out in order to measure the efficiency of the processes have revealed how the microwaves represent a technology, at present, extremely energizing and not compatible with the more recent guidelines of the industry 4.0, which privilege processes able to preserve the natural resources.

Experimental evidence has led to the exclusion of the industrial scale-up of microwave technology: the only advantage constituted by the significant contraction of processing times did not match the desired increase in yields [21]; the lack of energy efficiency, moreover, represented a threat of increasing production costs incompatible with the production context that offers limited margins of profit.

Promising, on the contrary, was the premise for the implementation of ultrasound technology linked to the positive increase in yield, the mild thermal effect, and the high energy efficiency: three evidences that opened the prospect of achieving the goal of increasing yields and the concentration of minor compounds, reducing production costs, and improving company profit margins [20, 23–25].

How is it possible to pass from the batch laboratory device, which is able to treat limited quantities of olive paste (about 3 kg) to plants that operate continuously, working tens of quintals of olives?

It is here that it becomes fundamental to combine the multidisciplinary skills of the research groups. From the collaboration between knowledge areas, food technologies, food chemistry, and mechanical engineering, a design strategy has been realized. The starting point was the definition of the ideal geometry and then on the energy calculations necessary to create a plant able to guarantee the conversion of the conditions tested in batch (lab-scale) in an ultrasonic treatment administered continuously (full-scale).

In terms of geometry, the construction of an ultrasonic system must start from the characteristics of the transducers present on the market and from the flexibility that these can offer during the design phase, also with a look at the possibility of realizing plant solutions suited to the different working capacities of the oil mills. The most commonly used transducers are the so-called probe transducers. The first prototypes made have favored this model because it integrates well with the triple tube heat exchangers already widespread on the market. This combination was chosen to maximize the effects of ultrasound, which are emphasized by the simultaneous heating of the oil paste, which, by reducing the viscosity of the fluid, promotes the propagation of the wave in the medium. Fluid dynamic simulation tests, carried out simultaneously with the experimental tests, have however highlighted some limitations of this geometry, proving how long, tortuous, and costly is the path necessary to develop an innovation.

So the next step was the design and build of an ultrasound system based on the use of plate transducers. An octagonal section system has been created that combines ultrasonic treatment with heat exchange (**Figure 2**). It allows a thermal conditioning of the olive paste aimed at both heating and cooling, depending on the environmental and territorial context in which the technology is implemented. The sizing, based on the calculation of the specific energy to be administered, has shown that the amount of energy necessary to maximize the advantages obtainable from the use of ultrasound, for frequencies between 20 and 40 kHz, is equal to about 18,000 J/kg. 18,000 J/kg is a number that can mean nothing if not compared to other process operations [25]. In order to make clear the meaning of ultrasonic treatment, it is sufficient to think that the specific energy transferred from a mechanical crusher is approximately 30,000–36,000 J/kg.

The ultrasonic treatment, in this perspective, can be considered a sort of finishing of the crushing step. The ultrasonic treatment of the olive paste is fully classified as a mild technology. It is a delicate technology that allows to combine, for the first time in the history of the development of oil mills, the increase in yield (more than 1 kg of oil per 100 kg of olives) with the increase of the content in polyphenolic substances, minimizing the thermal and oxidative damage, demonstrated by the chemical analyzes aimed at the product classification and by the panel test.

The use of ultrasound in the oil sector is part of key enabling technology, as it represents a technological solution capable of revitalizing the production system, and meets the social challenges related to food safety, sustainable agriculture, and bio-economy as it represents an efficient production system that can accelerate the conversion of companies toward sustainability.

Ultrasounds also concretely open the way to a production model that, consistent with the principles of circular economy, leads the mills to exploit the potential to

Figure 2.
The inner part of the sono-heat-exchanger (on the left). The external structure of the sono-heat-exchanger (on the right).

profitably integrate the use of differentiated pressing within the processing line. The use of the pitting machine, which is not widespread today due to the known yield losses, can be stimulated by the use of ultrasounds which have a positive effect on the extractability of the oil. The elimination of the core before the product enters the processing line has the advantage of increasing the working capacity of the plants and improving energy efficiency and offers the possibility of allocating the de-stoned pomace to more profitable purposes.

The implementation of ultrasound in the olive oil extraction process is characterized by a high level of technological maturity (TRL, technology readiness levels) of 8, which corresponds to the development of the system and its validation on a real scale.

3. The introduction of ultrasound in extra-virgin olive oil extraction process can improve the income of the olive millers

Table 1 shows the economic comparison between the traditional system and the innovative system with ultrasounds. The simulation is done on a crusher with a working capacity of 1500 kg/h that works 10 h a day for 80 days, about 3 months.

Assuming an average price of olives equal to €90 per quintal, and the selling price of oil equal to €7, without including in the comparison the premium price of oil extracted by ultrasound due to the increase in polyphenols and the highest health value, an increase in incomings of 116,700 euros is achieved. The return on investment can be quantified in just 2 years.

ADITIONAL PLANT		INNOVATIVE PLANT		COMPARISON OF INCOMING	
Olive cost €/kg	0.9	Olive cost €/kg	0.9	Difference in incoming between the INNOVATIVE AND TRADITIONAL system €/h	145.88
Olive flow capacity kg/h	1500	Olive flow capacity kg/h	1500	WORKING DAYS of the olive mill	80
Olive cost €/h	1350	Olive cost €/h	1350	Working hours per day	10
Oil yield %	14.6	Oil yield %	16	Duration of harvesting season h	800
Olive oil flow capacity kg/h	218.8	Olive oil flow capacity kg/h	239.6	Total incoming with traditional system €	145.200
Selling price of oil €/kg	7	Selling price of oil €/kg	7	Total incoming with innovative system €	261.900
Incoming per hour €/h	1531,5	Incoming per hour €/h	1677.38	Increase in incoming during a single harvesting season €	116.700
Gain per hour €/h	181,5	Gain per hour €/h	327.38		

Table 1.
Simulation of economic budget comparison between the traditional system and the innovative system equipped with ultrasounds during a single harvesting season.

4. Conclusion

The introduction of ultrasound in extra-virgin olive oil extraction is the first technology for the simultaneous increment of yield and quality of the product. The innovative EVOO process based on ultrasound extraction has several advantages useful to improve olive miller income: higher yield extraction, higher polyphenols, and lower bitter and pungent taste than traditional EVOO samples.

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Conflict of interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this article.

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