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Review

Olive Sound: A Sustainable Radical Innovation

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Abstract: Olive Sound is the acronym of a Horizon 2020 European Project aimed at the development of a high-flow oil extraction plant, the Sono-Heat-Exchanger, which combines ultrasound and heat exchange in order to break, through a radical innovation model in the oil mill, the historical paradigm that sees as inversely correlated the oil yield and the content of bio-phenols. These compounds are biologically active molecules that transform the product, extra virgin olive oil, from a mere condiment into a functional food. The primary objective of the project, financially supported by the European Union through the "Fast Track to Innovation" program, is the development of a product "ready for the market" (TRL 9) capable of making the involved companies more competitive while increasing the competitiveness of European extra virgin olive oil in the international context.

Keywords: malaxation; sonication; competitiveness

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1. Introduction

Innovation is the process that allows individual companies, or entire production sectors, to create value, remain in or enter new markets, increase profitability, generate employment, and increase competitiveness [1].

Considering the trends of the last decade, it is possible to affirm, with a certain degree of awareness, that the European olive oil sector has an urgent need to innovate to generate competitive advantage; that is, the set of elements that must characterize the product with the aim to create added value and differentiate, mainly by exploiting health properties, its offer from its global competitors [2]. It is worth pointing out that, in the market, product competitiveness is a strategy pursued by companies to generate greater profit. In the world of olive oil, dominated by information asymmetry, the problem of marginal profits and below-cost sales is considered the principal reason for penalizing companies in the sector. Currently, the price strategy, which sees companies challenge each other on the lowest price and which is based on a production model that aims at maximum production yield, leads to the production of an extra virgin olive oil (EVOO) devoid of distinctive chemical and organoleptic characteristics; therefore, this is a product that does not have elements to compete on the market. Controlling and reducing overhead costs, designing an efficient production line, and differentiation are three of the company's strategies for gaining a competitive advantage.

Conway and Steward stated that "innovation can be briefly defined as the successful exploitation of new ideas". This means that to generate an innovative process it is not enough to have an idea, but it is also necessary to act so that the idea can be put into practice by transforming the effective contest where innovation finds application [3].

Technological innovation is the result of a creative process that involves a series of actors motivated by the common goal of responding to a need in a specific sector [4]. In the case of the olive oil sector, in the transformation phase, which occurred more than 40 years after the introduction of the last real radical innovation of the extraction process, the decanter [5] combined with the malaxer [6], the need for research has been expressed by

the community of olive millers in all the olive-growing areas of the globe. These needs can be summarized in the following points:

- Making the extraction process effectively continuous [7];
- Contracting processing times [8];
- Increasing extraction yields by reducing fat residues in the olive pomace [9];
- Maximizing the extraction capacity of bio-phenols, molecules with a recognized health effect, with the aim to place the product in the highest range of the market certified by the application of health claims approved by the European Food Safety Authority (EFSA) [10–12];
- Using extraction temperatures (~20 °C) useful for the development of the volatile fraction without affecting the yields [13];
- Creating a sustainable process consistent with the objectives of the 2030 Agenda and in line both with the directives of the European Green Deal and with the emerging needs of consumers [14].

When a change process is stimulated by the community of future users (i.e., stakeholders), an innovation model defined as bottom-up is created, which comes from the collection of needs that really take into account the needs of the various stakeholders [15].

The mapping of these needs, collected by researchers from the Departments of Medicine and Pharmacy of the University of Bari [16–21], has been transformed into a project resource that has led to the creation of an award-winning partnership, in an extremely competitive tender, by the European Union with a commitment total income of EUR 2.5 million. The strength of the idea, which sees the collaboration of three nations (Italy, France, and Spain) and five partners (three companies and two research institutions), is in the way it is generated, which has never imposed standard solutions but has been able to aggregate people around a common and shared project born from the participation, involvement, and enhancement of the skills and knowledge of the human resources involved.

