Mechanical Innovation for Sustainable Olive Oil Extraction: Application of Ultrasound and Thermal Integration

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Dedication

From the bottom of my heart and with great pleasure, I dedicate this final year project:

To my beloved parents, *Nouredine & Nedia*,

No words can truly express the depth of my respect, my eternal love, and my gratitude for all the sacrifices you have made for my education and well being. Thank you for your unconditional support and love since my childhood. I hope that your blessings will always accompany me throughout my life.

To my dear mother, thank you so much for your constant encouragement, motivation, and above all, your moral and spiritual guidance. You are the best mother in the world.

In memory of our sincere and deep friendship and the wonderful moments we have shared together. Please accept through this work the expression of my deepest respect and sincere affection.

To everyone who contributed to the realization of this project, Your support, advice, and kindness have been invaluable. This accomplishment is also yours.

Acknowledgment

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Abstract

This work presents the design, modeling, and simulation of a continuous **Ultrasonic Thermal Inline Reactor (UTIR)** for sustainable extra virgin olive oil extraction. The proposed system integrates a **double tube heat exchanger** for rapid thermal preconditioning and an **ultrasonic reactor** for enhanced oil recovery and preservation of bioactive compounds. Analytical design calculations were performed to size the heat exchanger, and the **CFD simulations (SolidWorks Flow Simulation)** that validate the thermal performance are presented in the final section.

The system demonstrated stable operation with minimal energy loss. Compared to a traditional two phase mill, where malaxation requires about **45 minutes** and the average extraction efficiency is **86.7%**, the UTIR enables a continuous process with a reduced processing time of only **10–25 minutes** by combining thermal and ultrasonic treatment inline. The integration of ultrasound increases extraction performance by up to **+5.5 points**, allowing yields of **92.2%** and a final oil recovery of **25–27%** instead of the typical 21%. the UTIR provides a continuous, and environmentally sustainable alternative to conventional batch malaxation, suitable for medium scale industrial operation and supporting modernization of the olive oil sector.

Keywords: Olive oil extraction; ultrasound; heat exchanger; CFD simulation; sustainable processing; SolidWorks Flow Simulation; continuous reactor.

Resumo

Esta dissertação apresenta o projeto, modelação e simulação de um **Reator Térmico Ultrassónico em Linha Contínua (UTIR)** concebido para melhorar a eficiência e a sustentabilidade do processo de extração de azeite virgem extra (EVOO). O sistema integra um **permutador de calor de tubos concêntricos** para o aquecimento rápido da pasta de azeitona e um **reator ultrassónico** que utiliza cavitação acústica para potenciar a libertação do azeite.

A integração dos ultrassons aumentou a eficiência de extração em até **5.5 %** permitindo rendimentos de **92,2%** em comparação com os sistemas convencionais de duas fases. Enquanto a malaxagem tradicional apresenta um rendimento de cerca de 21%, o sistema UTIR pode alcançar **26–27% de rendimento**, assegurando uma qualidade superior do azeite e um tempo de processamento reduzido. Foram realizadas análises analíticas e **simulações CFD** (SolidWorks Flow Simulation) para avaliar o desempenho térmico e hidráulico. Os resultados demonstraram um funcionamento estável, com temperaturas de saída de aproximadamente 58.5 °C para a água e 21.8 °C para a pasta.

O sistema UTIR proposto oferece uma solução **contínua e ambientalmente sustentável**, ideal para lagares de média dimensão, promovendo a modernização e o desenvolvimento sustentável do setor oleícola.

Palavras-chave: Extração de azeite; ultrassons; trocador de calor; simulação CFD; processamento sustentável; SolidWorks Flow Simulation.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Introduction

Extra virgin olive oil (EVOO) represents not only a staple of the Mediterranean diet but also a high value product appreciated for its sensory, nutritional, and health promoting properties [1]. Despite advances in automation and mechanical design, conventional extraction systems, particularly those based on batch malaxation, are still constrained by several limitations. These include long residence times, significant energy consumption, limited extractability, and partial loss of bioactive compounds such as polyphenols and tocopherols [2]. Furthermore, conventional methods can contribute to the generation of large volumes of wet pomace and olive mill wastewater, creating environmental and logistical challenges [3].

In response to these limitations, researchers and engineers have explored innovative techniques such as ultrasound assisted extraction (US), microwave heating (MW), megasonics (MS), and pulsed electric fields (PEF). These emerging technologies aim to enhance oil yield, reduce processing time, preserve minor compounds, and decrease environmental impact [4], [5]. However, many of these approaches remain underutilized at the industrial scale, particularly in small and medium sized olive mills, due to cost, complexity, or integration challenges [6].

1.2 Goals

This thesis proposes a new mechanical solution: the **Ultrasonic Thermal Inline Reactor (UTIR)**, developed in partnership with **Arnox** Engineering is a global leader in CAD, CAM, CAE, PDM, and PLM training and consulting. Its programs are delivered by internationally recognized experts to meet the evolving needs of industry professionals[7]. This continuous flow system integrates controlled thermal preconditioning and ultrasonic cavitation to improve olive paste conditioning before oil separation. Unlike traditional malaxers, the UTIR is designed to increase extraction efficiency, preserve phenolic content, and minimize energy consumption and waste.

By exploring this hybrid solution, the study contributes to the advancement of innovative, scalable, and sustainable technologies in olive oil production. It targets not only improved technical performance but also alignment with evolving regulatory and market demands for higher quality, environmentally responsible EVOO.

1.3 Structure and Organization of the Thesis

This thesis is organized into five main chapters, each addressing a specific aspect of the study and contributing to the overall objective of designing and evaluating an innovative **Ultrasonic Thermal Inline Reactor (UTIR)** for extra virgin olive oil (EVOO) extraction.

- **Chapter 1: Introduction:** Presents the background, motivation, objectives, and structure of the thesis.
- **Chapter 2: State of the Art and Technological Evolution:** Reviews the historical and technological development of olive oil extraction, from ancient pressing methods to modern centrifugation based systems. It also discusses process optimization using three and two phase decanters, technical limitations in current technologies, and emerging physical techniques such as heat exchangers and ultrasound for enhancing extraction efficiency.

- **Chapter 3: Design Methodology and System Calculations:** Describes the case study of the Taher Bouzid olive oil mill, identifying process limitations and proposing improvement strategies. It includes design objectives, system calculations, and sizing of the heat exchanger, ultrasonic treatment section, and tank dimensions.
- **Chapter 4: Design and Development of the Olive Oil Extraction System:** Details the overall system architecture and the design of key components, including the heat exchanger, ultrasonic reactor, crushing and separation systems, and oil collection unit.
- **Chapter 5: Simulation of the Heat Exchanger System:** Presents the CFD based simulation and validation of the designed heat exchanger using **SolidWorks Flow Simulation**. It covers boundary conditions, flow trajectories, temperature profiles, and heat transfer results to verify the system's thermal performance.

Chapter 2

State of the Art and Technological Evolution

2.1 Introduction

Olive oil has been a cornerstone of Mediterranean culture, nutrition, and commerce for more than 4,000 years. From the rudimentary pressing stones of Minoan civilization to the sophisticated centrifugate systems of today, olive oil extraction has evolved alongside human ingenuity. Despite significant mechanical and technological advances, the modern olive oil industry continues to face challenges related to extraction efficiency, environmental sustainability, and product quality. With the growing global demand for extra virgin olive oil (EVOO) and the increasing emphasis on clean technologies, the need for innovative extraction methods has become more urgent than ever. This chapter provides a comprehensive review of the historical, traditional and modern evolution of olive oil production systems, identifies critical limitations, and introduces advanced physical processing technologies aimed at enhancing oil recovery and quality [8].

2.2 History of Olive Oil Extraction

Olive oil is believed to have been discovered by primitive, barefooted, and unclothed humans who accidentally crushed fallen olive fruits and observed that the released oil softened and moisturized their hardened sole [9]. These are the most important civilizations famous for olive oil production and their machines

2.2.1 Minoan Civilization , 3000 BCE

In the ancient Minoan civilization, olive oil production was not only a practical activity but also a refined artisanal craft that demonstrated the community's ingenuity in harnessing natural resources. The process began with the careful selection of mature olives, which were placed into hand carved stone basins. Lukewarm water was added to facilitate the softening of the olive pulp and reduce paste viscosity. The olives were then crushed manually using a rudimentary stone mortar a device featuring a central protrusion within a concave basin. This allowed for effective breakdown of the fruit into a homogenous paste. As the mixture settled, the lighter oil gradually separated from the water and pulp, rising to the surface where it was meticulously skimmed off, as illustrated in Figure 2.1. This extraction technique served both culinary and medicinal purposes and laid a foundational framework later advanced by Greek and Roman technologies. The compact, domestic-scale nature of the Minoan apparatus highlights the early Mediterranean legacy of iterative technological refinement in olive oil production [9], [10].

Figure 2.1: Findings from the Phaistos archaeological site [10]

The Figure 2.2 illustrates key olive oil extraction tools discovered at the Minoan Palace of Phaistos. It features a stone crusher and a shallow basin likely used to process the olive paste, along with a large ceramic storage jar (pithos) intended for storing the extracted oil. These artifacts reflect the technical sophistication and domestic scale of early olive oil production in Minoan society[9].

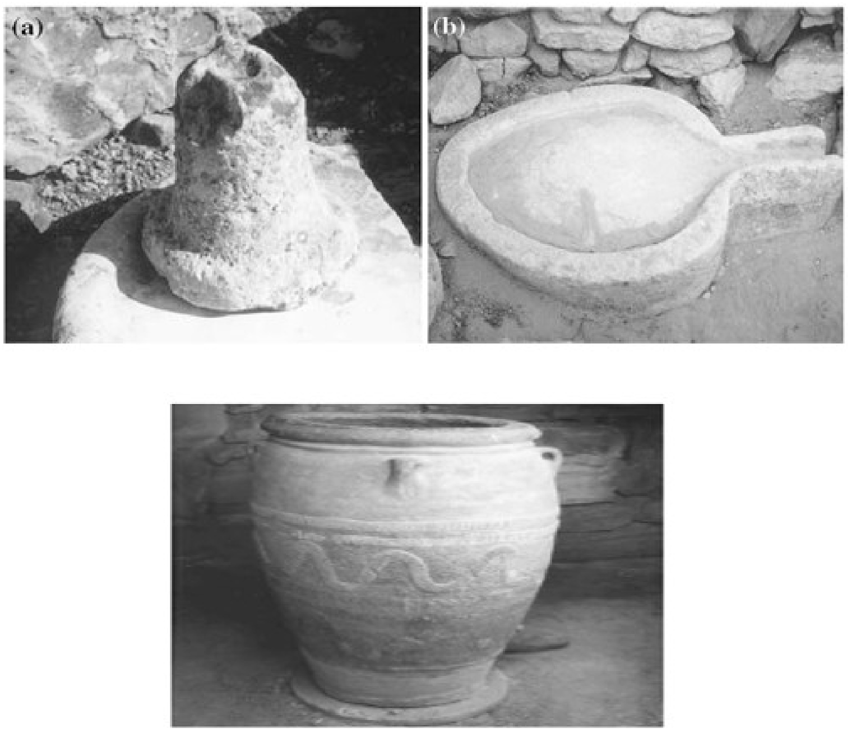

Figure 2.2: Tools from the Minoan Palace of Phaistos used for olive oil extraction [9]

Figure 2.3 presents a two part visual representation of ancient olive oil processing at Venerato, in central Heraklion. Part (a) displays the carved stone troughs embedded directly into the bedrock. These semi-permanent installations were designed for large-batch processing and reflect an early attempt at scaling production beyond household use. Olives were deposited into these troughs along with a small amount of water to facilitate the separation of oil [10].

Part (b) illustrates the operational sequence: a cylindrical stone roller was used to crush the olives into a uniform paste within the trough. Due to differences in density, the oil gradually floated to the surface while the denser solid residues settled below. This passive separation technique enabled efficient oil recovery without mechanical centrifugation. Together, these visual elements depict a system optimized for communal or high-volume olive oil extraction, offering insight into early innovations that laid the groundwork for modern techniques [10].

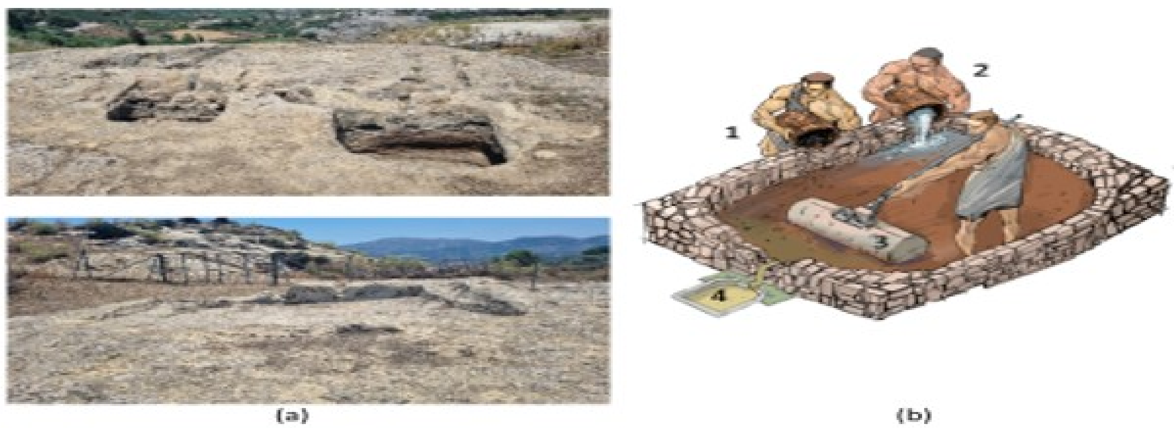

Figure 2.3: (a) Carved troughs at Venerato; (b) Illustration of the traditional olive oil extraction process [10].

2.2.2 Greek civilization in the 5th century BCE

In ancient Greek olive oil production, the evolution of mechanical apparatuses represented a major leap in both efficiency and consistency of extraction [10]. Central to this progress was the development of the *Trapetum*, a rotary mill featuring two counter rotating millstones positioned around a fixed central mortarium. These stones, typically crafted from durable volcanic or basaltic rock to withstand wear, rotated at controlled speeds to impart kinetic energy to the olive mass. The design harnessed both frictional and compressive forces to rupture olive cells and facilitate oil release. The millstones were often concave with radial grooves, which intensified shear stress on the olive tissue, thereby producing a more uniform, high quality paste, as illustrated in Figure 2.4[11].

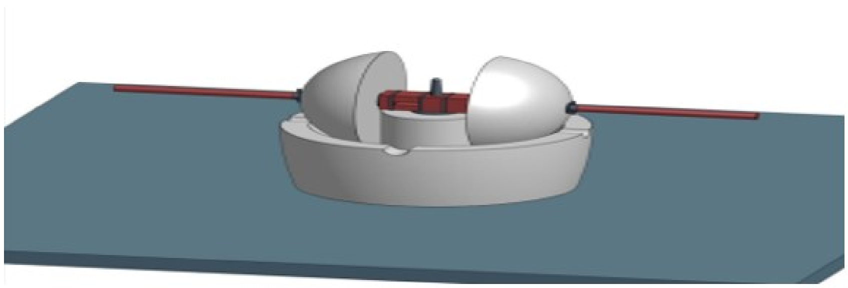

Figure 2.4: Trapetum [11]

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The Trapetum system operates in three streamlined steps, as illustrated in figure 2.5 below. First, ripe olives are evenly placed into a fixed central mortar. Next, two counter rotating millstones typically made from durable volcanic rock crush the olives by applying both friction and pressure, breaking down their cellular structure into a uniform paste. Finally, the resulting olive paste is collected through an outlet system for further processing. Similar installations have been discovered in Aptera, Chania, Skopi, Trypitos, and Sitia, demonstrating the widespread use of this efficient extraction method throughout the region [10].

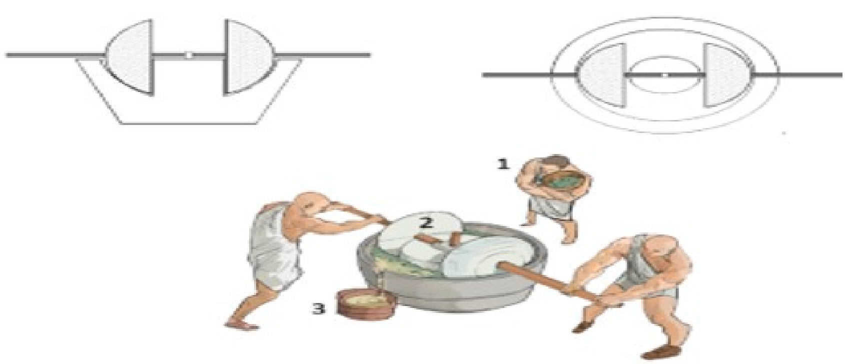

Figure 2.5: illustration of the mode of the Trapetum [10]

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2.2.3 Roman Civilization in the 8th Century CE

Roman olive oil production saw significant advancements beyond earlier Greek methods through innovations that enhanced efficiency and enabled large-scale processing.The new technologie , often powered by animals and later hydraulic means, contributed to more durable equipment, higher oil yields, and greater scalability to meet commercial demands. An example of such traditional machinery is shown in Figure 2.6 [10].

Figure 2.6: The rotary mill animal-powered with larger cylindrical millstones [10].

The rotary mill, shown in Figure 2.7, illustrates a traditional Roman oil extraction method using an animal-driven system known as a "ghani." In this setup, a horse turns a wooden beam in a circular motion, rotating a heavy grinding stone that crushes oilseeds. The oil, extracted by pressure, is collected in a container placed at the edge. This process represents an early form of cold pressed oil production and relies entirely on animal power [10].

