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Second Cycle Degree (MSc) in Italian Food and Wine

Olive Mill Wastewater: A Sustainable Resource for Italian Products, Current Status and Future Prospects

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Abstract

Olive mill wastewater (OMWW), a byproduct of olive oil production, presents a double-edged effect. While its high organic content and toxicity pose a significant environmental threat, OMWW also contains valuable components like polyphenols, nutrients, and organic matter. This thesis explores the characteristics of OMWW, examining both its detrimental effects on the environment and its potential for resource recovery.

Traditionally, OMWW treatment focused solely on detoxification for environmental disposal. However, this approach often proves costly and impractical for small-scale producers. This research investigates a shift towards a more sustainable approach, transforming OMWW into valuable products while mitigating its environmental impact.

This thesis reviews current treatment methods for OMWW, analyzing their advantages and disadvantages. These methods include various approaches, each with its own set of considerations. Biological methods, utilize microorganisms to degrade organic matter but often require dilution due to OMWW's strength. Chemical methods employ coagulants and flocculants to remove solids and pollutants, but can potentially generate hazardous byproducts. Physical methods, such as filtration and membrane separation, remove contaminants but can be energy-intensive. Finally, thermal methods apply evaporation or incineration to concentrate or destroy OMWW, raising concerns about energy consumption and air emissions. The choice of the most appropriate treatment method depends on several factors, including simplicity, safety, energy efficiency, and waste production.

This thesis also explores various potential applications of OMWW, including its use in soil amendment and agriculture as compost or biopesticides, while considering the proper management to avoid harming soil health or crops. The bioactive compounds in OMWW hold promise for the development of new drugs and treatments due to their antioxidant, antimicrobial, and anti-inflammatory properties. Additionally, OMWW can be a source of renewable energy through biogas production. The thesis delves into applications of OMWW in various sectors of the food industry in Italy and around the world, including meat preservation, dairy products, smart food packaging, etc.

In conclusion, this review thesis emphasizes the current and future needs for a sustainable approach to OMWW management. By finding valuable applications for this byproduct and employing appropriate treatment methods, the olive oil industry can minimize its environmental impact while creating new economic opportunities.

Introduction

Olive Oil Production and Distribution

Olive tree (*Olea europaea L.*) cultivation for olive oil manufacturing is one of humanity's oldest agricultural activities. Olive oil is a vital ingredient in the Mediterranean diet because of its high nutritional value and health benefits. Olives are mainly grown in the Mediterranean region, Europe, the Middle East, the United States, Argentina, and Australia (Shabir 2022). Olive tree cultivation is distributed in 58 countries around the world with almost 11.5 Mha. Among them, Mediterranean countries are the main producers of olives (European Commission 2023). While Figure 1 provides the average composition of olive fruit (water, protein, oil, carbohydrate, cellulose, and inorganic substances), Table 1 delves deeper into the specific percentages of phenolic compounds and other essential components like pectin, organic acids, and pigments. The composition of the olives depends on the cultivar, the meteorological conditions that characterize the different stages of flowering, as well as the growth and maturation of the fruit, the degree of ripeness at the time of harvest, the harvesting techniques, the duration and conditions of temporary storage, the cultivation practice, the location of the olive grove (P. R. Gabriele Di Giacomo 2022). Understanding these factors allows for a more comprehensive understanding of the multifaceted composition of olives.

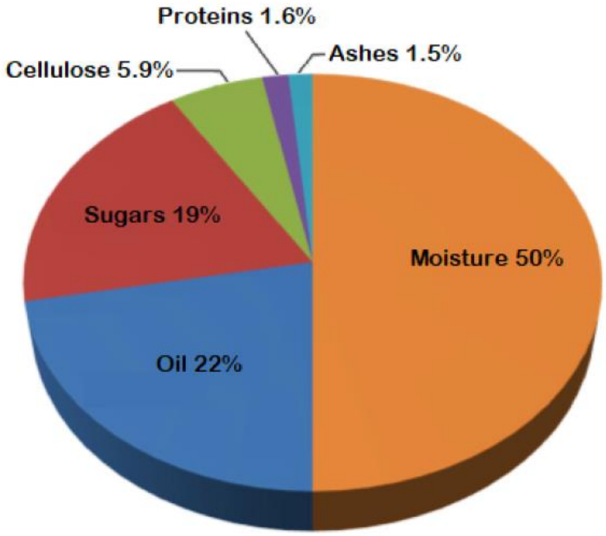

Figure 1: the average composition of olive fruit (Gabriele Di Giacomo 2022)