The scientific dissemination activity dedicated to the operators in the olive oil sector conducted by the University of Bari, and in particular by the professors M. L. Clodoveo and F. Corbo, in the Italian territory and also abroad, has transformed over the years into a fundamental tool for building relationships with the olive millers, sharing values, knowledge, skills, and previous experiences, to create a real community in which the various stakeholders have been constantly involved and encouraged to weave a dense network of exchanges both within the entire production system and towards academic interlocutors. In fact, in the first stages of the development of innovation (from TRL, Technology Readiness Level, 3 to TRL 7), that is, the simultaneous application of ultrasound and heat exchange in the process of extraction of extra virgin olive oil [1], the community of millers (in particular some companies located in Apulia, which is the Italian region that holds the leading production) has contributed to the co-generation of knowledge, through the development, experimentation, and optimization of Sono-Heat-Exchanger innovation within industrial olive mills [22] (Figure 1). They also favor an interactive transfer of know-how focused on the specificities of the oil sector and open an effective and constructive dialogue between all the subjects aimed at stimulating the processes of mutual learning.

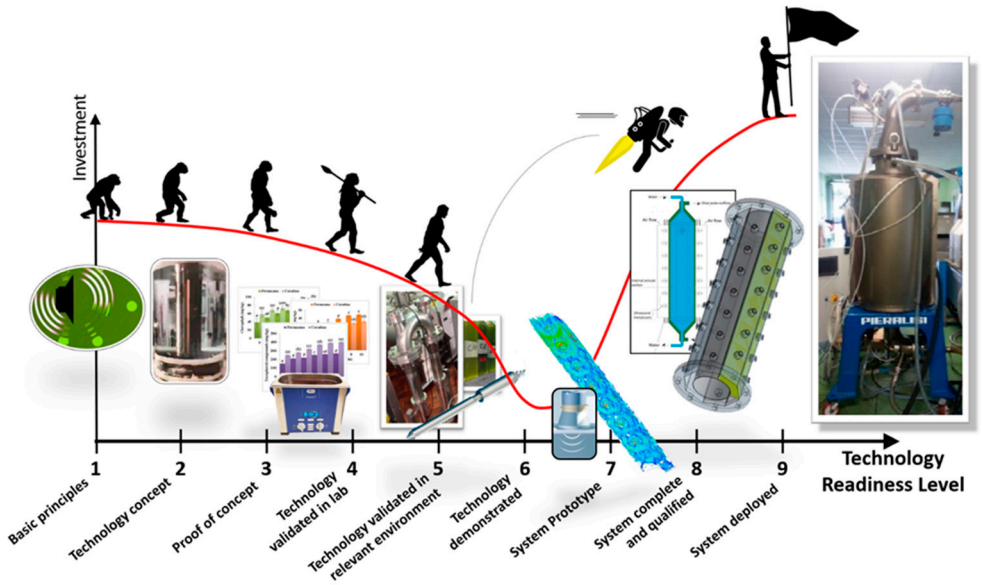

Figure 1. The stages of the TRL—technology readiness level—in the development of the Sono-Heat-Exchanger.

This approach has made it possible to undertake a preparatory path for the industrial implementation of innovation based on three principles: (1) the creation of opportunities for interaction and discussion with the various stakeholders; (2) listening to the needs of stakeholders; and (3) co-planning.

2. Fast Track to Innovation

The Fast Track to Innovation (FTI) [23], a funding instrument that supported the European Olive Sound Project, is a completely bottom-up innovation support program that promotes innovation activities close to the market.

This tool requires that the project leader be a company, and in the case of Olive Sound it is Pieralisi di Jesi, the leading company in the international market of oil machines (Figure 2).