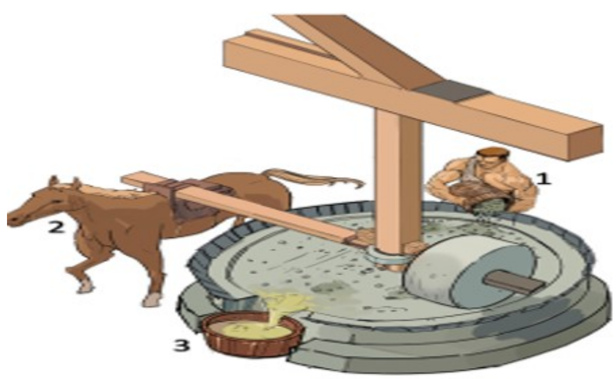
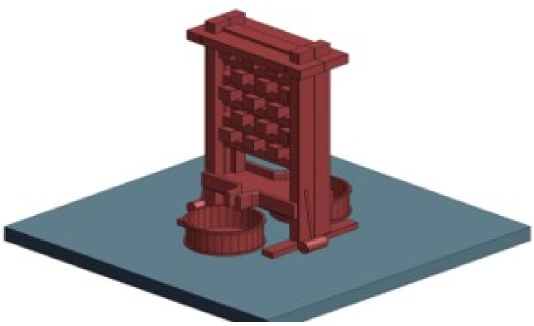
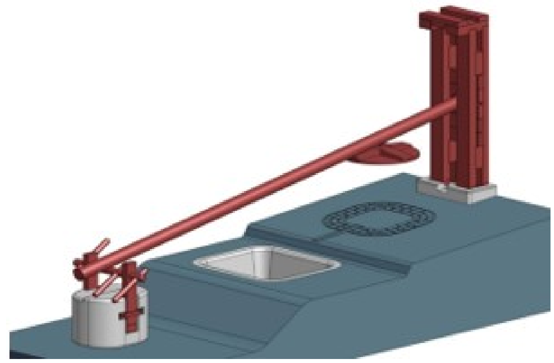


Figure 2.7: Illustration of olive oil production in Roman civilization [10].

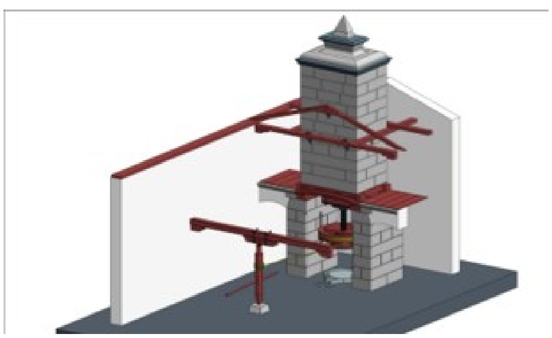
Figure 2.8 shows various types of Roman press machines used for extracting oil or juice from olives and grapes. These presses, such as the wedge, winch, tower, and corner press, demonstrate the ingenuity of Roman engineering in maximizing mechanical advantage and productivity for communal or commercial use [11].



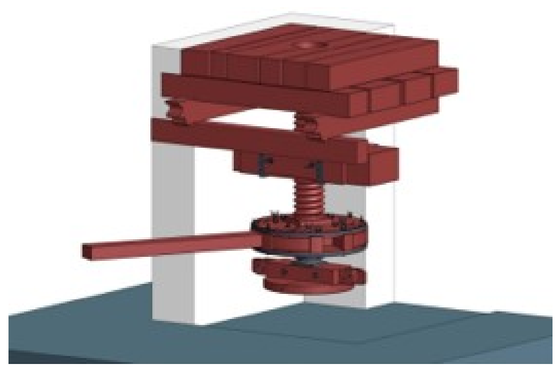
(a) Wedge press



(b) Winch press



(c) Tower press



(d) Corner press

Figure 2.8: Different types of Roman press machines [11].

2.2.4 Modern Civilization – 19th Century

During the 19th century, olive oil production underwent a major transformation as it began shifting from manual methods to mechanized processes, marking the dawn of industrialization in the field. One of the most significant developments during this era was the introduction of mechanical lever and screw presses. These machines replaced earlier stone and wooden systems, providing a more consistent and powerful means of applying pressure to the olive paste, which resulted in higher oil yields and more efficient extraction [9], [10].

Later in the century, hydraulic press systems were introduced, utilizing Pascal's principle to create high pressure environments. Although many of these were still manually operated, they allowed for greater uniformity in processing and significantly reduced physical labor. However, olive oil production during this period remained batch based: olives were first crushed using stone or metal mills, then the resulting paste was placed into mats or pressing compartments for oil extraction [10].

Figure 2.9 depicts a typical 19th-century olive press system with a metal frame and portable stone settling vats. This type of press combined mechanical strength with gravity based separation methods, offering better oil quality control compared to earlier systems [10].

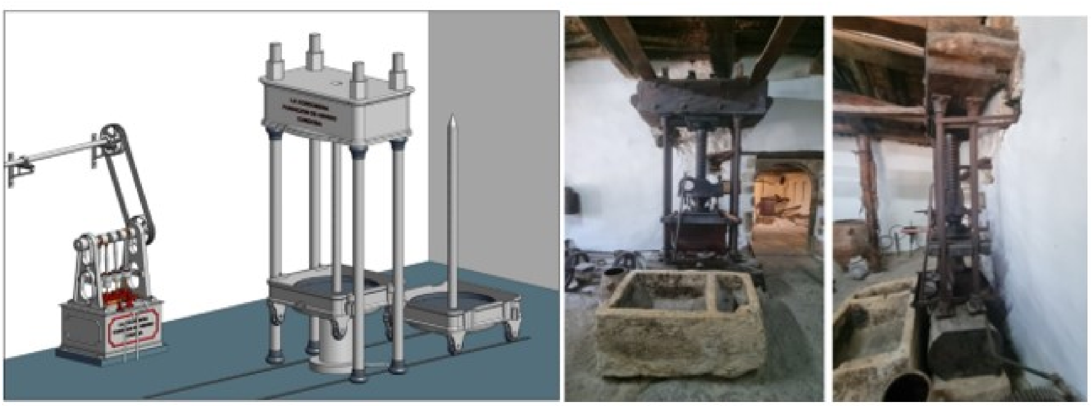


Figure 2.9: An olive press with portable stone successive settling vats [10]

The extracted mixture containing oil, water, and solid residues was directed into a three-stage settling system for separation. This is clearly illustrated in Figure 2.10, which provides a schematic overview of olive oil processing and the associated waste streams. The diagram outlines the four major stages: **crushing**, **pressing**, **separation**, and **storage** [9].

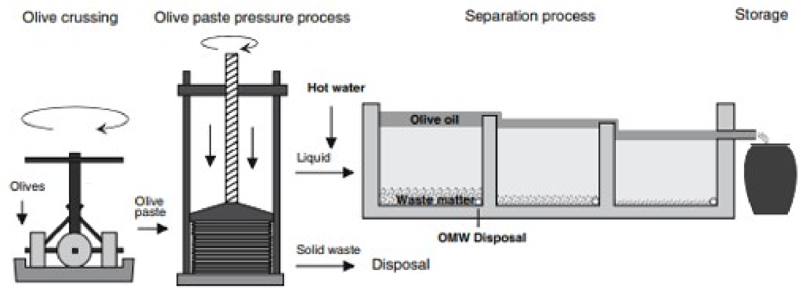


Figure 2.10: Schematic overview of a three-tank olive oil separation system [9].

The three tank separation system played a crucial role in refining the oil and enhancing it's quality:

- **Tank 1:** Heavy solids and sediment settled to the bottom.
- **Tank 2:** Gravity separation occurred oil floated to the top, while water and finer particulates sank.
- **Tank 3:** Final clarification removed any remaining impurities to produce cleaner oil.

Once separated, the oil was transferred to sealed storage containers, often made of clay or metal, and occasionally filtered before bottling. Although innovations such as electric crushers and centrifuges had not yet emerged, the advancements made during the 19th century laid the essential groundwork for the fully continuous, industrialized systems that would define olive oil production in the 20th century [9].

2.3 Methodology and Contemporary Processing of Olive Oil

The methodology of the review involves analyzing the major transformations in olive oil production in the past 50 years by dividing the production chain into three key stages:

cultivation and harvesting, oil extraction and waste by product management. This structured approach helps assess how irreversible these changes are, how quickly they occurred, and what future trends might emerge [12]

2.3.1 Optimization of Olive Oil Extraction with Three phase decanter system

Modern olive oil milling relies on advanced, automated machinery that ensures efficiency, hygiene, and high quality oil production. These systems have replaced traditional stone mills and manual presses, improving extraction performance and preserving the oil's nutritional and sensory properties [11]. The resulting paste undergoes malaxation for 20–60 minutes, allowing oil droplets to coalesce while maintaining temperatures below 30°C to preserve polyphenols and aroma [13].

In modern installations, such as the one shown in Figure 2.11, centrifugation replaces traditional pressing. The three phase decanter, introduced in the 1960s, separates oil, pomace, and vegetation water but requires additional water (20% of olive weight), which reduces phenolic content and increases wastewater generationr [12]. Today's fully automated systems have improved hygiene, energy efficiency, and product quality [10]. On average, 1 kg of olive oil is obtained from about 5 kg of olives [9].

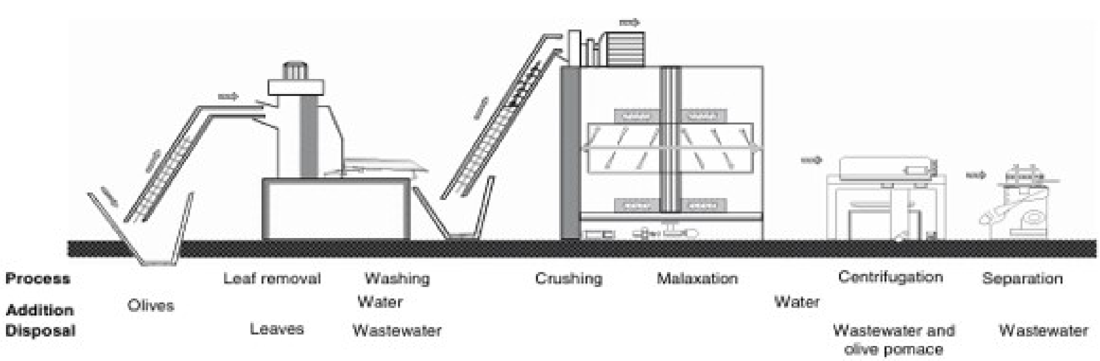


Figure 2.11: A modern olive oil mill based on the centrifugation process [9].

Figure 2.12 illustrates a real industrial extraction line, representing a fully automated and continuous olive oil production system.

Figure 2.12: Real image of an industrial olive oil production unit [13].

The three phase extraction process, shown in Figure 2.13, starts with 4 tons of olives per hectare. After removing 0.32 tons of leaves and adding 2 tons of water, the process yields 0.8 tons of olive oil, 2.27 tons of wet husk, and 2.61 tons of wastewater. The husk includes 1.94 tons of pomace and 0.33 tons of pits, leaving about 0.9 tons of exhausted pomace after further treatment [14]. Despite lower pomace moisture (15–25% in pits, 40–50% in pomace), the three phase system produces significantly more polluting wastewater than the two-phase process [14].

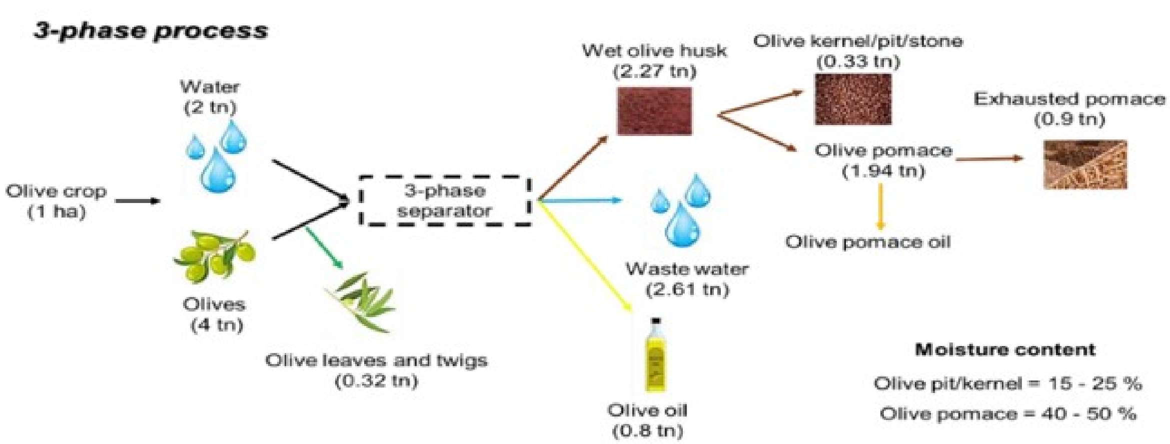


Figure 2.13: The three-phase olive oil extraction process [14].

2.3.2 Optimization of Olive Oil Extraction with Two Phase Decanter System

To overcome the environmental and quality limitations of the three phase process, the two phase decanter system was introduced in the 1990s and quickly adopted worldwide. Unlike the three-phase method, it does not require additional water during centrifugation, producing only two outputs olive oil and wet pomace thus reducing wastewater and environmental impact [15].

The absence of dilution preserves more phenolic compounds, enhancing both nutritional and sensory quality. Yields are generally comparable or higher than older systems, making this method the preferred choice for modern producers [15]. After extraction, oil undergoes vertical centrifugation to remove residual moisture and solids, ensuring purity and aroma retention [14].

As shown in Figure 2.14, processing 4 tons of olives (from 1 ha) in a two-phase separator yields 0.8 tons of olive oil and 2.88 tons of wet husk, containing about 2.46 tons of pomace and 0.42 tons of pits. Further pomace oil extraction produces roughly 1.3 tons of exhausted pomace. However, high moisture content (30–35% in pits, 60–80% in pomace) remains a major drawback [14].

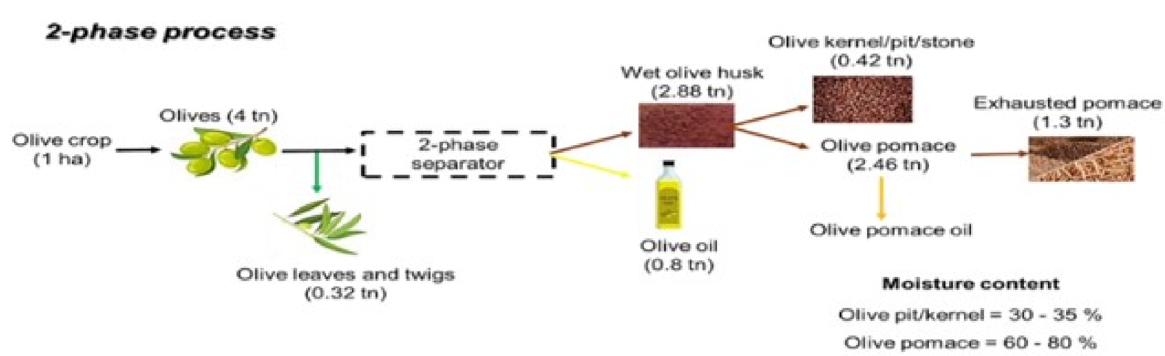


Figure 2.14: Two phase olive oil extraction process [14].

2.3.3 Technical Constraints in Existing Olive Oil Processing Methods

Each olive oil extraction method presents specific advantages and limitations, as illustrated in Figure 2.15. The two phase system prioritizes oil quality and environmental sustainability by eliminating added water during centrifugation, thus avoiding olive mill wastewater (OMW) generation and preserving antioxidants in the final oil. However, it produces wetter pomace (≈ 800 kg *alperujo*) that is more difficult to handle and requires precise technical control, which may increase operational costs [11], [16]. Conversely, the **three-phase system** is well suited for large scale processing and facilitates by product recovery (≈ 550 kg dry olive cake). Yet, it requires additional hot water (0.6–1.3 m^3) and produces large volumes of OMW (≈ 1–1.6 m^3), leading to higher treatment costs and dilution of phenolic compounds [16]. Both systems yield similar oil quantities (≈ 200–210 kg per 1000 kg of olives), but different in efficiency and environmental performance [16].

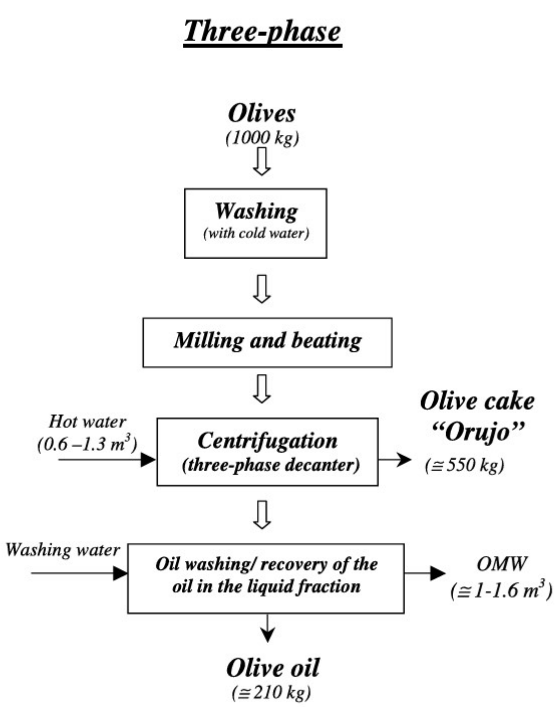


Figure 2.15: Comparison of the three and two phase centrifugation systems [16].