Table 1: Composition of Different Parts of Olive Fruit (Gabriele Di Giacomo 2022)

Constituents	Pulp (%wt.)	Core (%wt.)	Whole Fruit (%wt.)
Water	50-60	9.3	40-50
Oil	15-30	0.7	27.3
Nitrogen-containing compounds	2-5	3.4	10.2
Carbohydrates	6-13.5	79	8.5-28.5
Minerals	1-2	4.1	1.5
Polyphenols (aromatic compounds)	2-2.25	0.1	0.5-1
Others	-	3.4	1.5-2

Olive oil is one of the important products of the olive tree and the European Union is one of the leading producers, consumers, and exporters of olive oil. The EU produces (68% of the world's olive oil), around 2 million tons of olive oil, and 866 thousand tons of table olive per year (P. R. Gabriele Di Giacomo 2022). Since 2009-2023, Spain with 62.4% of total production is the leader in olive oil production, Italy is the second largest olive oil producer with 17.4% and finally, Greece (14.3%) and Portugal (5.2%) are the third, and fourth largest olive oil producer country respectively (Khaoula Khwaldia 2022). Figure 2 shows the distribution of olive oil in leading countries. olive oil production leads to the production of enormous amounts of by-products, including leaves, pomace residue, stone, and wastewater. Olive trees (*Olea europea L.*) are moderate salt-tolerant, evergreen trees that have been cultivated for their fruit and oil around the world.

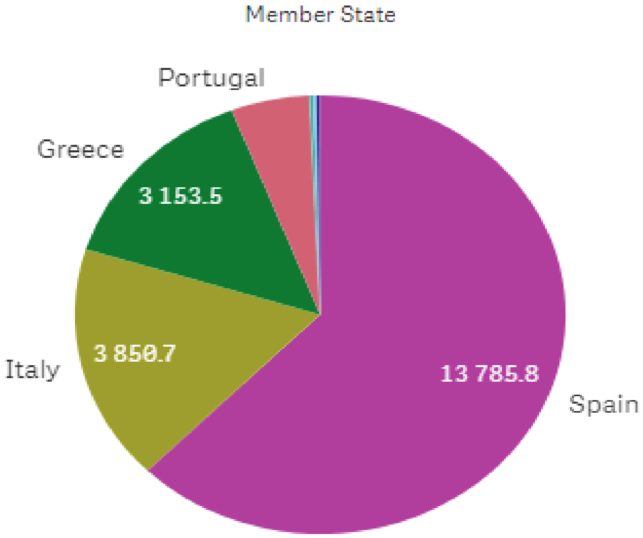

Figure 2: Distribution of olive oil from 2009-2023 (Khaoula Khwaldia 2022)

Extraction of Olive Oil

Different steps of olive oil extraction include olive fruit washing, crushing, malaxation to break into the emulsion, and then oil separation and extraction. Procedures of olive oil extraction have improved throughout time due to increased oil output and technological advancements targeted at improving the end product's quality. The process of extraction of olive oil is shown in Figure 3. The process of olive oil extraction can be different, but the most common way is the conventional pressing process; two-phase decanter, and three-phase decanter process (Rosa Palmeri 2022). In traditional processes olives are collected, washed, crushed mixed, and malaxed with a small quantity of water, this amount of water facilitates the separation of oil from other fractions. The resulting paste goes to further processing which is pressing to drain the residual oil and liquid waste from the press. This contains a mixture of olive juice, water, and residual oil. In the end separation of olive oil from other ingredients will be done by centrifuge or decanting (Donatella Restuccia 2022).