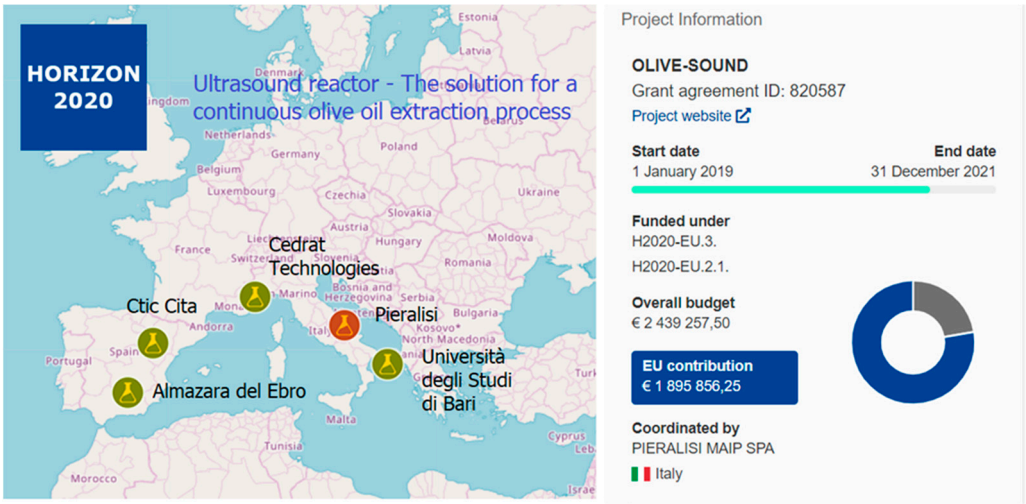

Figure 2. Composition of the partnership of the Horizon 2020 Olive Sound project.

In the European vision, companies are the engine of the European economy, essential for the creation of jobs and for economic growth and capable of ensuring social stability. Therefore, the Fast Track program aims to ensure that innovative ideas are transformed *quickly* into new products *ready for the market* that stimulate growth, create quality jobs,

and contribute to addressing the challenges of European and global society. Indeed, the promoted actions, *guided by the business*, aim to give the last push to innovative ideas to ensure their rapid adoption by the market. The term *rapid* in the sense of the fast track founding program means *within a period of three years from the start of the action*. On average, the success rate for consortia that aspire to receive the funding is extremely low, less than 5%, reflecting the rigorous selection process applied by international auditors which rewards only European entrepreneurial and academic excellence.

3. Radical Innovations

According to Joseph A. Schumpeter [24], innovation is the main determinant of industrial change as a force that destroys the old competitive environment to create a completely new one. It is, therefore, "a creative response that occurs whenever an industry offers something that is outside existing practice". The Sono-Heat-Exchanger (Figure 3), which breaks the historical paradigm of the olive mill that sees as opposite the technological conditions that favor the extraction yield and those aimed at increasing quality and effectively eliminates the bottleneck represented by the now obsolete malaxer, can truly be considered a radical innovation in the field of olive oil extraction plants, and is capable of opening up opportunities for the development of new markets [1,8,25,26].

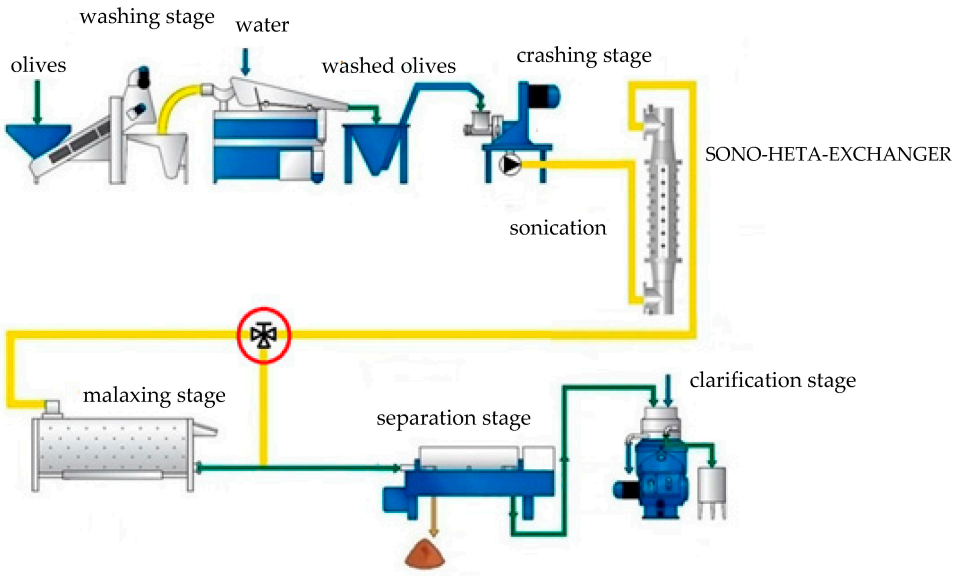

Figure 3. Olive oil processing line.

As part of the Olive Sound project, innovation management was based on a multi-faceted approach divided into three development phases which involved collaboration and integration of the partners' skills:

- Planning (design);
- Physical realization (manufacturing);
- Marketing of the Sono-Heat-Exchanger.