As shown in Figure 2.16, the two phase system eliminates added water and reduces environmental impact compared with traditional pressing and three stage decanters. Although it generates wetter pomace (0.8–0.95 t/t, 3% residual oil), it achieves similar yields (0.2 t/t) and remains the most efficient and sustainable extraction option [12].

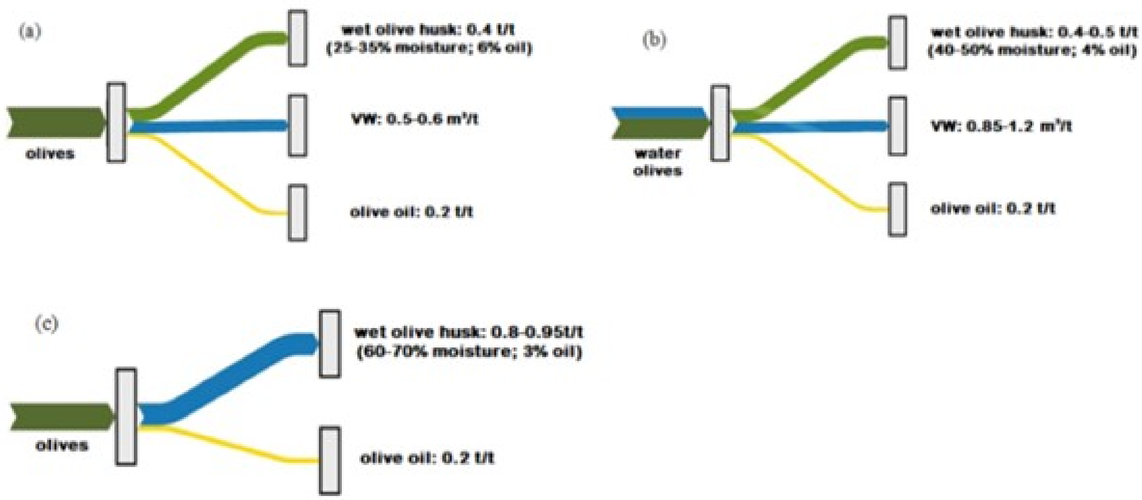


Figure 2.16: Olive oil extraction processes and by product outputs for different systems [12].

2.4 Innovative Physical Technologies for Enhancing Extra Virgin Olive Oil Extraction Efficiency

2.4.1 Heat Exchangers (SHE and AHE)

Heat exchangers (AHEs) are used to preheat olive paste before malaxation, ensuring rapid and uniform temperature control. This helps reduce malaxation time, limits microbial growth, and improves enzymatic activity management, all of which enhance oil quality. However, since AHEs do not break olive cell walls, their role is limited to thermal conditioning rather than increasing oil yield [4].

Figure 2.17 shows a counter current heat exchanger where the olive paste (red/green channels) flows opposite to a heating fluid (blue channels). This design allows efficient heat transfer, with inlets and outlets labeled A–D for paste and fluid flow. [4].

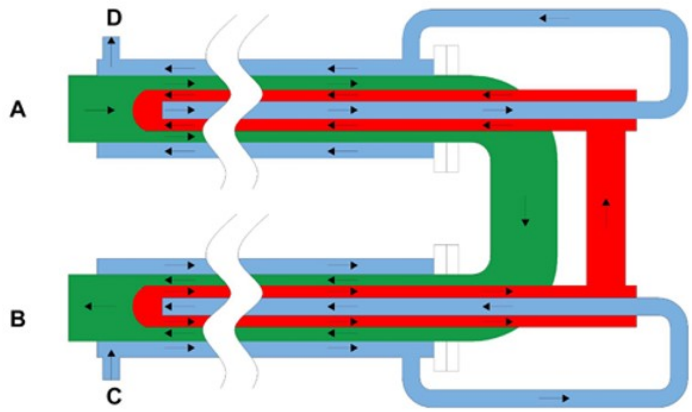


Figure 2.17: Schematic Diagram of a Double Tube Heat Exchanger [4].

2.4.2 Microwave (MW) Treatment

Microwave (MW) technology enables rapid and uniform heating of olive paste, reducing thermal conditioning time from about 40 minutes to under one minute. It inactivates degradative enzymes such as PPO, helping preserve phenolic compounds and reduce oxidation. Figure 2.18 shows the MW unit, including the reverberant chamber (1), magnetrons (3), and paste inlet and outlet (4–5) [4]. .

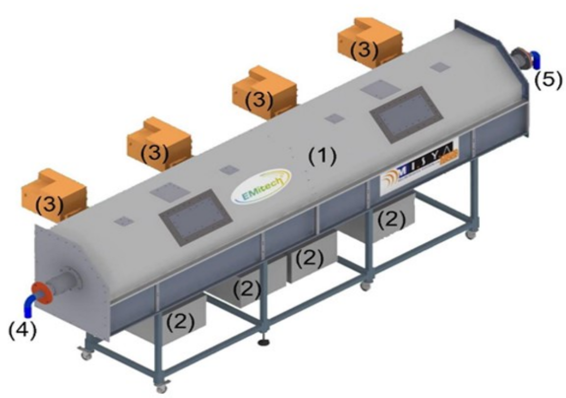


Figure 2.18: MW represented as a unit operation [4].

2.4.3 Ultrasound (US)Technology

Ultrasound (US) technology enhances olive oil extraction through acoustic cavitation, where collapsing microbubbles generate shear forces that rupture cell walls, improving oil release and extractability by 5–10% [5]. It also promotes droplet coalescence and phenolic transfer, enhancing oil quality. US can be applied before, during, or instead of malaxation, though excessive intensity may degrade sensitive compounds. Figure 2.19 shows a typical US system with a sonotrode, booster, power generator, and flowcell for continuous paste treatment [4].

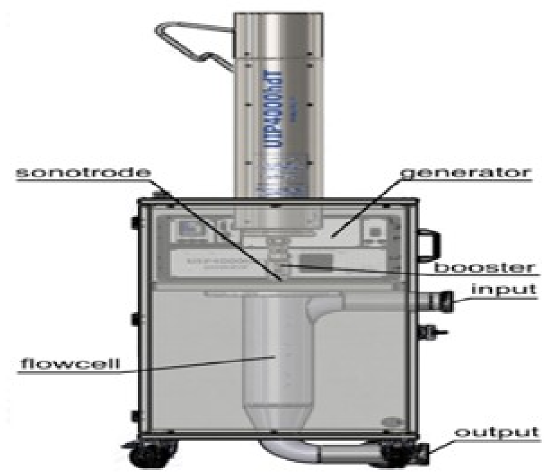


Figure 2.19: Representation of an US equipment used in industrial trials [4].

2.4.4 Megasonic (MS)

Megasonic (MS) technology utilizes high frequency acoustic waves (typically above 400 kHz) to enhance olive oil extraction [4]. Unlike conventional ultrasound, which produces strong cavitation and mechanical effects, MS generates gentler cavitation that disrupts olive cell membranes while minimizing damage to sensitive bioactive compounds [6]. This improves oil release and enhances the migration of phenolic compounds into the oil phase, leading to better nutritional and sensory quality. Additionally, MS is non-thermal and energy-efficient, making it a promising alternative to traditional mechanical methods [4].

Figure 2.20 presents an industrial megasonic setup integrated with a decanter system (Amenduni REC250), demonstrating its potential for continuous, large-scale processing. The technology is implemented upstream of phase separation, allowing the olive paste to be conditioned acoustically before reaching the decanter [4].

Figure 2.20: Megasonic reactor set for operation [4].

A more detailed view of the processing line is shown in Figure 2.21. After initial operations like defoliation (B), washing (C), and crushing (D), the olive paste is pumped through a series of megasonic reactors (F). These units apply acoustic energy to enhance oil extraction prior to the decanter (G) and vertical centrifuge (H), which complete the separation of the oily and aqueous phases. This configuration highlights MS as a modular, integrable step aimed at improving yield and oil quality without relying solely on malaxation [4].

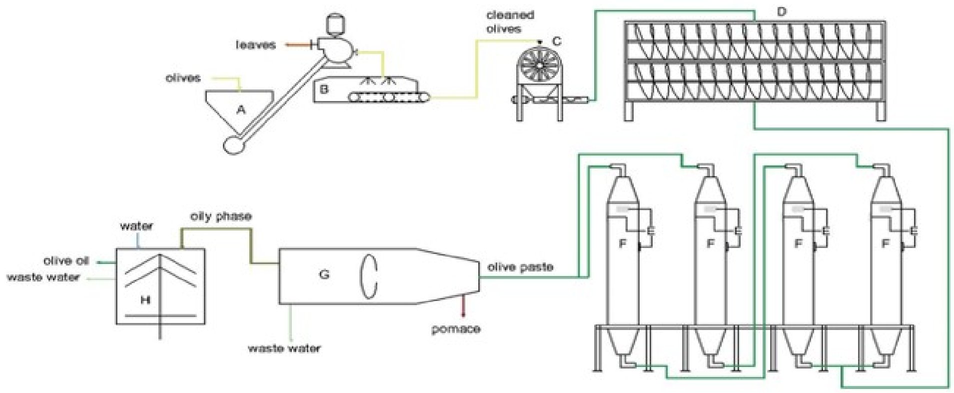


Figure 2.21: layout of the industrial olive oil plant [4].

2.4.5 Pulsed Electric Fields (PEF)

Pulsed Electric Field (PEF) technology is emerging as a highly promising innovation in olive oil extraction. It works by delivering short pulses of high-voltage electric fields up to 50 kV/cm to the olive paste, inducing electroporation of cell membranes. This process facilitates the release of oil and bioactive compounds during the subsequent centrifugation stage, improving extractability. PEF has been shown to increase oil yield by 5–15% and, in some cases, allows for reduced or even eliminated malaxation, leading to significant time and energy savings [4]. In addition to improving yield, PEF treatment helps preserve or enhance phenolic content and antioxidant levels, thereby improving oil quality[17].

Figure 2.22 presents the integration of a continuous PEF system (5) into a full olive oil extraction line. After defoliation (2), washing (3), and crushing (4), the olive paste passes through the PEF unit before entering the malaxers (6). The treated paste is then pumped (7) to a horizontal decanter (8) for initial separation, followed by vertical centrifugation (9) to isolate oil from water. This layout demonstrates how PEF can be efficiently incorporated into traditional extraction workflows to enhance yield and oil quality [4].

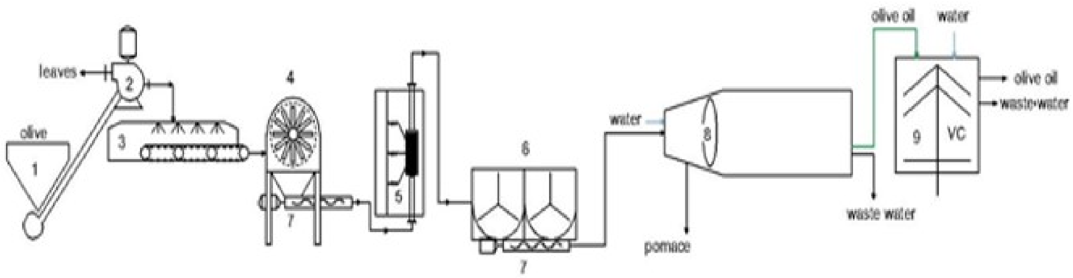


Figure 2.22: Layout of olive oil extraction line including a PEF system [4].

2.4.6 Technology Comparison Summary

New physical techniques aim to boost olive oil yield, preserve quality, and improve efficiency. The tables below compare their advantages, limitations, and readiness for industrial use.

Table 2.1: Comparative Performance of Innovative Olive Oil Extraction Technologies [4]

Technology	**Oil Recovery ↑**	**Phenolics ↑**	**Processing Speed**
AHE/SHE	baseline	+12–27% high	Thermal control[6]
MW	baseline	Phenolics ↓	Fastest process[18]
US	+5–6%	+24–41% best	Before/after MM[5]
MS	+3.7–3.9%	Likely ↑	Post-MM[6]
PEF	+6% highest	Expected moderate	Post-MM, fast[17]

Table 2.1 summarizes the main innovative technologies for olive oil extraction, comparing their effects on oil recovery, phenolic preservation, and processing time. Advanced Heat Exchangers (AHE/SHE) maintain standard oil recovery while increasing phenolic content by 12–27% through precise thermal control. Microwave (MW) treatment is the fastest method but tends to reduce phenolic content. Ultrasound (US) provides a balanced improvement, enhancing oil yield by 5–6% and phenolics by 24–41%. Megasonics (MS) offer moderate gains in yield (3.7–3.9%) and phenolic retention, while Pulsed Electric Fields (PEF) achieve the highest oil recovery improvement (6%) with moderate phenolic enhancement. Overall, each method presents trade-offs between efficiency, speed, and oil quality [4].

Table 2.2: Advantages and Limitations of Emerging Olive Oil Extraction Technologies

Technology	Advantages	Limitations
Heat Exchangers(AHE/SHE)	-Ensures uniform heating of olive paste -reduces thermal shock -easily integrated into existing liness [6].	-Does not rupture cell walls -ineffective alone in improving yield -requires combination with other techniques -involves capital cost for thermal units [6].
Microwave (MW)	-Provides rapid and uniform heating -shortens processing time -may replace malaxation under optimized use [18].	-performance varies by olive type and moisture -needs precise tuning -commercial systems are costly [18].
Ultrasound (US)	-Enhances oil recovery (5–10%) -improves phenolic extraction -supports continuous flow -energy efficient when optimized [5].	-May degrade sensitive compounds at high intensity -requires fine tuned settings (power, time, frequency) -high initial investment [5].
Megasonics (MS)	-Delivers mild cavitation -preserves phenolics -non thermal and energy efficient [6].	-Technology still maturing (TRL 6–7) -large footprint -high equipment cost -not yet widely scalable [6].
Pulsed Electric Fields (PEF)	-Increases yield by up to 15% -preserves antioxidants -can reduce or replace malaxation -speeds up extraction [17].	-High capital and energy costs -requires trained operators -limited regulatory adoption -sensitive to process parameters [17].

Despite offering numerous benefits, these innovative technologies each face technical, economic, or operational barriers that hinder widespread adoption as it show in the Table 2.2 . As the demand for sustainable and efficient EVOO production grows, further research and system optimization are needed to overcome these limitations and enable full industrial deployment of these advanced methods.

2.5 Objective of the Study

Our objectives of this study is to develop and evaluate an innovative mechanical solution to enhance the extraction efficiency of extra virgin olive oil (EVOO). Based on our analysis of the benefits and limitations of emerging extraction technologies, we propose the design and integration of an Ultrasonic Thermal Inline Reactor into the olive oil pressing line. This approach aims to increase oil yield while preserving the quality of the final product.

Ultrasound technology has demonstrated strong potential to improve extraction efficiency without compromising key quality attributes of olive oil. In particular, it enhances the recovery of bio active compounds such as polyphenols and tocopherols. To further optimize performance, we also suggest preheating the olive paste before ultrasonic treatment, as thermal conditioning can enhance the effects of cavitation and improve cell wall disruption.

The proposed system combines controlled thermal preconditioning with ultrasonic cavitation to more effectively break down olive cell structures compared to conventional malaxation. This study will assess reactor performance in terms of increased oil production, reduced processing time.

2.6 Types of Ultrasonic Systems

2.6.1 Sonotrode equipped ultrasonic reactor

The ultrasonic extraction stage is a horn type ultrasonic flow cell reactor that enables continuous olive paste processing. As shown in Figure 2.23, a piezoelectric transducer, booster, and titanium sonotrode convert electrical power into high frequency vibrations (20–25 kHz), producing cavitation that ruptures olive cell walls and releases oil and phenolic compounds with minimal thermal impact. As the paste flows through the sealed chamber, rapid oscillations generate localized shear and micro jets that break down cell structures. A dedicated control unit adjusts amplitude, power, and treatment time to ensure precise control, higher extraction yields, and preserved oil quality[19].

Figure 2.23: Real photo and schematic diagram of a flow cell ultrasonic reactor[19].

2.6.2 Flow Cell Ultrasonic Reactors

The flow cell ultrasonic reactor is a closed system designed to treat liquids continuously as they pass through a chamber equipped with an ultrasonic sonotrode. Inside the unit, a piezoelectric transducer converts electrical energy into high frequency vibrations, which are transmitted into the product stream to create intense cavitation. This phenomenon generates microscopic bubbles that rapidly form and collapse, producing localized shear forces and shock waves that break down cell structures, enhance mass transfer, and improve extraction efficiency [19].

The Figures illustrate both the internal configuration of the reactor and a real photo of the device. The schematic (2.24) shows how the sonotrode is positioned in the flow channel to ensure that the entire liquid stream is exposed to the ultrasonic field, while the photograph (2.25) highlights its compact and hygienic design for continuous inline processing [19].

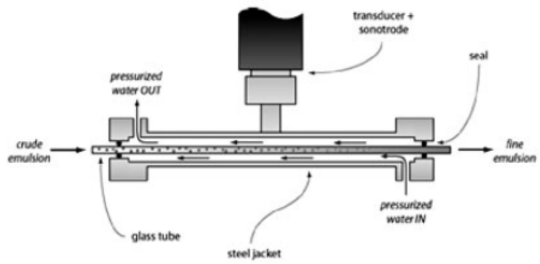


Figure 2.24: Schematic diagram of a flow cell ultrasonic reactor[19].