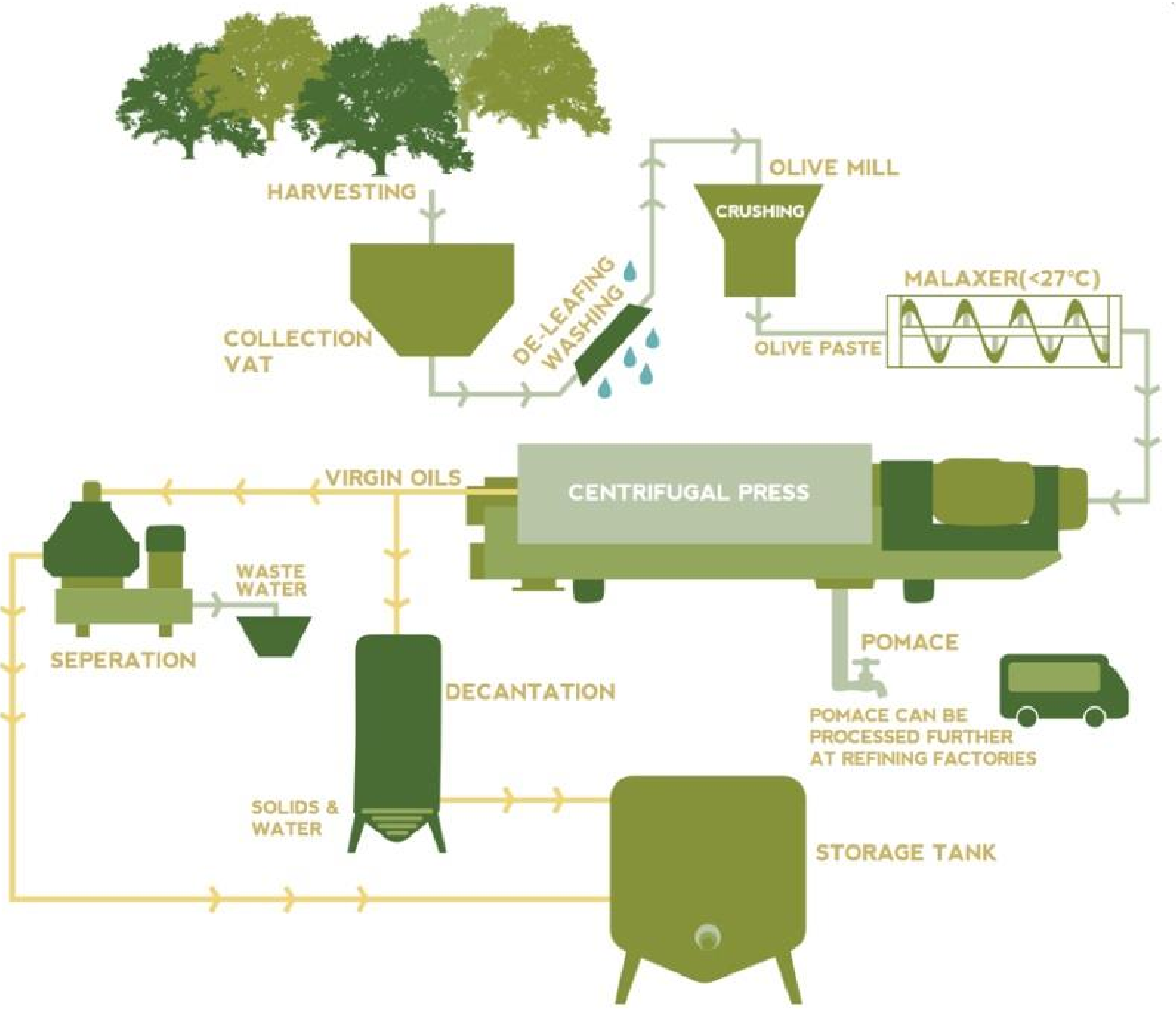

Figure 3: The process of extraction of olive oil (Australian Olive Oil Association 2024)

Pomace mainly consists of skin pulp and pit fragments. Its separation is carried out using a horizontal decanter centrifuge and an olive oil press. The centrifuge step can be performed in two- or three-phases. In the two and three phases instead of a non-continuous pressing process, a horizontal continuous centrifuge was added. In a two-phase system that is mostly used in Spain, there is no need to add hot water which results in olive oil and semi-solid olive cake. Finally, in a three-phase system that is widely used in Italy, adding hot water (0.6 – 1.3 m^3 / 1000 kg of processed olive) leads to the generation of a huge amount of OMWW, while the advantage of this method is a lower amount of olive cake, higher yield of olive oil extraction and lower need of labor (Rosa Palmeri 2022, Paola Foti 2021, Melissa G. Galloni 2022). So, because of these advantages, the three-phase system is widely spread in most Mediterranean countries. Figure 4 shows both two different methods of centrifuge step.