3.1. The Design Phase

The design phase involved the definition of the geometry of the ultrasonic device, such as to ensure that the ultrasonic waves emitted by the transducers were effective in inducing the phenomenon of cavitation, responsible for the mechanical action of ultrasound, and efficient in penetrating the entire thickness of the olive paste, all without representing a threat to the wear of the components. In order for this phase to be compatible with the timing of the project, the University of Bari made use of the technical-scientific collaboration of the Polytechnic of Bari, in particular of Prof. Amirante, to benefit from the support of numerical simulation [27,28]. Numerical simulation is an indispensable tool for reducing

the time to market necessary for the final product because it is an approach capable of determining a rapid orientation of the design towards the optimal design, as well as reducing design costs, including the number of prototypes and experimental tests to be performed [29].

The design instead made use of a simulation program in ANSYS Fluent environment, which, for the first time, allows the simulation of the pressure transients induced by transducers in a pipeline in which the fluid flows tangentially in order to optimize the sonication process (geometry, thicknesses, position of the transducers, operating pressures) so that it is effective and efficient. This process is also combined with the heat exchange technology for heating or cooling the oil paste (Figure 4).

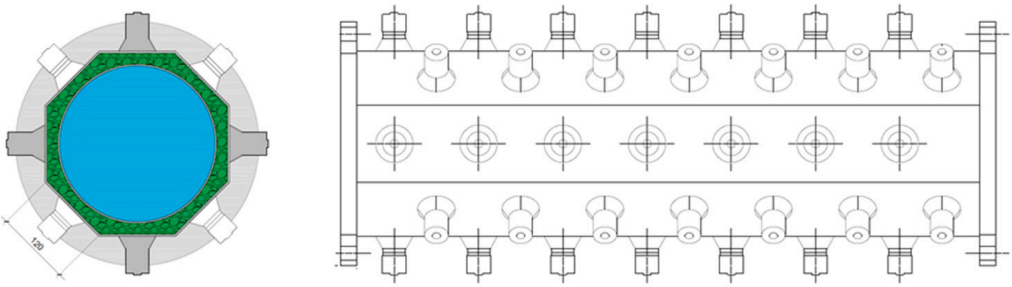

Figure 4. The device has been designed with an octagonal section equipped with a plate transducer, each of 100 W of power and 23 kHz of frequency. The inner circular section is the heat exchanger. The olive paste flows in the external annular section, while the water (cold or hot) flows in the internal annular section to modulate the temperature inside the olive paste.

The numerical simulation conducted on the Sono-Heat-Exchanger made use of an instrument designed ad hoc by the Polytechnic of Bari, which has taken into account the complex rheological characteristics of the triphasic fluid constituted by the olive paste, composed of two immiscible liquids (i.e., oil and water) and a solid (i.e., pulp and stone).

Moreover, the numerical simulation made possible the reproduction of the pressure transients induced by the action of the ultrasonic transducers (Figure 5) and the fluid dynamic profiles induced by the transport of the fluid (Figure 6), allowing for the advance knowledge of the performance or behavior of the innovative device before the first prototype had been physically built, thus speeding up the decision-making process of the design phase.