Figure 2.25: real photo of a flow cell ultrasonic reactor[19].

2.6.3 Plate Mounted Ultrasonic Transducers

A plate-mounted ultrasonic transducer is an external system designed to deliver ultrasonic energy into a tank or reactor without direct contact with the product. Several piezoelectric transducers are bonded to a stainless steel plate that is fixed to the outside wall, making the setup compact, hygienic, and easy to maintain.

As shown in Figure 2.26, the transducers excite the plate at ultrasonic frequencies (typically 20–40 kHz), causing it to vibrate and transmit energy through the wall of the vessel to the liquid or paste inside. These vibrations generate violently collapsed cavitation bubbles, producing shear forces that intensify mixing, enhance extraction, or support cleaning processes. This configuration is particularly suitable for food applications, such as the processing of olive paste, where sanitation and space efficiency are essential [20]

Figure 2.26: Plate mounted ultrasonic transducer unit [20].

Table 2.3 compares different ultrasonic reactor, outlining their main advantages and limitations in terms of efficiency.

Table 2.3: Comparison of ultrasonic reactor configurations for olive paste processing

Ultrasonic Type	**Advantages**	**Disadvantages**
Ultrasonic Reactor	- Higher extraction yield and faster processing. - Better preservation of antioxidants. - Precise control of parameters (amplitude, time, power) [21].	- Ultrasound weakens with distance in viscous paste. - Reactor design and cleaning can be complex. - Local heating [21].
Flow Cell Ultrasonic Reactor	- High reproducibility. - Flexible geometry and material selection. - Good chemical compatibility and hygiene. - Higher throughput [22].	- Scaling trade-offs. - Potential risk of clogging with high-viscosity olive paste. - Possible dead zones [22].
Plate-Mounted Ultrasonic Transducers	- Easy cleaning and maintenance. - Permanent and robust installation. - Hygienic design [23].	- Lower energy transfer efficiency. - Dead zones and limited flexibility. - Reduced suitability for variable setups [23].

Design Choice:

After comparing the different ultrasonic systems, the Flow Cell Ultrasonic Reactor was selected for the design. This option offers key advantages such as reproducibility, flexibility in geometry and material selection, and high throughput, which are critical for continuous processing. Its compatibility with hygienic requirements and ability to adapt to various process conditions make it particularly suitable for olive paste treatment.

2.7 The type of Heat exchange

2.7.1 Double Tube Heat Exchanger

A double pipe heat exchanger, also called a tube in tube or hairpin exchanger, is one of the simplest designs for transferring heat between two fluids. It consists of two concentric pipes, where one fluid flows inside the inner tube while the other flows in the surrounding annular space [24]. As illustrated in Figure 2.27, the arrangement allows heat to pass through the wall of the inner tube, efficiently exchanging energy between the two streams without mixing. Depending on the configuration, the fluids may flow in the same direction (parallel flow) or opposite directions (counter flow). [24].

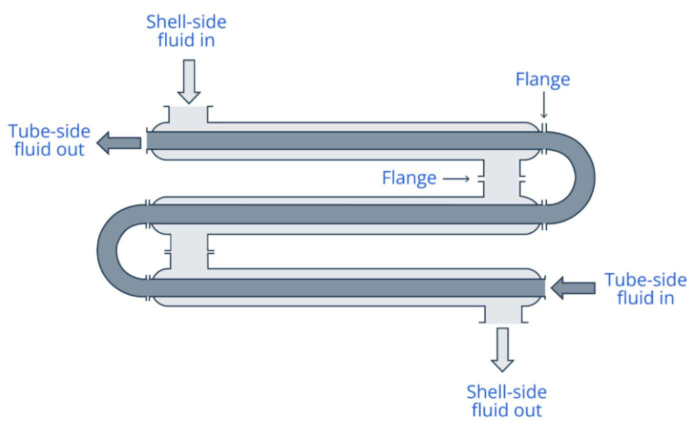


Figure 2.27: Flow Diagram of a Double Tube Heat Exchanger [24].

2.7.2 Plate Heat Exchanger (PHE)

Plate heat exchanger (PHE) is a compact device designed to transfer heat between two fluids using a stack of thin, corrugated metal plates. Each fluid flows through alternating channels, separated by gaskets, which prevent mixing while allowing efficient thermal exchange. As shown in Figure 2.28, the hot and cold streams pass through adjacent channels in opposite directions (counter current flow), maximizing heat transfer efficiency. The corrugated surface of the plates induces turbulence, which enhances thermal performance while maintaining structural rigidity [25].

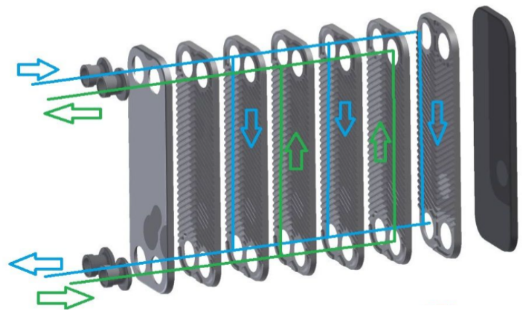


Figure 2.28: Plate Heat Exchanger Structure and Flow Direction [25].

2.7.3 Shell and tube heat exchanger

A shell and tube heat exchanger is a robust design where one fluid flows through a bundle of tubes, while another fluid circulates around them inside a cylindrical shell. This configuration allows efficient thermal exchange, even under high pressures and large flow rates. As illustrated in Figure 2.29, the shell side fluid is directed across the tubes by internal baffles, creating turbulence that improves heat transfer. Meanwhile, the tube side fluid flows inside the tubes, with the two streams usually arranged in counter current to maximize efficiency. This arrangement makes shell and tube exchangers ideal for demanding industrial applications such as power generation, oil refining, and chemical processing [26].

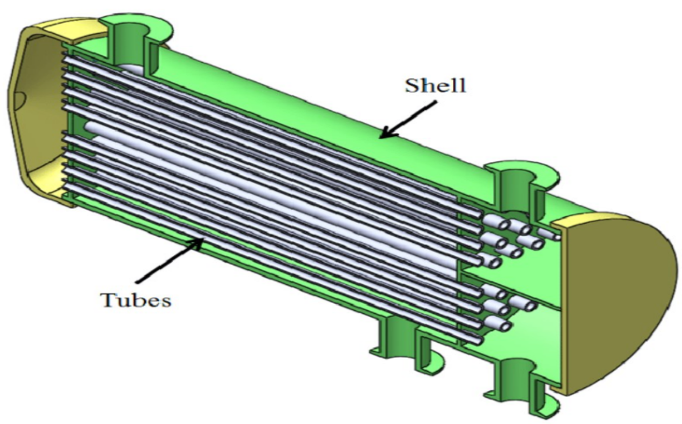


Figure 2.29: shell and tube heat exchanger [26].

Table 2.4 compares different heat exchanger types, outlining their main advantages and limitations in terms of efficiency, pressure handling, and suitability for various fluid condition.

Table 2.4: Comparison Table of Heat Exchanger Types

Heat Exchanger Type	**Advantages**	**Disadvantages**
Double Tube Heat Exchange	- Simple, modular, easy to build and maintain [27] - Handles high pressures; good for small applications - Easy access and repair [27]	- Less efficient per area than PHE - Limited thermal expansion - Not suitable for high heat loads [27]
Plate Heat Exchanger (PHE)	- High efficiency due to large surface area and turbulence - Compact, modular, easy to expand - Easy to clean - hygienic for food [28]	- Not suitable for very viscous fluids (risk of clogging) - Less flexible - pressure limits [28]
shell and tube heat exchanger	- Handles very viscous, sticky, fouling fluids (pastes, creams, chocolate, margarine) - Suitable for dirty or fouling fluids - Flexibility with design options [29] - High pressure and temperature capability [30]	- Mechanically complex (rotors, blades , higher maintenance) [29] - More expensive than PHE or shell and tube - Lower thermal efficiency per volume [30]

Design Choice:

After evaluating the different types of heat exchangers, the Double Tube Heat Exchanger was selected for this study. This choice is based on its simple and modular design, ease of construction and maintenance, and suitability for small and medium scale applications. Additionally, its ability to handle high pressures and provide easy access for repair makes it a practical and cost effective option compared to more complex alternatives systems.

2.8 Conclusion

This chapter reviewed the historical evolution of olive oil extraction, from ancient civilizations to modern processing systems, highlighting the gradual improvements in efficiency and quality. Contemporary methodologies, particularly the two and three phase decanter systems, were discussed along with their inherent technical constraints. To address these limitations, were examined the innovations technologies and compared in terms of their advantages and challenges. Among these, ultrasonic systems demonstrated significant potential for enhancing extraction yield, product quality, and process efficiency, with different configurations offering distinct operational benefits. Furthermore, various heat exchanger types were analyzed to determine their suitability for olive oil processing. The comparative analysis provided a foundation for selecting the most appropriate technologies namely, the flow cell ultrasonic reactor and the double tube heat exchanger as the basis for the proposed design in this study. These findings establish a strong technological context for the experimental work presented in the following chapter.

Chapter 3

Design Methodology and System Calculations

3.1 Introduction

This chapter outlines the experimental approach and methodological framework adopted to evaluate and improve olive oil extraction in small to medium scale mills in Tunisia. The experimental investigation in this work focuses on the case study of the *Taher Bouzid Olive Mill* located in Sfax, Tunisia. The mill employs a two phase continuous extraction system, which, although more environmentally friendly than the traditional three phase system, still generates substantial quantities of wet pomace and wastewater [3], [31].

This study aims to assess the limitations of the existing process and propose a modernized approach using an **Ultrasonic Thermal Inline Reactor (UTIR)**. This innovative technique integrates ultrasound treatment and thermal conditioning to improve oil yield, reduce processing time, and minimize waste. The UTIR system operates under continuous flow and is designed to replace the conventional malaxation stage, which is known to be time and energy intensive [1], [2].

3.2 Case Study and Analysis of the Taher Bouzid Olive Oil Extraction Process

3.2.1 Description of the Existing Process

To ground this study in a real industrial context, a site analysis was conducted at **Tahar Bouzid Olive Mill**, located on Route Gremda – Km 4.5, 3000 Sfax, Tunisia [32]. This medium scale olive mill operates a two phase continuous extraction system typical of many Tunisian facilities. The Taher Bouzid mill uses a modern two phase decanter system that eliminates the need for added water during extraction, thereby reducing wastewater generation. The process includes several main steps: olive reception cleaning, crushing, malaxation, and decantation for oil separation.

Mill information:

- **Name:** Tahar Bouzid Olive Mill
- **Address:** Route Gremda – Km 4.5, Sfax, Tunisia
- **Phone:** +216 74 211 334
- **Zone:** Gremda Industrial Zone, within an area that hosts over 400 olive mills [32]
- **Technology:** Two phase continuous extraction system

Table 3.1: Production using Two Phase Olive Mills

Input (Olives)	**Outputs**
1000 kg/h olive paste	220 kg oil

The images below document the different stages of the olive oil extraction process observed during our visit to the Taher Bouzid mill.

Figure 3.1: Conveyor belt feeding system

Figure 3.2: Olives being transferred to crusher

Figure 3.3: Stone mill crusher

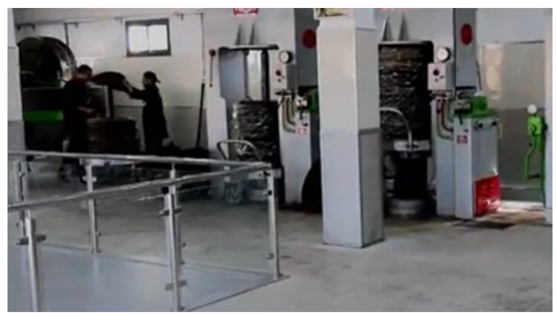


Figure 3.4: Pressing machine

Figure 3.5: Final extraction phase

3.2.2 Identified Limitations

Despite their environmental advantages, two phase olive oil extraction systems such as the one used at the Taher Bouzid mill present several operational and efficiency challenges.

Although these systems significantly reduce water consumption compared to traditional three-phase decanters, they still face certain drawbacks that limit their overall performance and scalability:

- **High Pomace Moisture Content:** Around 85% of the processed olive mass ends up as wet pomace, which increases the cost and complexity of transport, handling, and disposal [3].
- **Energy Requirements for Pomace Drying:** To valorize pomace for energy or agricultural applications, energy-intensive drying processes are needed, reducing overall cost-efficiency [3].

These limitations affect both productivity and sustainability, particularly in small and medium sized mills that still depend on conventional malaxation systems with limited automation and process control.

3.3 Improvement Strategy

To overcome the limitations of conventional malaxation, this project proposes an innovative process design that integrates a controlled heating stage and ultrasonic treatment within a continuous flow configuration, designed to replace conventional malaxation with a continuous flow configuration that integrates ultrasound treatment and controlled heating. The system aims to enhance oil yield, preserve phenolic compounds, and minimize processing time and waste generation. The UTIR is designed for a target throughput of 1,000 kg of olive paste per hour, producing approximately 250 kg of extra virgin olive oil per hour . This performance supports the modernization of traditional olive mills by improving extraction efficiency, reducing environmental impact, and promoting sustainable production practices [4].

The improvement strategy developed in this study specifically targets the process limitations observed at the Taher Bouzid mill, including long malaxation times, batch operation, and uneven thermal control. The proposed design integrates two key innovations: a double-tube heat exchanger and a sonotrode equipped ultrasonic reactor. The heat exchanger ensures uniform and precise thermal conditioning of the olive paste prior to extraction, optimizing viscosity and separation efficiency. Meanwhile, the ultrasonic reactor induces acoustic cavitation, facilitating the disruption of the cell wall and the coalescence of oil droplets, which significantly improving oil release while maintaining its nutritional and sensory quality. Together, these improvements transform the traditional batch process into a continuous, energy efficient extraction system increasing oil yield, reducing processing time, and ensuring consistent, high quality olive oil production

3.3.1 Impact of Thermal Treatment on Olive Oil Extraction

The study evaluated the effect of paste temperature on olive oil quality and extraction yield following malaxation at 20°C. Three final paste temperatures were investigated: maintaining 20°C, heating to 27°C, and heating to 35°C. The resulting oils were extracted by centrifugation and analyzed to assess extraction yield and quality parameters established by the European Union (EU), focusing on triglyceride degradation, hydrolytic activity, and oxidation phenomena [2].

The findings, summarized in Table 3.2, include key parameters such as oil yield (OY), extractability (EY), free acidity, oxidation indices, phenolic content, and volatile compound composition [2]. Results indicate that a paste temperature of 27°C provides the most favorable balance between oil yield and quality. At this temperature, both the extraction efficiency and the concentration of bioactive antioxidants particularly polyphenols and 3,4-DHPEA-EDA increased without compromising flavor or chemical stability. In contrast, heating the paste to 35°C yielded slightly higher extraction rates but also elevated the formation of volatile compounds such as E-2-Heptenal, which are linked to undesirable rancid notes. These changes could adversely affect the sensory profile and classification of the oil. Therefore, processing at 27°C offers the optimal compromise between maximizing oil recovery and preserving nutritional and sensory quality [2].

Table 3.2: Parameters extracted from olive paste at different temperatures [2]

Parameter	**At time $t = 0$**	**20 °C**	**27 °C**	**35 °C**	**p**
OY (%)	n.d.	20.7 ± 0.8^{b}	23.3 ± 0.3^{a}	23.7 ± 0.9^{a}	0.01
EY (%)*	n.d.	79 ± 4^{b}	89 ± 2^{a}	91 ± 6^{a}	0.01
Free fatty acids (%)	n.d.	0.43 ± 0.01	0.47 ± 0.04	0.47 ± 0.06	ns
Peroxide number (meq/kg)	n.d.	11.4 ± 0.7	11 ± 3	11 ± 1	ns
K_{232}	n.d.	1.73 ± 0.03	1.67 ± 0.04	1.74 ± 0.03	ns
K_{270}	n.d.	0.08 ± 0.02	0.08 ± 0.01	0.09 ± 0.01	ns
ΔK	n.d.	0.002 ± 0.001^{a}	0.003 ± 0.001^{ab}	0.003 ± 0.001^{b}	0.03
Total phenolic content (mg/kg)	230 ± 31^{b}	238 ± 23^{b}	290 ± 10^{a}	298 ± 37^{a}	0.04
3,4-DHPEA-EDA (mg/kg)	21 ± 1^{a}	23 ± 1^{a}	29 ± 2^{b}	46 ± 2^{c}	0.03
Total LOX compounds (mg/kg)	n.d.	45.36 ± 5.50	46.00 ± 13.45	44.90 ± 6.01	ns
E-2-Hexenal (mg/kg)	n.d.	41.88 ± 4.95	42.20 ± 12.69	41.13 ± 5.15	ns
1-Penten-3-ol (mg/kg)	n.d.	0.26 ± 0.03^{a}	0.31 ± 0.01^{b}	0.33 ± 0.03^{b}	0.05
E-2-Heptenal (μg/kg)	n.d.	25 ± 3^{a}	27 ± 3^{a}	39 ± 3^{b}	0.04

3.3.2 Impact of Ultrasound on Olive Oil Extraction

This study evalute the Ultrasound assisted extraction is a promising technique to enhance olive oil yield and processing efficiency. The table 3.3 show the ultrasound methods across different olive varieties, highlighting their effects on extractability and pomace properties [1]. The data in Table 3.3 demonstrates that ultrasound-assisted extraction, especially at higher pressures, has a positive impact on olive oil extractability across different olive varieties. While pomace moisture remained relatively stable, a noticeable reduction in pomace oil content was observed in some treatments, indicating improved oil recovery. The extractability percentage increased significantly with ultrasound application, particularly at 3.5 bar, where the Nocellara and Coratina varieties reached the highest yields (87.1% and 86%, respectively). These results suggest that applying ultrasound especially at higher pressure is an effective strategy to enhance oil extraction efficiency without compromising the physical characteristics of the pomace, offering a promising solution for more productive and sustainable olive oil processing [1].

Table 3.3: Quantitative results and process parameters [1]

Test Trial	Condition	Variety	Ultrasound power (kW)	Mean specific energy (kJ/kg)	Pressure in US-cell (Bar)	POMACE Moisture (%)	POMACE Oil (%, db)	Extractability (%)
1st	Control	Arbequina	–	–	–	$56.0 \pm 0.6a$	$10.4 \pm 0.8a$	$83.5 \pm 1.3a$
	US 1.7 bar	Arbequina	2.64 ± 0.26	4.13	1.7 ± 0.04	$56.2 \pm 0.6a$	$10.7 \pm 0.9a$	$84.2 \pm 0.3a$
2nd	Control	Peranzana	–	–	–	$55.3 \pm 0.8a$	5.6 ± 0.3	$83.0 \pm 0.6a$
	US 1.7 bar	Peranzana	2.61 ± 0.21	4.09	1.7 ± 0.02	$55.6 \pm 0.6a$	$5.5 \pm 0.7b$	$83.1 \pm 0.8a$
3rd	Control	Nocellara	–	–	–	$56.0 \pm 0.5ab$	7.4 ± 0.7	$82.7 \pm 1.5b$
	US 1.7 bar	Nocellara	$2.63 \pm 0.25b$	4.12	$1.7 \pm 0.03b$	$55.5 \pm 0.3b$	$7.4 \pm 0.8a$	$83.0 \pm 1.1b$
	US 3.5 bar	Nocellara	$3.52 \pm 0.38a$	5.51	$3.5 \pm 0.03a$	56.5 ± 0.3	$5.6 \pm 0.6b$	$87.1 \pm 1.3a$
4th	Control	Coratina	–	–	–	$56.3 \pm 1.0a$	$8.4 \pm 0.5a$	$82.3 \pm 0.6b$
	US 3.5 bar	Coratina	3.54 ± 0.41	5.54	3.5 ± 0.02	$56.4 \pm 1.2a$	$6.2 \pm 1.4b$	$86.9 \pm 2.2a$

3.3.3 Design Objectives and Expected Performance

To overcome the operational limitations of traditional two-phase extraction systems, this project proposes the development of a novel **Ultrasonic Thermal Inline Reactor (UTIR)** system. The UTIR integrates a **double tube heat exchanger** for precise thermal conditioning and a **sonotrode equipped ultrasonic reactor** for enhanced cell disruption, replacing conventional batch malaxation with a fully continuous process. The comparison in Table 3.4 summarizes the main differences between the conventional two-phase extraction process used at the Taher Bouzid Mill and the proposed Ultrasonic Thermal Inline Reactor (UTIR) system. The traditional setup relies on indirect heating in the malaxer for about 45 minutes, achieving an extraction efficiency of 86.7% [33]. Assuming a fruit oil content of 25%, the practical yield is calculated as:

$$Y = \frac{25 \times 86.7}{100} = 21.7\%$$

Industrial validations of the sono heat exchanger concept have shown an improvement of up to 5.5 percentage points in extraction efficiency compared to standard two phase systems [34]. By integrating a double tube heat exchanger with an ultrasonic reactor, the UTIR system enhances heat transfer and cell disruption, raising efficiency to about 92.2% and increasing yield to approximately 26.7% [34].

This approach not only boosts oil recovery but also shortens processing time to 10–25 minutes, improves temperature control, and enhances product quality through better phenolic retention and reduced oxidation. Overall, the UTIR system delivers a measurable performance gain raising oil yield from roughly 21% to 26% while ensuring continuous, energy efficient, and sustainable olive oil production.

Table 3.4: Comparison between the Conventional Taher Bouzid Mill and the Improved UTIR System

Parameter	**Taher Bouzid Mill**	**Improved UTIR System**
Process Mode	Semi continuous	Continuous flow
Thermal Conditioning Method	Indirect heating in malaxer [33]	Double tube heat exchanger [4]
Cell Disruption Method	Mechanical malaxation	Acoustic cavitation via ultrasonic reactor [4]
Processing Time (min)	45 (malaxation) [33]	10–25 (continuous thermal and ultrasonic treatment)
Extraction Efficiency (%)	86.7% [33]	+5.5 points (≈92.2%) [34]
Oil Yield (%)	≈21%	25–26% (expected)
Thermal Control	Variable	Precise control with consistent paste conditioning [34]
Environmental Impact	High pomace moisture and energy use [3]	Reduced waste generation and improved sustainability [34]
Quality Indicators	Standard phenolic content [3]	Higher phenolics, reduced oxidation [4]

3.4 Calculation system

In this project, I developed an innovative olive oil pressing machine based on a two phase decanter system. To improve both yield and efficiency, I integrated a heat exchange section and an ultrasonic treatment section. These design choices are crucial to balance productivity, processing time, and product integrity. By tailoring the dimensions of each component, the system can achieve higher oil recovery while maintaining the sensory and nutritional properties of the final product.

3.4.1 Calculations for heat exchange section

The aim of this section is to determine the thermal capacity required to heat the olive paste to its target temperature before ultrasonic treatment. The diagram bellow 3.6 shows the heat exchanger with two fluid streams. T_{1I} and T_{1O} represent the inlet and outlet temperatures of the olive paste, while T_{2I} and T_{2O} are the inlet and outlet temperatures of the hot water. This diagram 3.6 is the basis of the thermal balance used in the calculations.

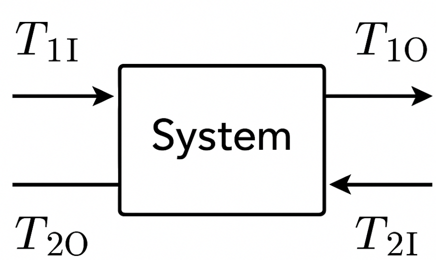


Figure 3.6: Flow diagram of the system heat exchanger.

Geometry

Table 3.5 summarizes the geometric dimensions of the double tube heat exchanger used for thermal conditioning of the olive paste. In this configuration, the inner tube carries hot water, while the outer annular region transports the olive paste.

Table 3.5: Geometric parameters of the double tube heat exchanger

Inner tube (hot water)	$d_i = 0.100$ m, wall $= 0.002$ m $\Rightarrow d_o = 0.104$ m
Outer pipe (olive paste)	$D_i = 0.150$ m, wall $= 0.002$ m $\Rightarrow D_o = 0.154$ m

Fluid properties

Table 3.6 summarizes the thermophysical properties used in the heat exchanger calculations. The water properties correspond to the heating fluid flowing inside the inner tube, while the olive paste properties describe the cold stream circulating in the annular section. These constants were taken from experimental and literature sources and were used to determine the heat transfer rate, Reynolds number, convective coefficients, and overall thermal performance of the exchanger.

Table 3.6: Fluid properties and operating conditions

Quantity	Water (tube)	Paste (annulus)
Mass flow rate	$\dot{m}_w = 0.425 kg.s^{-1}$ [35]	$\dot{m}_p = 0.278 kg.s^{-1}$ [35]
Inlet temperature	$T_{w,\text{in}} = 60\,^{\circ}\text{C}$	$T_{p,\text{in}} = 20\,^{\circ}\text{C}$
Outlet temperature	—	$T_{p,\text{out}} = 27\,^{\circ}\text{C}$
Specific heat	$c_{p,w} = 4182 J.kg^{-1}.K^{-1}$ [36]	$c_{p,p} = 3.31 kJ.kg^{-1}.K^{-1}$ [37]
Thermal conductivity	$k_w = 0.648 W.m^{-1}.K^{-1}$ [36]	$k_p = 0.46 W.m^{-1}.K^{-1}$ [37]
Dynamic viscosity	$\mu_w = 4.74 \times 10^{-4} Pa.s$ [36]	$\mu_p = 19 Pa.s$ [37]
Density	$\rho_w = 984 kg.m^{-3}$ [36]	$\rho_p = 1050 kg.m^{-3}$ [4]

Energy balance

To quantify how much energy must be transferred from the hot water to the paste, the heat duty is first calculated using the principle of energy conservation. The heat gained by the paste must be equal to the heat lost by the water [38]:

$$\boxed{|\dot{Q}_{\text{in}}| = |\dot{Q}_{\text{out}}| = |\dot{m}\, c_p\, (T_{\text{out}} - T_{\text{in}})|}$$

$$Q = \dot{m}_p\, c_{p,p}\, (T_{p,\text{out}} - T_{p,\text{in}}) = 0.278 \times 3310 \times (27 - 20) = \ 6441W \ (\ 6.44kW),$$
$$\Delta T_w = \frac{Q}{\dot{m}_w\, c_{p,w}} = \frac{6441}{0.425 \times 4182} = \ 3.62K, \quad T_{w,\text{out}} = 60 - 3.62 = 56.38\,^{\circ}\text{C}$$

LMTD

To determine the effective temperature driving force inside the exchanger, the logarithmic mean temperature difference (LMTD) is calculated as follows:

$$\Delta T_1 = T_{w,\text{in}} - T_{p,\text{out}} = 60 - 27 = \ 33K,$$
$$\Delta T_2 = T_{w,\text{out}} - T_{p,\text{in}} = 56.38 - 20 = \ 36.38K,$$
$$\Delta T_{\text{lm}} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)} = \ 34.66K.$$

Velocities & Reynolds numbers

To verify the flow regime and estimate the convective heat transfer coefficients, Reynolds and Nusselt numbers were evaluated using standard correlations for internal flow of viscous fluids.

Tube (water).

$$A_i = \frac{\pi d_i^2}{4} = \frac{\pi (0.10)^2}{4} = 7.854 \times 10^{-3}\ \text{m}^2, \quad Q_{v,w} = \frac{\dot{m}_p}{\rho_p} = \frac{0.425}{984} = 4.32 \times 10^{-4}\ \text{m}^3\text{s}^{-1},$$

The fluid velocity is calculated as:

$$V_i = \frac{Q_{v,w}}{A_i} = \frac{Q_{v,p}}{A_a} = 0.0550\ \text{m}\,\text{s}^{-1}$$

The Reynolds number is:

$$\mathrm{Re}_i = \frac{\rho_w V_i d_i}{\mu_w} = \frac{984 \times 0.0550 \times 0.10}{4.74 \times 10^{-4}} \approx 1.14 \times 10^4$$

Since Re > 4000, **the flow is turbulent**.

The Prandtl number is calculated as:

$$\mathrm{Pr}_i = \frac{c_{p,w}\mu_w}{k_w} \approx 3.06$$

$$\mathrm{Pr}_i = \frac{c_{p,w}\mu_w}{k_w} \approx 3.06.$$

Annulus (paste).

$$A_a = \frac{\pi}{4}\left(D_i^2 - d_o^2\right) = \frac{\pi}{4}\left(0.150^2 - 0.104^2\right) = 9.17 \times 10^{-3}\ \mathrm{m}^2,$$

$$Q_{v,p} = \frac{0.278}{1050} = 2.655 \times 10^{-4}\ \mathrm{m^3 s^{-1}}, \quad V_a = \frac{Q_{v,p}}{A_a} = 0.0289\ \mathrm{m\,s^{-1}},$$

$$D_h = D_i - d_o = 0.150 - 0.104 = 0.046\,\mathrm{m}, \quad \mathrm{Re}_a = \frac{\rho_p V_a D_h}{\mu_p} = \frac{1050 \times 0.0289 \times 0.046}{19} \approx 0.074$$

Since $\mathrm{Re}_a < 2300$, **the flow is laminar**.

Film coefficients

Water in tube

$$\mathrm{Nu}_i = 0.023\,\mathrm{Re}_i^{0.8}\,\mathrm{Pr}_i^{0.4} \approx 63, \quad h_i = \frac{\mathrm{Nu}_i k_w}{d_i} = \frac{63 \times 0.648}{0.10} \approx 4.08 \times 10^2\ \mathrm{W\,m^{-2}\,K^{-1}}.$$

Paste in annulus

Although olive paste is a non Newtonian material, its flow in the annular section of the exchanger is highly viscous and strongly laminar ($\mathrm{Re}_a < 1$). In this regime, treating the paste as a Newtonian fluid using its apparent viscosity at the operating shear rates provides a reliable engineering approximation. For fully developed laminar flow with constant wall temperature, the Nusselt number becomes independent of Reynolds and Prandtl numbers. Therefore, the classical constant value Nu = 3.66 is adopted to estimate the paste-side convective coefficient, consistent with standard internal convection correlations [39].

$$\mathrm{Nu}_o \approx 3.66, \quad h_o = \frac{\mathrm{Nu}_o k_p}{D_h} = \frac{3.66 \times 0.46}{0.046} \approx 36.6 \ \mathrm{W\,m^{-2}\,K^{-1}}.$$

Overall coefficient on A_o (outer area of inner tube)

Using the internal and external convection coefficients and wall resistance, the overall heat transfer coefficient U was computed. This value determines the exchanger length required to reach the target outlet temperature.

Thermal conductivity of wall: $k_{\mathrm{wall}} = 16 \ \mathrm{W\,m^{-1}\,K^{-1}}$.

$$\frac{1}{U_o} = \underbrace{\frac{d_o}{d_i}\frac{1}{h_i}}_{\text{water film}} + \underbrace{\frac{d_o \ln(d_o/d_i)}{2k_{\mathrm{wall}}}}_{\text{wall}} + \underbrace{\frac{1}{h_o}}_{\text{paste film}},$$

$$\frac{1}{U_o} = \frac{0.104}{0.100}\frac{1}{408} + \frac{0.104 \ \ln(0.104/0.100)}{2 \times 16} + \frac{1}{36.6} = 0.00255 + 0.00013 + 0.02732 = 0.0300,$$

$$\boxed{U_o \approx \frac{1}{0.0300} = 33.3 \ \mathrm{W\,m^{-2}\,K^{-1}}}.$$

Required area and length

$$A_o = \frac{Q}{U_o \, \Delta T_{\mathrm{lm}}} = \frac{6441}{(33.3)(34.66)} \approx 5.58 \ \mathrm{m}^2,$$

$$L = \frac{A_o}{\pi d_o} = \frac{5.58}{\pi \times 0.104} \approx 17.1 \ \mathrm{m}.$$

Paste heating time

The time a fluid element of paste spends in the heat exchanger is

$$t_{\mathrm{res}} = \frac{V_{\mathrm{annulus}}}{\dot{V}_p} = \frac{A_a\,L}{\dot{V}_p}.$$

With $A_a = 9.17 \times 10^{-3}$ m^2, $L = 17.1$ m, and $\dot{V}_p = \dot{m}_p/\rho_p = 0.278/1050 = 2.655 \times 10^{-4}$ m^3 s^{-1},

$$V_{\mathrm{annulus}} = A_a L = (9.17 \times 10^{-3})(17.1) = 1.568 \times 10^{-1}\ \mathrm{m}^3,$$

$$\boxed{t_{\mathrm{res}} = \frac{1.568 \times 10^{-1}}{2.655 \times 10^{-4}} = 5.91 \times 10^2\ \mathrm{s}\ \approx\ 9.8\ \mathrm{min}.}$$

The heat exchanger requires a surface area of 5.6 meter squared, and the paste heating time is approximately 9.8 min.

3.4.2 Calculations for Ultrasonic Treatment Section

This section evaluates the hydraulic behavior of the olive paste flowing through the ultrasonic reactor. The goal is to determine paste velocity, flow regime, pressure drop, and residence time inside the reactor tube.

Given (Paste)

The physical properties and operating parameters of the olive paste used for the calculations are:

$$\dot{m} = 0.278\ \mathrm{kg\,s^{-1}},$$

$$\rho = 1050\ \mathrm{kg\,m^{-3}}, \qquad \mu = 19\ \mathrm{Pa \cdot s}, \qquad c_p = 3.31\ \mathrm{kJ\,kg^{-1}\,K^{-1}} = 3310\ \mathrm{J\,kg^{-1}\,K^{-1}},$$

$$D = 0.10\ \mathrm{m}, \qquad L = 2.20\ \mathrm{m}.$$

Volumetric flow rate

To convert mass flow into volumetric flow rate, the following expression is used:

$$Q = \frac{\dot{m}}{\rho} = \frac{0.278}{1050} = 2.6476 \times 10^{-4}\ \mathrm{m^3\,s^{-1}}.$$

Flow velocity

The internal cross sectional area and average axial velocity of the paste are calculated as:

$$A = \frac{\pi D^2}{4} = \frac{\pi(0.10)^2}{4} = 7.853 \times 10^{-3}\ \mathrm{m^2},$$
$$v = \frac{Q}{A} = \frac{2.647 \times 10^{-4}}{7.853 \times 10^{-3}} = 3.371 \times 10^{-2}\ \mathrm{m\,s^{-1}}.$$

Reynolds number

The Reynolds number is evaluated to identify the flow regime and confirm whether the paste moves in laminar or turbulent conditions:

$$\mathrm{Re} = \frac{\rho v D}{\mu} = \frac{(1050)(0.0337)(0.10)}{19} \approx \mathbf{0.186}$$

Since $\mathrm{Re}_a < 2300$, **the flow is laminar**.