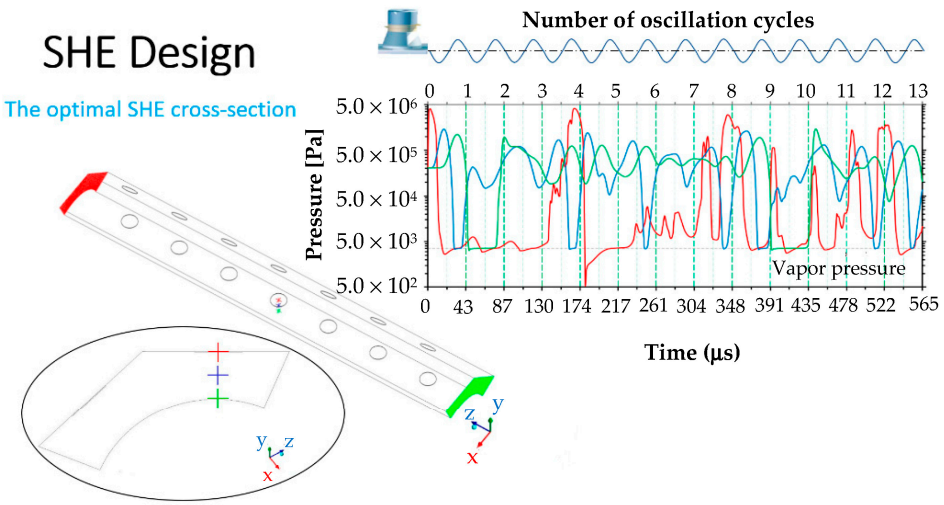

Figure 5. Determination of pressure transients inside the Sono-Heat-Exchanger—Olive Sound induced by the action of the ultrasound on the olive paste.

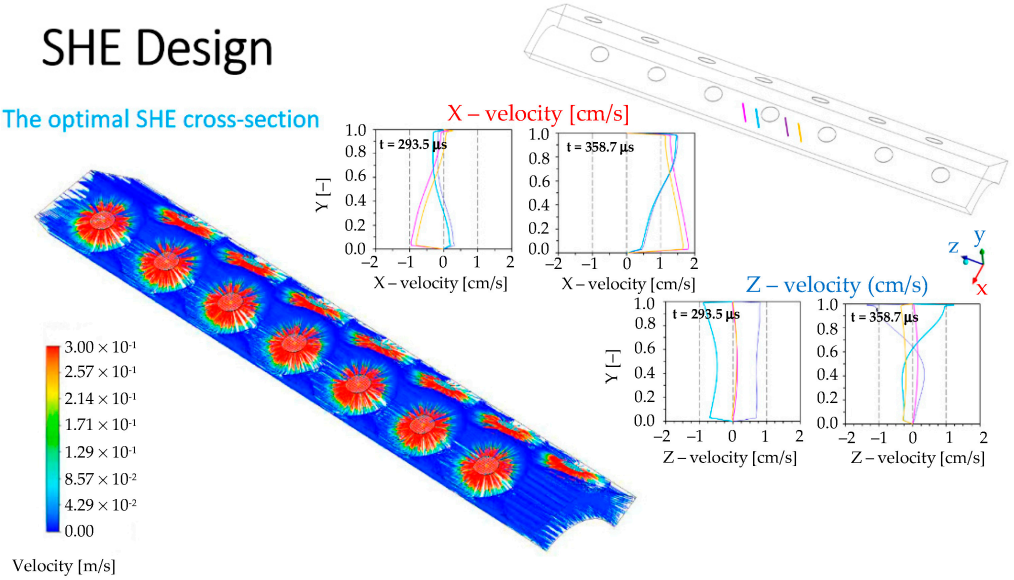

Figure 6. Fluid dynamic analysis of the olive paste inside the Sono-Heat-Exchanger—Olive Sound.

Finally, the numerical simulation made it possible to highlight two important effects of the ultrasound on the olive paste that explain the theoretical basis of the effects measured in the experimental phase. The first effect is the increase in yield and polyphenol content due to the determination of the pressure transients in the predetermined operating conditions. Indeed, the minimum pressure values reached inside the olive paste are below the vapor pressure of the water at the process temperature (~25 °C); therefore, they are compatible with effective cavitation (formation and collapse of vapor microbubbles) and useful for breaking the cells of the drupe passed intact to the crusher and for freeing the oil and minor compounds (polyphenols, tocopherols and carotenoids) trapped in them.

The second effect deals with the elimination of the malaxer because the pulsating action of the transducers causes swirling movements on the olive paste that agitate the flow of olive paste in transit in the apparatus, inducing agitation similar to that inside the malaxer and favoring coalescence phenomena among the minute drops of oil released by cavitation, which increase in diameter and are more easily separable in the centrifugal field.

3.2. The Manufacturing of the Sono-Heat-Exchanger

The simulation, combined with the mechanical design, has allowed the Pieralisi and Cedrat Technologies companies to create the first prototype within workshops and laboratories that specialize in piezoelectric technologies, a modular unit built for the validation phase (Figure 7) and used for the acquisition of technical and analytical data functional to the optimization preparatory phase and for the realization of the high working capacity model, which is compatible with the size of mills typical of the Spanish model.