Pressure drop

For laminar flow in a cylindrical tube, the friction factor is computed as $f = 64/\mathrm{Re}$. The pressure drop along the reactor length is then obtained using the Darcy Weisbach equation:

$$f = \frac{64}{0.186} \approx 344.08,$$
$$\Delta p = f\,\frac{L}{D}\,\frac{\rho v^2}{2} = 344.08 \times \frac{2.20}{0.10} \times \frac{(1050)(0.0337)^2}{2}$$
$$= \mathbf{4.51} \times \mathbf{10^3}\ \text{Pa} \approx \mathbf{4.51}\ \text{kPa}.$$

volume and residence time

To determine how long the paste remains inside the ultrasonic reactor (important for cavitation effectiveness), the internal volume and residence time are calculated:

$$V = AL = (7.853 \times 10^{-3})(2.20) = 1.7279 \times 10^{-2}\ \text{m}^3 = \mathbf{17.28}\ \text{L},$$
$$t = \frac{V}{Q} = \frac{17.28\ \text{L}}{0.265\ \text{L}\,\text{s}^{-1}} = \mathbf{65.3}\ \text{s}.$$

The results show that the paste flows under strongly laminar conditions with a residence time of about 65 s ensures sufficient ultrasonic exposure for cavitation and cell disruption, supporting improved oil recovery without interrupting the production flow.

3.4.3 Calculations for the Tank Dimensions

In this section, the storage tank used to collect the extracted olive oil is dimensioned based on the expected production capacity of the system. Since the UTIR machine operates in continuous flow, the storage volume must be large enough to contain several hours of production without interruption or overflow.

Given Data and Assumptions

The tank is designed as a vertical right cylindrical vessel. Its internal diameter is specified as $D = 0.80$ m, which corresponds to a radius of $r = D/2 = 0.40$ m. The straight cylindrical height of the tank is selected as $h = 2.00$ m. These dimensions are chosen to provide compact geometry while maintaining adequate storage capacity.

Volume Calculation

The internal volume of the tank is obtained using the standard geometric relation for a cylinder:

$$V = \pi r^2 h = \pi(0.40)^2(2.00) = 1.0053 \text{ m}^3.$$

To express this value in practical units:

$$V \approx 1.005 \text{ m}^3 \approx 1005 \text{ L}.$$

The calculated tank volume of approximately 1.0 m^3 confirms that the selected diameter and height provide adequate storage capacity for a full four hour production cycle.

3.5 Conclusion

This chapter presented the methodology and key design calculations for the proposed olive oil extraction system. After analyzing the existing process at the Taher Bouzid mill, major limitations in malaxation, heat control, and extraction efficiency were identified. To overcome these issues, a new approach combining a double tube heat exchanger and an ultrasonic reactor was developed, forming the basis of the Ultrasonic Thermal Inline Reactor (UTIR).

Thermal and ultrasonic analyses confirmed the potential for improved oil yield, product quality, and process continuity. Additionally, the storage tank was dimensioned to ensure stable operation and sufficient capacity of up to 1,000 liters. Overall, this chapter established the technical foundation for a continuous, energy efficient, and high quality olive oil extraction system.

Chapter 4

Design and Development of the System

4.1 Introduction

This chapter presents the functional layout and operating principle of the proposed olive oil extraction system. It describes how each component from the crusher to the final storage tank interacts to ensure a continuous and efficient process.

4.2 Block diagram

Figure 4.1 shows the block diagram of our system .

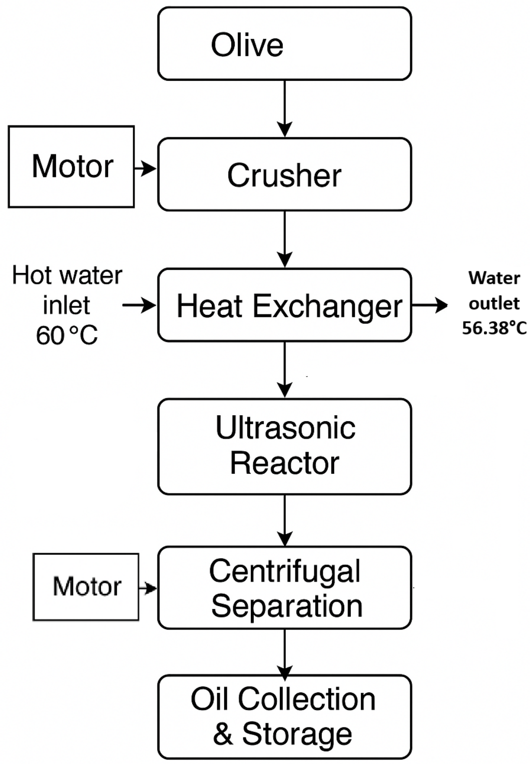


Figure 4.1: block diagram

4.3 General System Architecture

The designed olive oil extraction line follows a continuous and integrated configuration, aimed at improving yield, reducing processing time, and ensuring consistent oil quality. The overall process consists of five main stages. A schematic representation of the system is provided in Figure 4.2.

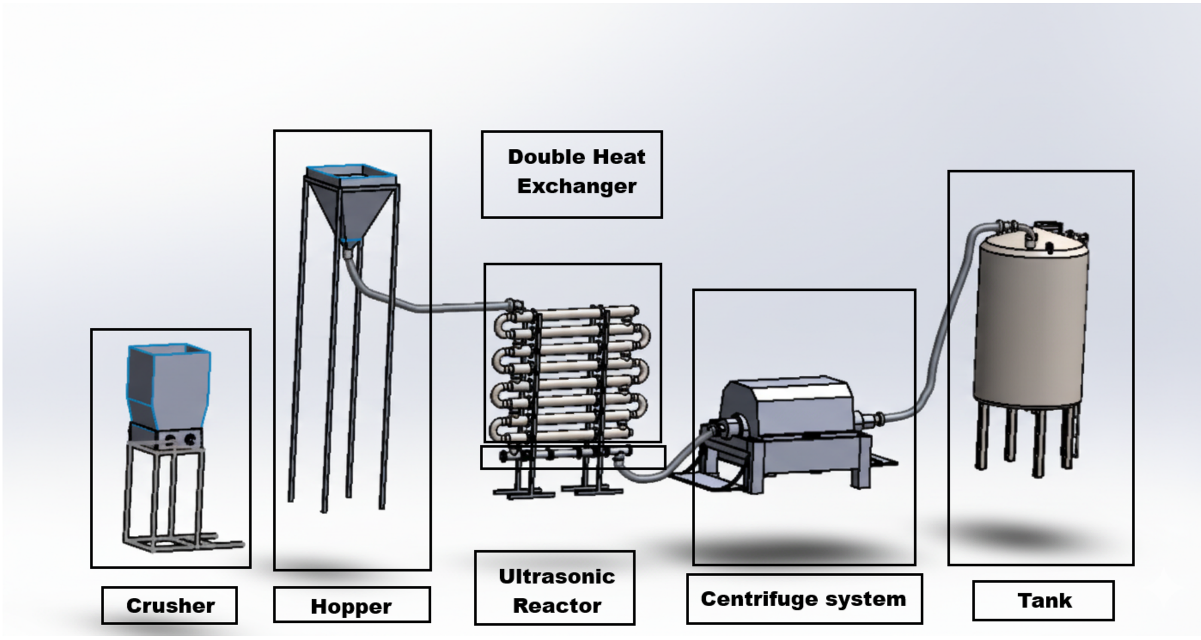


Figure 4.2: the design of all the system

4.3.1 Process Description

- **Stage 1: Crushing** The process begins with the mechanical crushing of freshly harvested olives using a double shaft crusher. This unit breaks the olive tissues, releasing oil droplets and forming a uniform olive paste.

- **Stage 2: Thermal Conditioning** The crushed paste is then conveyed into a double tube heat exchanger where it is rapidly heated to the optimal temperature range of 27°C. This controlled preheating step improves the fluidity of the paste and facilitates the release of oil droplets without overheating or degrading sensitive phenolic compounds.

- **Stage 3: Ultrasonic Treatment** After the process of heating, the olive paste is subjected to an ultrasonic reactor with a titanium sonotrode. The ultrasonic waves create minute bubbles that instantly form and collapse, breaking the walls of olive tissue cells. The process increases the efficiency of oil recovery and preserves the original quality, taste, and nutrients of the olive oil.

- **Stage 4: Decanter Centrifugation** The treated paste is fed into a horizontal decanter centrifuge that separates the mixture into 2 distinct phases: oil, and solid pomace. Centrifugal force ensures continuous and efficient separation, reducing manual handling and processing time compared to traditional batch systems.

- **Stage 5: Storage and Collection** The clarified oil is collected and transferred into stainless steel storage tanks. The storage tanks maintain stable temperature and protection from oxidation, ensuring preservation of oil quality before packaging or further analysis.

4.3.2 Operating Principle

The system operates in a continuous flow mode with a steady feed rate of approximately **1000 kg/h** of olive paste. Each unit is connected in series to maintain smooth material flow and consistent residence time. This configuration minimizes manual intervention, reduces processing variability, and increases production efficiency. By integrating the heat exchanger and ultrasonic reactor inline, the system eliminates the need for traditional malaxation tanks, enabling a faster and more energy efficient extraction process.

4.4 Crushing System

The olive crusher is designed as a dual shaft counter rotating system powered by an electric motor that transmits torque to the main shafts through a pair of synchronized spur gears. The motor provides the mechanical power required to initiate the crushing process, while the gear assembly ensures equal and opposite rotation of both shafts at a 1:1 speed ratio. Each shaft supports a series of intermeshing cutter discs and precision spacers that fracture the olive tissues, releasing oil droplets and forming a homogeneous paste suitable for subsequent thermal and ultrasonic treatment. Figure 4.3 presents the overall design of the crusher machine.

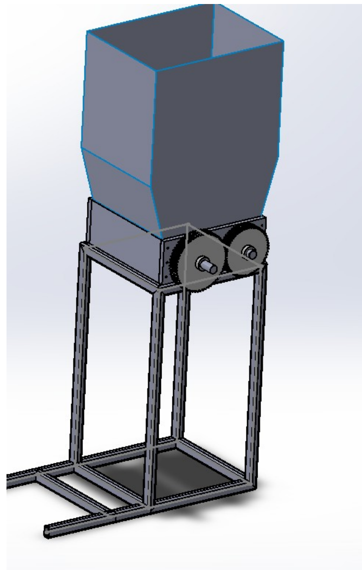


Figure 4.3: General design of the crusher system

Figure 4.4 shows the key elements of the crusher assembly, including the shaft, crushing discs, spacers, and locking nuts. The shaft delivers torque to the discs, while the spacers keep a constant distance between them to ensure uniform crushing. The locking system secures all rotating parts and maintains proper alignment during operation.

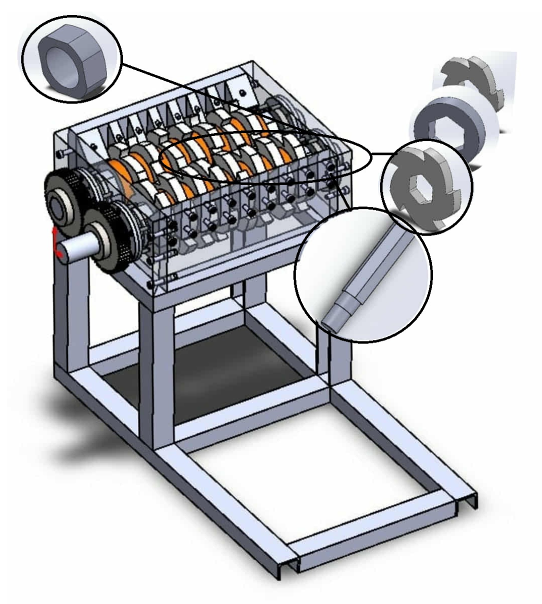


Figure 4.4: Crusher assembly components

Figure 4.5 illustrates the gear coupling mechanism that synchronizes the two crusher shafts. The spur gears are mounted on the shafts using a key and retaining ring system, ensuring secure torque transmission and precise axial alignment. The keys prevent rotational slippage between the gears and the shafts, while the retaining rings hold the gears firmly in position, preventing axial displacement. This robust coupling design guarantees accurate synchronization between the two rotating assemblies, resulting in consistent crushing efficiency, reduced mechanical stress, and improved system durability.

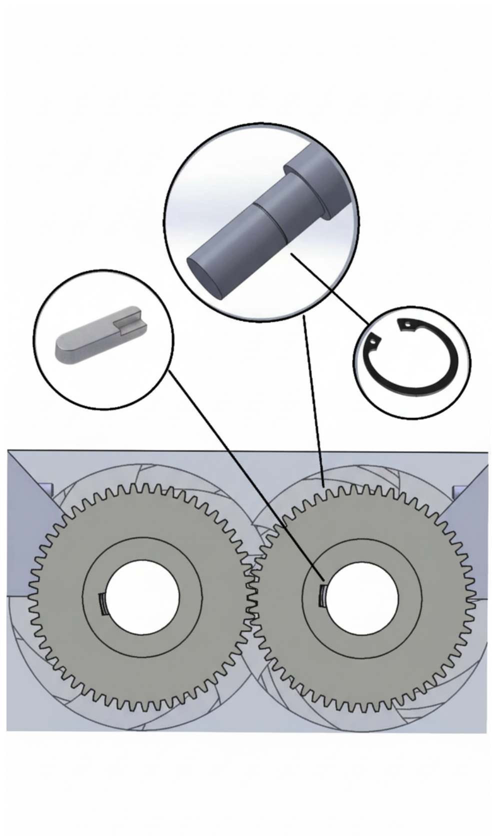


Figure 4.5: Gear coupling system

Finally,the bearing guidance system, shown in Figure 4.6, ensures precise rotational alignment of the shafts and smooth motion with minimal friction. The system consists of cylindrical roller bearings, retaining rings, and locking nuts that collectively maintain the shaft position while allowing free rotation. The bearings provide radial support and absorb the high loads generated during crushing, while the retaining elements restrict any undesired axial movement. This configuration enhances operational stability, minimizes vibration, and improves the long term reliability and performance of the crusher mechanism.

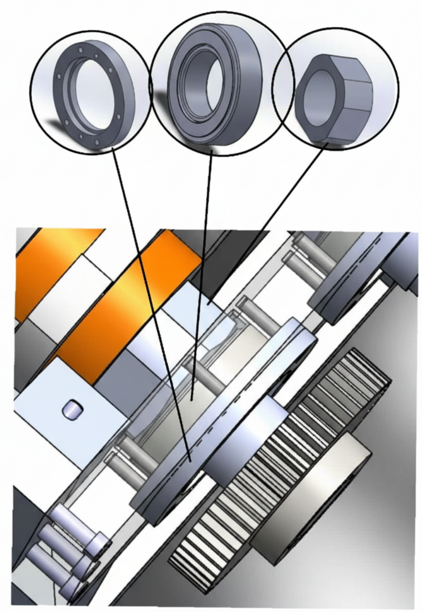


Figure 4.6: Bearing guidance system

4.5 Heat Exchanger Section

After the crushing stage, the resulting olive paste is discharged from the crusher outlet into a hopper, which transfers it to the heat exchange unit for controlled thermal treatment. To ensure continuous flow of the high-viscosity paste through the 98.12 cm^2 section, a pump is installed between the hopper and the heat exchanger. The heat exchange system, shown in 4.7, is designed as a concentric annular heat exchanger, where the olive paste flows through the annular space between two coaxial pipes, while hot water circulates inside the inner tube in a counter current arrangement. This configuration ensures efficient heat transfer and a uniform temperature distribution throughout the exchanger length. The inner tube, dedicated to the water flow, has an inner diameter of 0.10 m. The outer pipe, which carries the olive paste, has an inner diameter of 0.15 m. Based on the calculations presented in the previous chapter, the heat exchange system is composed of four double pipe modules, each 2.125 meters in length, giving a total effective length of 17.1 meters. During operation, the olive paste temperature increases from 20°C to 27°C, while the hot water temperature decreases from 60°C to 56.38°C. This controlled counter-current heat exchange process provides efficient thermal conditioning of the paste prior to the extraction stage, ensuring high energy efficiency, stable operation, and hygienic processing conditions throughout the system.

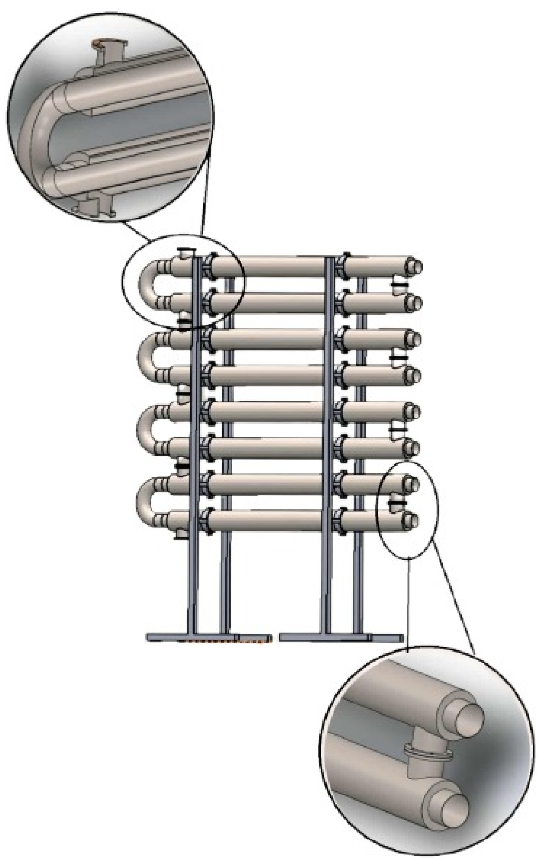


Figure 4.7: Heat Exchange System

4.6 Ultrasonic Reactor section

The outlet of the heat exchanger is directly connected to the inlet of the ultrasonic treatment reactor, as shown in Figure 4.8. After the olive paste passes through the heat exchanger and reaches the desired preheating temperature, it enters the ultrasonic reactor for the next stage of processing.

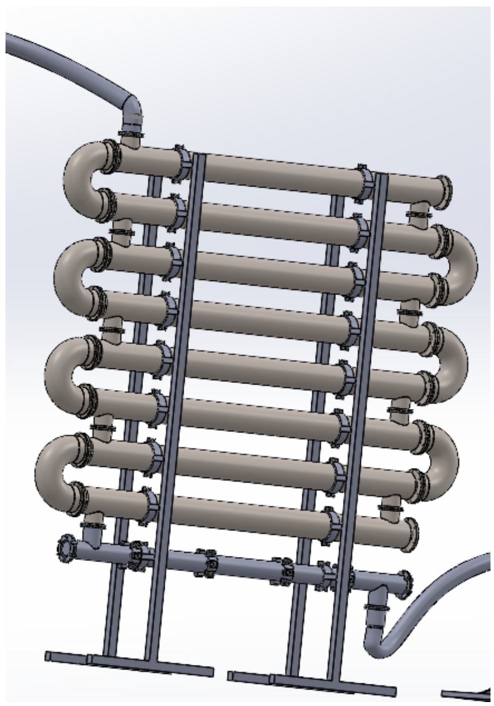


Figure 4.8: Integration of the Ultrasonic System

The reactor consists of a cylindrical chamber with a diameter of 0.10 m and a length of 2.20 m, equipped with multiple ultrasonic transducers distributed uniformly along its length. The use of several transducers ensures a homogeneous acoustic energy field within the chamber, enhancing cavitation intensity, promoting cell wall rupture, and improving oil droplet coalescence and release efficiency, while simultaneously preventing localized overheating.

To ensure proper alignment and structural stability, a dedicated mechanical fixation system was developed for transducer mounting. Each transducer is installed using a threaded support housing and locking ring assembly as shown in Figure 4.9, which guarantee a secure mechanical connection and optimal acoustic coupling with the chamber wall. This configuration minimizes vibration losses, facilitates maintenance, and ensures consistent ultrasonic performance throughout the operation, resulting in a highly efficient and reliable olive paste treatment process.

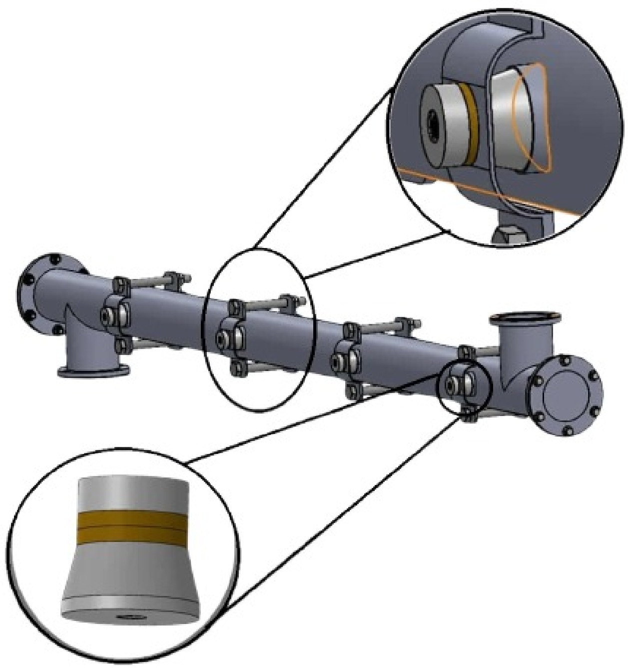


Figure 4.9: Ultrasonic Transducer Assembly

4.7 Separation System

The paste goes through the stage of heat exchange and the ultrasonic reactor, where it remains undergoing treatment for a period of about 10 minutes. It is then passed on to the centrifugal separation system. In the final step, the separation of olive oil from solid wastes occurs under intense centrifugal forces. Figures 4.10 and 4.11 indicate the overall layout and internal design of two phase olive oil separation system, based on the principle of centrifugal separation.

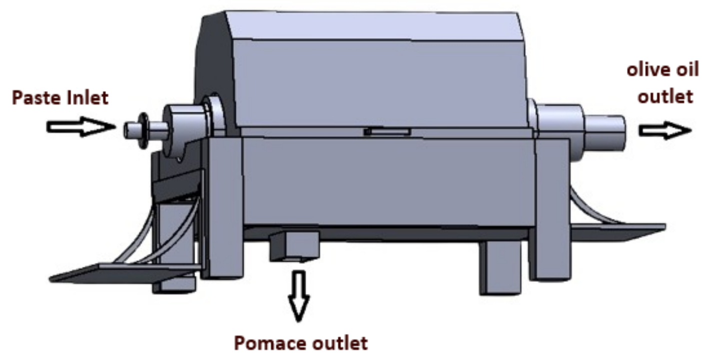


Figure 4.10: the design of all the system.

In the decanter as it show in the Figure 4.11, the paste is pumped into a revolving cylindrical bowl with an internal screw conveyor. When the bowl rotates at high velocity, it generates a centrifugal field of hundreds of thousands of times the strength of gravity that induces separation based on differential density of the constituents. The dense solid particles and excess water migrate to the wall of the bowl, yet the lighter olive oil phase collects in the middle. The separated oil is pumped out continuously via the olive oil outlet, and solid fraction (pomace) is transported in the opposite direction and discharged through a separate outlet.

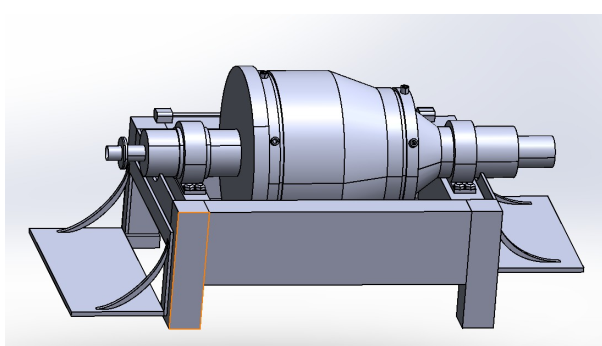


Figure 4.11: system inside

This configuration offers continuous and efficient phase separation with low energy consumption. The historical mechanical design guarantees dynamic balance, vibration stability, and high rotational precision, all of which are essential for guaranteeing product quality and system reliability. Moreover, the two phase operation eliminates the need for supplementary water, preserves the natural antioxidants of the olive oil, and improves both the efficiency and sustainability of the extraction process.

4.8 Oil Collection and Storage System

The final stage of the system is the olive oil storage tank, shown in Figure 4.12, which is designed to store the extracted oil after the centrifugal separation process. The tank has a cylindrical geometry with a diameter of 800 mm and a height of 2000 mm, providing a total storage capacity of approximately 1000 liters.

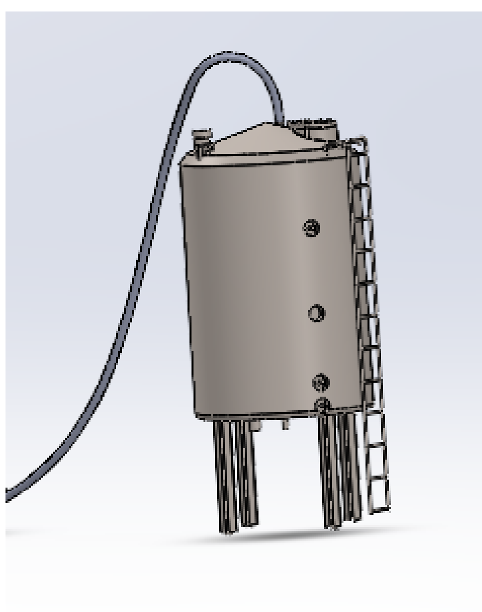


Figure 4.12: the design of all the system.

4.9 Conclusion

This chapter presented the complete design and development of the olive oil extraction system, with a special focus on each step the olive paste undergoes from crushing and thermal conditioning to ultrasonic treatment and final centrifugal separation. The mechanical, thermal, and ultrasonic subsystems were carefully coordinated to ensure efficient paste handling, optimal oil release, and high product quality.

Chapter 5

Simulation of the Heat Exchanger System

5.1 Introduction

This chapter presents the numerical simulation of the double tube heat exchanger using **SolidWorks Flow Simulation**. The objective of the simulation is to analyze the heat transfer behavior between the hot water flowing inside the inner tube and the paste circulating in the annular region. The goal is to verify the thermal performance, temperature distribution, and pressure variation along the heat exchanger during steady state operation.

5.2 Mass Flow Boundary Conditions

To ensure accurate simulation of the heat exchanger performance, mass flow inlet boundary conditions were applied to both fluids. For the olive paste, an **Inlet Mass Flow** condition was assigned to the annular inlet face with a mass flow rate of $\dot{m}_p = 0.278 \ \mathrm{kg \cdot s^{-1}}$ and a uniform inlet temperature of $20\,^{\circ}\mathrm{C}$ as shown in the Figure 5.1. The flow direction was defined normal to the inlet surface.

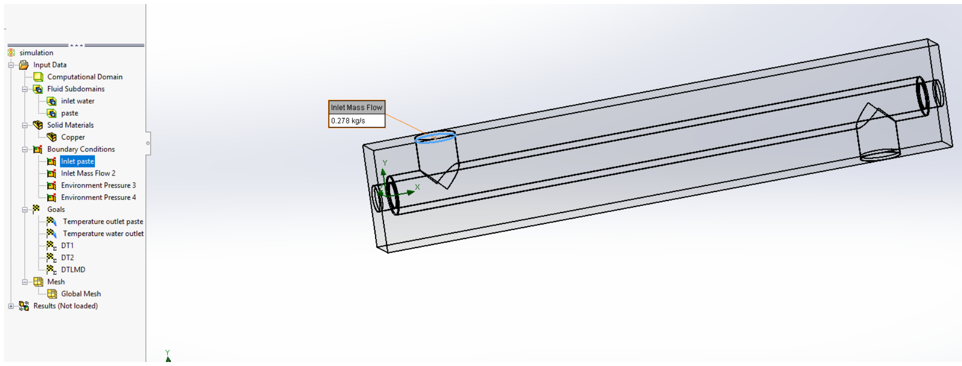


Figure 5.1: Mass flow boundary condition applied to the paste inlet.

Similarly, the hot water flowing inside the inner tube was assigned an **Inlet Mass Flow** boundary condition of $\dot{m}_w = 0.425\ \text{kg} \cdot \text{s}^{-1}$ at a uniform temperature of 60 °C as shown in the Figure 5.2. Both fluids were configured in a counter flow arrangement to maximize heat transfer efficiency.

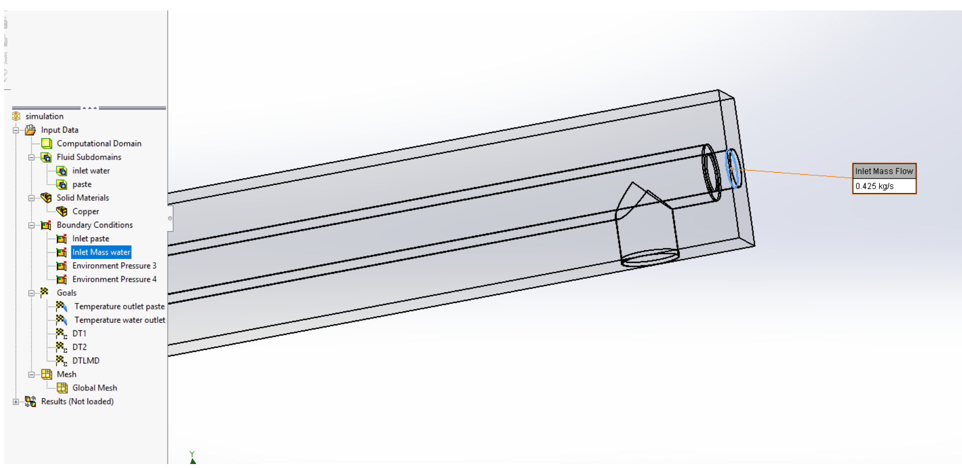


Figure 5.2: Mass flow boundary condition applied to the water inlet.

At the outlet of the heat exchanger, a static pressure outlet boundary condition was applied to both fluid streams and set to atmospheric pressure ($p = 101,325$ Pa), as shown in Figures 5.3 and 5.4. This configuration allows the fluids to exit freely, ensuring a fully developed flow profile without artificial back pressure that could affect heat transfer or velocity distribution.

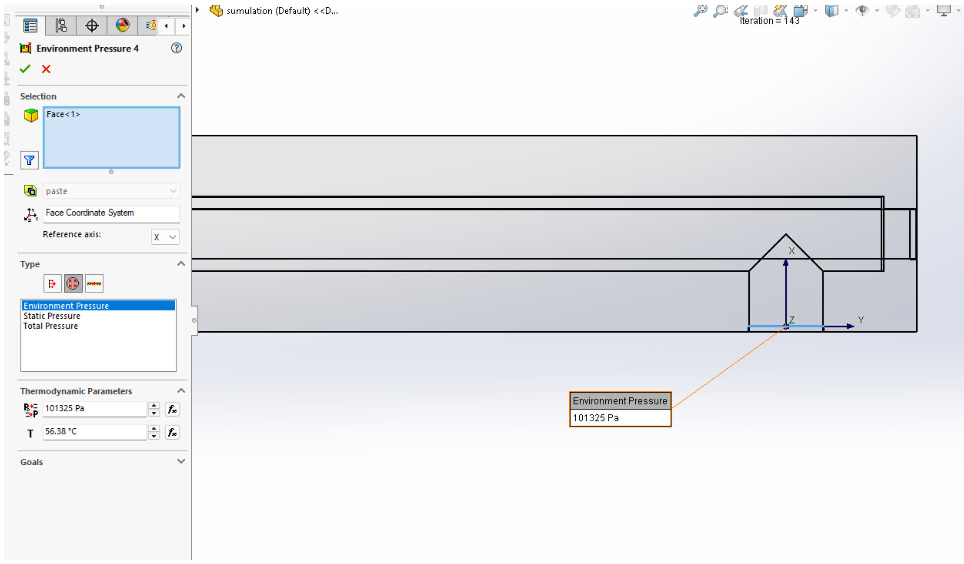


Figure 5.3: Static pressure outlet boundary condition applied to the olive paste.

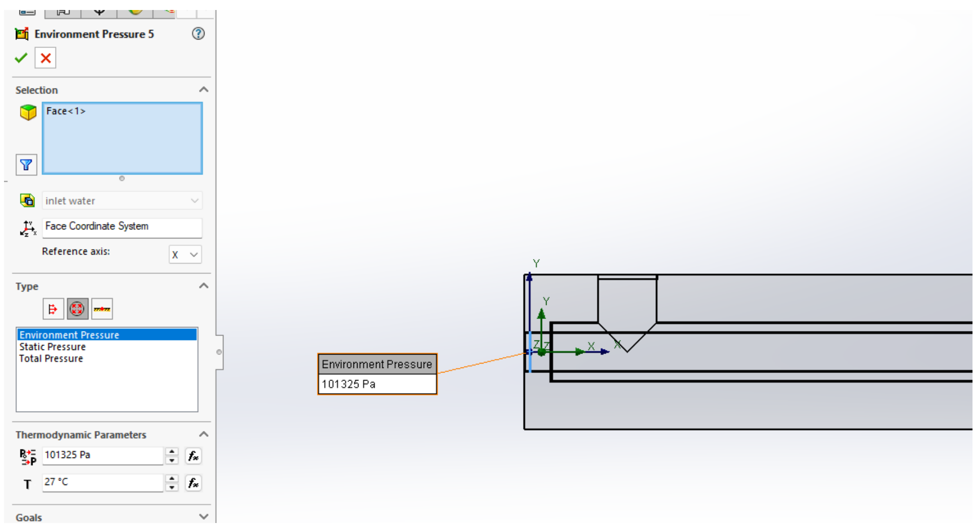


Figure 5.4: Static pressure outlet boundary condition applied to the hot water.

All solid walls of the exchanger were modeled as stainless steel, meaning that no heat is exchanged with the external environment. The material properties of stainless steel were assigned using the SolidWorks material database, with a thermal conductivity of $k = 16\ \mathrm{W\,m^{-1}\,K^{-1}}$, as well as its standard density and specific heat. This configuration reflects the real industrial construction of food grade heat exchangers and prevents thermal losses to the surroundings.

The thermophysical properties of olive paste and water used in the simulation were identical to those employed in the analytical calculations, ensuring consistency between theoretical and numerical analysis.

5.3 Flow Trajectories

To visualize the flow behavior inside the double tube heat exchanger, particle trajectories were generated for both the hot water and the olive paste using **SolidWorks Flow Simulation**. As shown in Figure 5.5, the hot water flows smoothly through the inner tube.