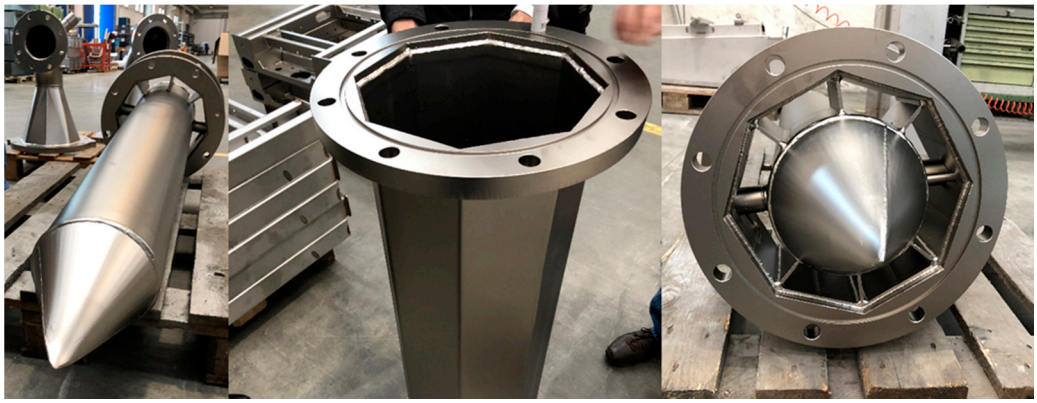

Figure 7. Some phases of the construction of the modular unit of the Sono-Heat-Exchanger—Olive Sound built for optimization tests at the Pieralisi company.

The tests of the prototype were carried out over two oil years and in two areas (northern Spain and southern Italy) with a varietal panorama that covered 10 olive cultivars and, for each cultivar, three different ripening stages (green, partially dark, and totally uneven). The tests have made it possible to complete the modular unit with a series of sensors and actuators (Figure 8) implemented with the dual purpose of guaranteeing maximum protection of the machine and operators, and to proceed with the creation of the definitive model that will reach the international market of oil machines by January 2022 and help to create new jobs.

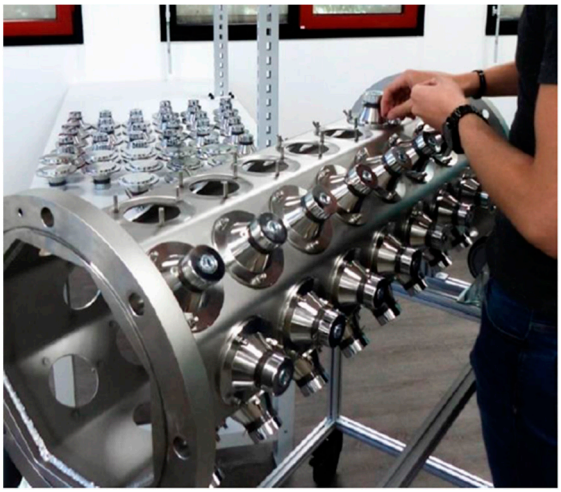

Figure 8. Installation of the transducers at Cedrat Technologies.

3.3. The Marketing Strategy of the Sono-Heat-Exchanger

The Fast Track to Innovation differs from other European funding programs because it provides, at the time of admission of the application, that the proposal is accompanied by a business plan that clearly describes the market potential (potential users/customers and their benefits, global markets/target Europeans, etc.), business opportunities for participants, measures that will improve the likelihood of eventual commercial adoption, and a credible marketing strategy.

The marketing strategy developed for the project focuses on two fundamental aspects: the description of the strengths of the new plant (Table 1) the demonstration that the Sono-Heat-Exchanger is the suitable solution to respond to the needs mapped out in the community of millers.

Table 1. The strengths of the new Sono-Heat-Exchanger compared to the obsolete malaxer.

Technological Effect	Malaxer	Sono-Heat Exchanger
Efficacy	The malaxer is a batch machine, which works between two continuous devices, the fruit crusher and the decanter. Its long kneading times, in addition to it constituting a threat to the quality of the oil, make this phase of mixing the oil paste at a controlled temperature the "bottleneck" of the continuous process.	The Sono-Heat-Exchanger is a continuous device. The major advantages of continuous processing are lower equipment costs, a reduced overall footprint, and the elimination of redundant plant equipment.
Efficiency	A bottleneck in the process tends to create a queue and increase the overall cycle time. The bottlenecks in production cause stalls and slowdowns in the production flow as with the same resources, production is slower and therefore smaller quantities are produced.	The elimination of the bottleneck in the oil sector translates into an effective tool if the innovation is able to increase the yields and content of antioxidants, and it is efficient if it achieves these objectives in a sustainable way, reducing energy costs with benefits regarding company economies and the impact on the environment.
Number of the devices	In the olive mill, currently, the limited working capacity of the malaxer penalizes the production efficiency of the decanter; the main plant engineering solution adopted to manage this inefficiency consists in multiplying the number of malaxers, in series or in parallel, to ensure continuity of the process, but not without an increase in investment in the crusher.	The Sono-Heat-Exchanger is a continuous machine that allows to synchronize its flow rate with the flow rate of the decanter and effectively eliminates the bottleneck of the process.
Mechanical effects	The mechanical crusher produces fruit fragments containing hundreds of cells that pass intact into the malaxer. The malaxer can be considered a finishing phase of the crushing phase by the cutting action of the stone fragments, which tears the cells passed intact to the crusher in a delicate manner but in an extremely long time (from 30 to 60 min), therefore helping to break the cells of the drupe passed intact to the crusher releasing a further amount of oil.	The ultrasounds determine a transient pressure gradient which, in some moments, reaches values lower than the saturated vapor pressure of the water contained in the olive paste, causing vaporization at low temperatures. "Cavitation bubbles" are created, which progressively increase their volume until they reach a critical value beyond which they implode, generating jets of liquid at high pressure that instantly tear the cells that have passed intact to the pressing.
Thermal effect	The malaxer is a bad heat exchanger due to an unfavorable ratio between the big volume of olive paste that should be warmed (or cooled) and the small surface for the heat exchange.	The Sono-Heat-Exchanger is equipped with an inner part that consists of a highly efficient spiral heat exchanger able to modulate the olive paste temperature (fast heating up or fast cooling of olive paste) simultaneously with the sonication treatment, adapting the results to the needs of olive millers [30].
Coalescence	The coalescence phenomena of oily drops inside the olive paste are due to hydrophobic interactions. During the malaxation, the drops of oil in the olive paste combine to form a larger drop. The role of the mixing in the hydrophobic interaction regards frequency of the collision of drops, which is one of the factors able to influence the coalescence of the oil in the olive paste. Mixing or agitation has been shown to improve coalescence by enhancing the rate of collisions.	The pulsating action of the transducers imposes swirling movements on the olive paste that agitate the flow of olive paste in transit in the apparatus, inducing agitation similar to what happens inside the malaxer, and favoring coalescence phenomena among the minute drops of oil released by cavitation, which, increasing in diameter, are more easily separable in the centrifugal field.

Table 1. *Cont.*

Technological Effect	Malaxer	Sono-Heat Exchanger
Plolyphenols	The mechanical action of the malaxer is mild and has a negligible effect on the ability to release further amounts of polyphenols. The thermal effect is limited to heating only, and the long stirring times are compatible with the activation kinetics of the oxidase enzymes [31], polyphenol oxidase, and peroxidase; therefore, the times favorable for kneading lengths to increase yields correspond to a loss of polyphenols and a lowering of oil quality.	The cavitation phenomena efficiently break the cells of the epicarp of the drupe, releasing high concentrations of polyphenols. The immediate thermal lowering of the olive paste temperature after olive crushing to lower than 20 °C permits partial inhibition of the endogenous enzymatic activity by polyphenol oxidase and peroxidase. The consequence is the reduction of degradation of phenolic compounds.
Volatile compounds	The lipoxygenase (LOX) pathway [31], responsible for the hydroperoxydation of polyunsaturated fatty acids, is activated upon crushing and grinding olive fruit tissue, which subsequently leads to the synthesis of volatile compounds. This biochemical reaction requires few seconds, if thermal condition are favorable (<24 °C). The malaxer, being a bad heat exchanger, could penalize the functionality of the pathway causing disharmonious organoleptic profiles if the temperatures of the crushed olive paste are high.	The sonicated oils have a more harmonious organoleptic profile and are rich in volatile components, as not only do the ultrasounds not damage the lipoxygenase pathway, but the rapidity of the transformation of the fruit into extra virgin olive oil contributes to a more timely stabilization of the product, thus avoiding technological threats, which could result in the loss or alteration of the profile of volatile compounds.