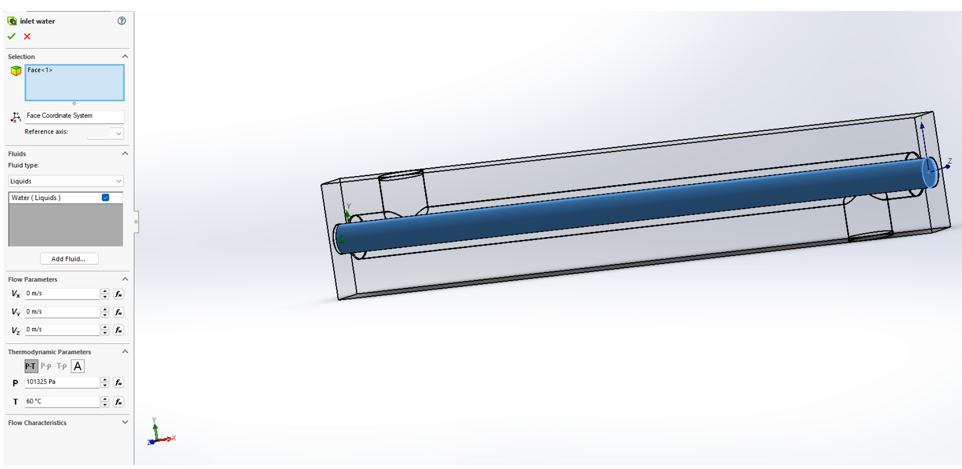


Figure 5.5: Flow trajectory of the hot water inside the inner tube.

Meanwhile, Figure 5.6 illustrates the motion of the olive paste in the annular region.

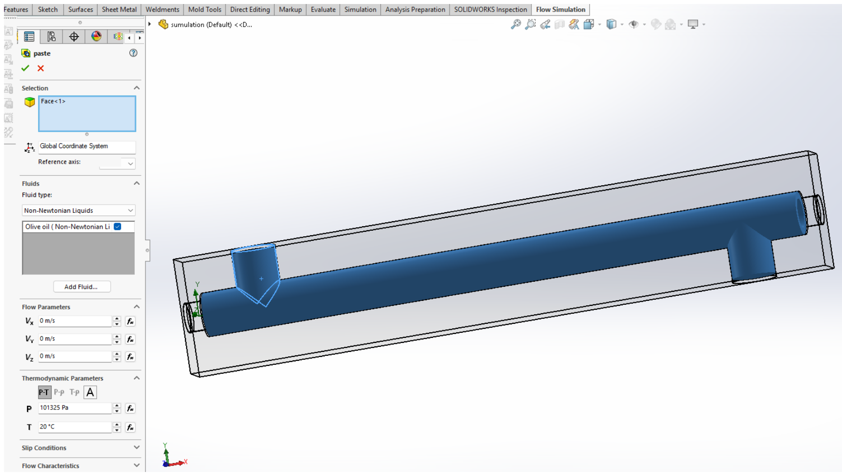


Figure 5.6: Flow trajectory of the water in the annular region.

The trajectory visualization confirms that both fluids maintain a steady and continuous flow along the exchanger length, ensuring consistent heat exchange performance throughout the system.

5.4 Temperature Difference and LMTD Goals

In order to evaluate the thermal performance of the heat exchanger, three temperature difference goals were defined in the simulation: ΔT_1, ΔT_2, and ΔT_{LMTD}. The first two goals quantify the temperature difference between the hot water and the olive paste at the inlet and outlet of the exchanger.

The inlet temperature difference was defined in SolidWorks using the expression:

$$\Delta T_1 = T_{w,\text{in}} - T_{p,\text{in}}$$

This formula was inserted directly into the goal settings, as shown in Figure 5.7.

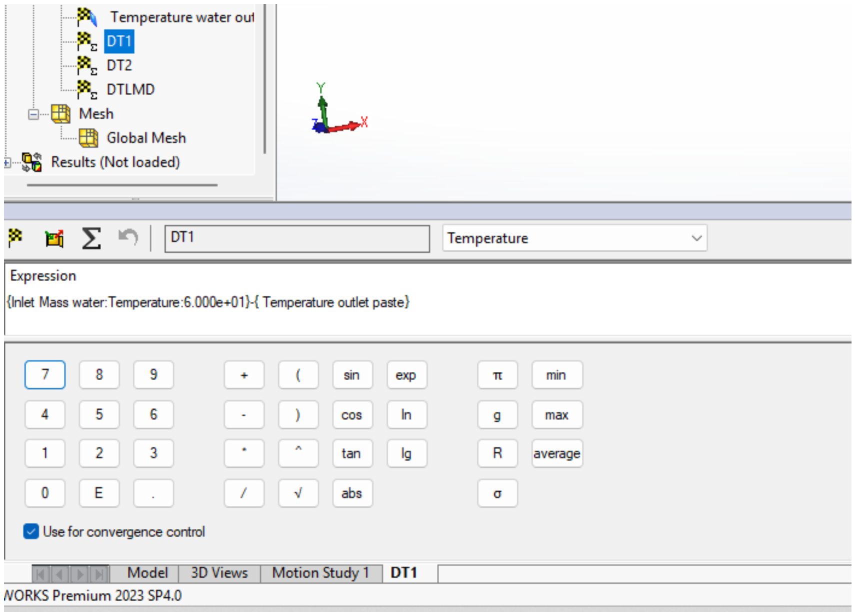


Figure 5.7: Definition of the first temperature difference goal (ΔT_1).

Similarly, the second temperature difference at the exchanger outlet was defined by:

$$\Delta T_2 = T_{w,\text{out}} - T_{p,\text{out}}$$

This expression was also entered into the SolidWorks goal formulation, as illustrated in Figure 5.8.

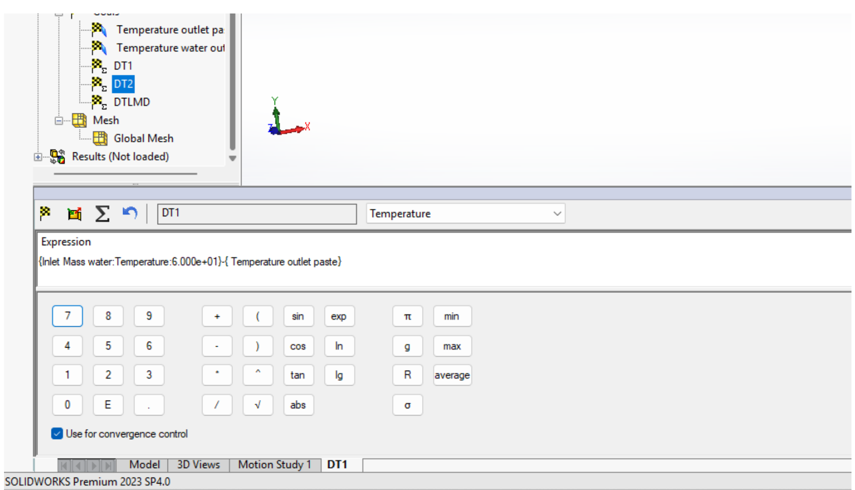


Figure 5.8: Definition of the second temperature difference goal (ΔT_2).

Figure 5.9 presents the setup of the ΔT_{LMTD} goal, which is automatically calculated by SolidWorks based on the relationship:

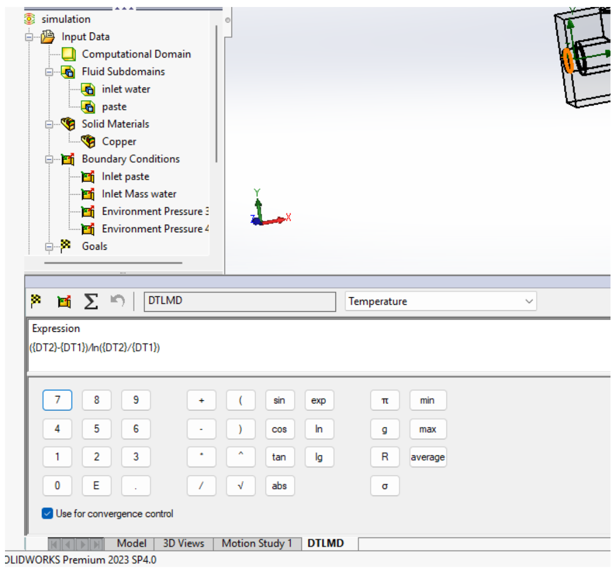


Figure 5.9: Definition of the logarithmic mean temperature difference goal (ΔT_{LMTD}).

$$\Delta T_{\text{LMTD}} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)}$$

These goals enable continuous monitoring of the temperature evolution during the simulation and ensure the convergence of the heat transfer process within the model.

5.5 Criteria for Mesh Selection

This section details the geometric modeling of the heat exchanger and the mesh optimization process performed to enhance the accuracy of the numerical simulation. Figure 5.10 presents the geometry of the designed heat exchanger,

Figure 5.10: Geometric Model of Heat Exchanger

Figure 5.11 illustrates the mesh applied to the heat exchanger model. In this step, different mesh levels were tested specifically for mesh level 2 and mesh level 6 to determine the most suitable resolution for the simulation. Although a coarse mesh (level 2) requires less computational time, it may not capture critical flow and temperature variations. Mesh level 6 provides finer detail, especially around boundary layers, resulting in more accurate thermal and flow predictions. For this reason, mesh level 6 was selected for the final simulation to achieve precise and reliable results.

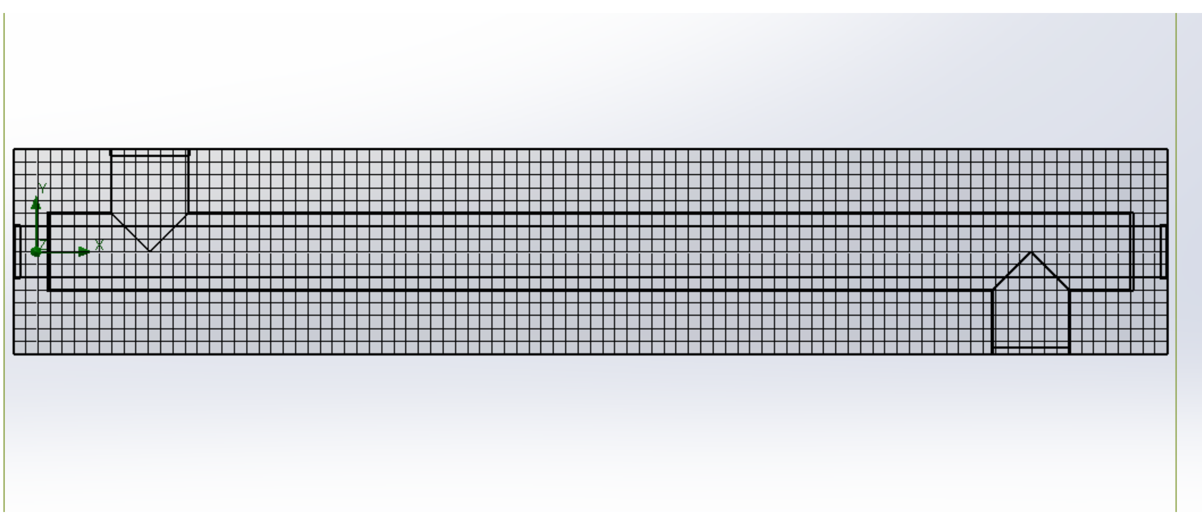
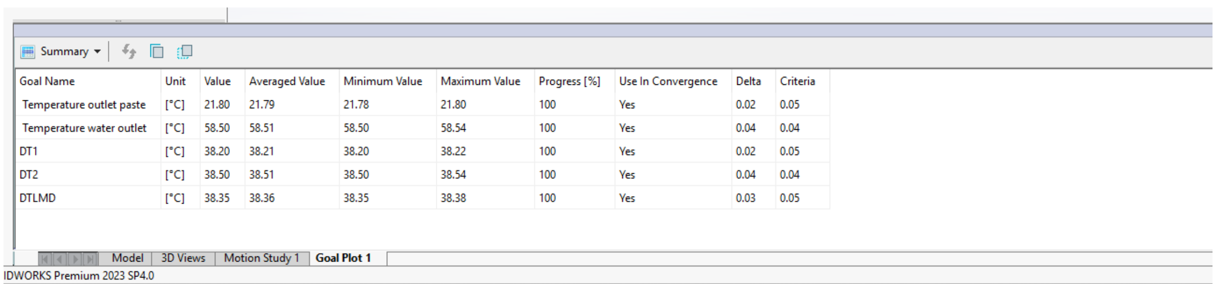


Figure 5.11: Structured Mesh

5.6 Simulation Results and Goal Values

The summary of goal results obtained from the simulation is presented in Figure 5.12. This table provides the calculated outlet temperatures for both fluids, along with the intermediate temperature differences (ΔT_1, ΔT_2) and the logarithmic mean temperature difference (ΔT_{LMTD}).



Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress [%]	Use In Convergence	Delta	Criteria
Temperature outlet paste	[°C]	21.80	21.79	21.78	21.80	100	Yes	0.02	0.05
Temperature water outlet	[°C]	58.50	58.51	58.50	58.54	100	Yes	0.04	0.04
DT1	[°C]	38.20	38.21	38.20	38.22	100	Yes	0.02	0.05
DT2	[°C]	38.50	38.51	38.50	38.54	100	Yes	0.04	0.04
DTLMD	[°C]	38.35	38.36	38.35	38.38	100	Yes	0.03	0.05

Figure 5.12: Summary of goal results for the heat exchanger simulation.

The simulation reached full convergence, with all goals meeting the defined criteria. The paste outlet temperature increased from 20 °C to 21.8 °C, while the water temperature decreased from 60 °C to 58.5 °C, confirming effective heat exchange between both fluids. Thus, the heat exchanger operates efficiently and steadily under the given conditions.

5.7 Temperature Distribution

Figure 5.13 illustrates the temperature distribution inside the double tube heat exchanger obtained from the SolidWorks Flow Simulation. The contour plot represents the steady state thermal field within both the inner tube (carrying hot water) and the annular region (carrying the olive paste).

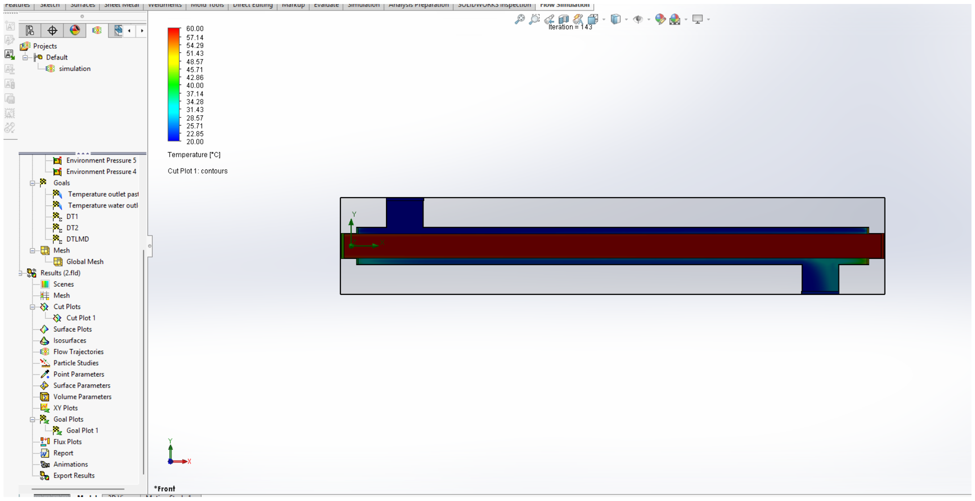


Figure 5.13: Temperature distribution within the double tube heat exchanger.

As shown in Figure 5.13, the hot water enters the inner tube at about 60 °C and exits at 58.5 °C, while the olive paste in the annulus warms from 20 °C to 21.8 °C. The color transition from red to blue confirms efficient heat transfer through the wall, with smooth and uniform temperature gradients along the exchanger.

5.8 Conclusion

The SolidWorks Flow Simulation verified that the stainless steel heat exchanger operates efficiently, with correct mass conservation, realistic pressure behavior, and effective heat transfer between both fluids. The close agreement with analytical calculations confirms the validity of the numerical model and its suitability for integration in the continuous olive oil extraction system.

Chapter 6

General Conclusion

This thesis presented the design of a continuous **Ultrasonic Thermal Inline Reactor (UTIR)** developed to improve the efficiency and sustainability of extra virgin olive oil (EVOO) extraction. The proposed system integrates a double tube heat exchanger for rapid and controlled thermal conditioning together with an ultrasonic reactor that enhances oil release through acoustic cavitation.

Compared to the conventional two phase extraction system (21% yield, 86.7% efficiency), the integration of ultrasound increased extraction performance, achieving approximately **25–27% yield** and **92% efficiency**. Moreover, the UTIR system ensures improved preservation of bioactive compounds while reducing total processing time and energy consumption.

In the final step, **CFD simulations** were performed using SolidWorks Flow Simulation in order to evaluate the thermal and hydraulic behavior of the system. The results confirmed stable and efficient operation, with minimal pressure loss and effective heat transfer. The outlet temperatures reached approximately 58.5 °C for water and 21.8 °C for olive paste.

In conclusion, UTIR technology provides a continuous, efficient, and environmentally sustainable solution for olive oil extraction. It represents an important step toward the **modernization of the Tunisian olive oil industry**, combining higher productivity with enhanced product quality and improved process control.

6.1 Future Work

Although the results are promising, several improvements and extensions can be pursued in future work:

- **Industrial Integration:** The system can be installed inline in existing olive mills as a replacement for traditional malaxation tanks, allowing continuous operation with minimal modification to the current process layout.
- **Energy Optimization:** Further optimization of heat recovery, insulation, and recirculation of hot water could reduce operating costs and improve thermal efficiency.
- **Quality Assessment:** Future studies may include detailed chemical and sensory analysis of extracted oils to confirm improvements in phenolic compounds, oxidation stability, and flavor profile.

Overall, future development and industrial deployment of the UTIR system would contribute to a more sustainable and economically competitive olive oil industry in Tunisia and other olive producing regions.

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