The strengths of the system emerged from the results of functional tests and performance optimization. Preliminary tests conducted in the two industrial mills have shown that the use of Sono-Heat-Exchanger to replace the malaxers always resulted in an increase in the extraction yield, up to 21% vs. 19%, respectively, especially at low temperature (~20 °C). However, this happened without compromising the polyphenols' content of the EVOO, which not only did not decrease in any sample analyzed, but, depending on the variety and the ripeness index of the olives, could even increase compared to the measured values in the oils obtained using the malaxers. For instance, the compounds (namely, decarboxymethyl-oleuropein aglycone in open dialdehyde form, 77 vs. 74 mg/kg, decarboxymethyl-ligstroside aglycone in open dialdehyde form, 110 vs. 105 mg/kg, lignans, 98 vs. 84 mg/kg, and oleuropein and ligstroside aglycones, 27 vs. 25 mg/kg) quantified in EVOO from Coratina and Frantoio blend green olives by the HPLC-MS/MS method as described by De Santis et al., 2021 [32], were more concentrated in the Sono-Heat-Exchanger samples than the malaxer ones.

Moreover, EVOO extracted by the Sono-Heat-Exchanger showed the identical values of the analytical parameters used for the product classification as for the oils from the same batches of olives by using the malaxers. Finally, the sensory analysis of EVOOs revealed that the new technology (i.e., Sono-Heat-Exchanger) did not just cause defects in the product, but in general allowed to obtain more intensely fruity and more harmonious oils than the samples obtained by the use of malaxers.

The functional tests have showed that the Sono-Heat-Exchanger is the suitable solution to respond to the needs mapped in the community of millers because it is a continuous system suitable for replacing the current malaxers by significantly reducing extraction times. It is also a continuous plant capable of breaking the historical paradigm about the extraction yield inversely correlated to quality, freeing millers from the dilemma of choosing whether to produce large quantities of a standard EVOO or smaller quantities of an EVOO of excellence.

Furthermore, the Sono-Heat-Exchanger is a system characterized by ease of use and maintenance, and it is sustainable, as it is built in accordance with the objectives of the 2030 Sustainability Agenda, from the selection of materials to the attention to energy saving and water consumption.

Pieralisi company has dealt with the design and construction of the Sono-Heat-Exchanger by applying integrated company management systems certified according to the international standards UNI EN ISO 9001, a management system that continuously improves the quality of products and processes, and UNI EN ISO 14001, an adequate management system that keeps the environmental impacts of its activities under control and systematically seeks improvement in a coherent, effective, and, above all, sustainable way.

The Sono-Heat-Exchanger has been designed and built according to strict quality and safety standards, ensuring compliance with the main EU directives (Machinery Directive 2006/42/EC, Low Voltage Directive 2014/35/EU, Electromagnetic Compatibility Directive 2014/30/EU, ATEX Directive 2014/34/EU) with a view to reducing the impact on the environment, protecting the health and safety of workers, and seeking the highest quality standards in products and services.

4. Conclusions

The Sono-Heat-Exchanger is the suitable solution to respond to the needs mapped in the community of millers because it is a continuous system and the best substitute for the old malaxer, it breaks the historical paradigm between yield and quality of EVOO, it is a sustainable plant solution, and it improves the health quality of the product by enhancing its polyphenols content without causing undesired sensorial defects, thus placing it in a higher production range.

All the actors involved in the innovative processes are well aware that it is possible to distinguish three fundamental moments within the research and technology transfer path: (1) the invention, or the moment in which a potentially beneficial idea arises, but is not necessarily implemented in a concrete form of product or process; (2) the innovation, which consists of transforming ideas into new or improved products and processes capable of leading to an economic and/or social benefit; and (3) the dissemination, or the phase in which the utility of an innovation is made known to the company and the sector concerned can actually receive an economic and social benefit.

The next step of the partnership will concern the dissemination actions.

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