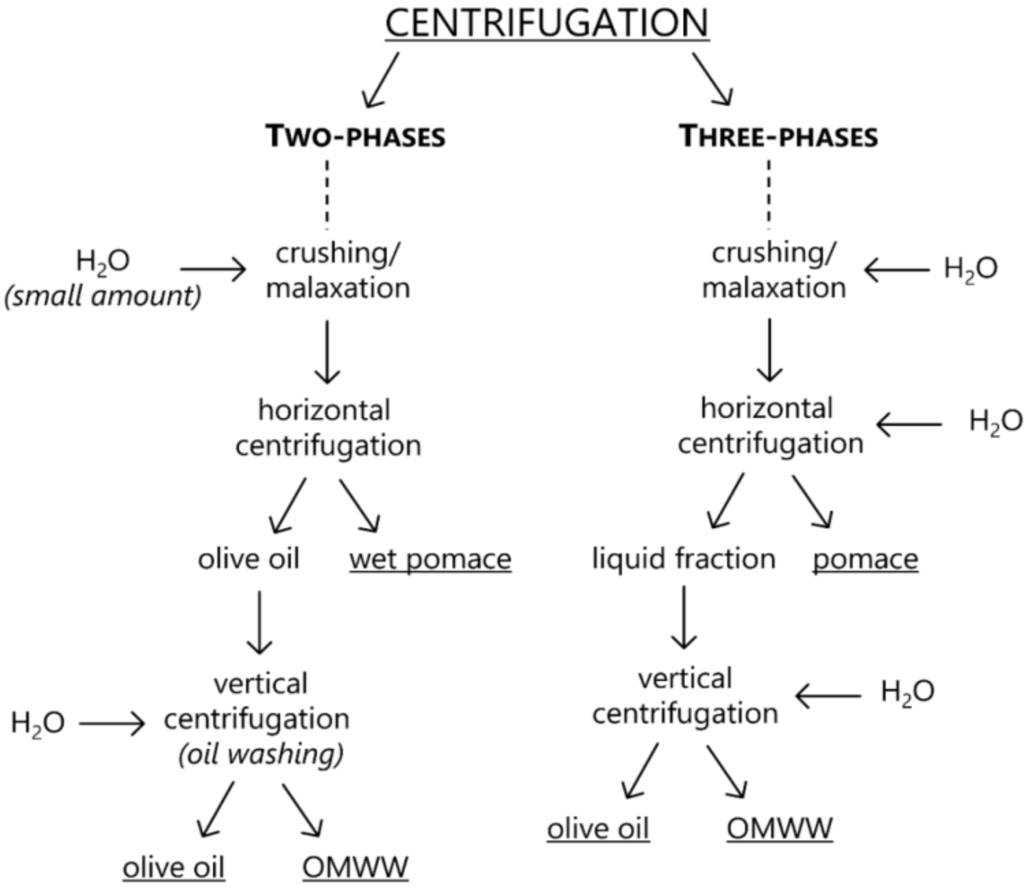

Figure 4: Two and three phases of centrifuge step (Melissa G. Galloni 2022)

By-products of Olive Oil Extraction

Despite the economic and dietetic benefits of olive oil, huge amounts of waste are generated either in the cultivation fields from pruning or in the olive mills during olive oil processing. Therefore, it is important to consider all potential pathways for a circular economy in the olive oil supply chain. Figure 5 illustrates the main components of by-products during olive oil production. This amount can be varied based on many reasons like, the type of olive, methods of processing systems, time of harvest, and so on (Khaoula Khwaldia 2022).

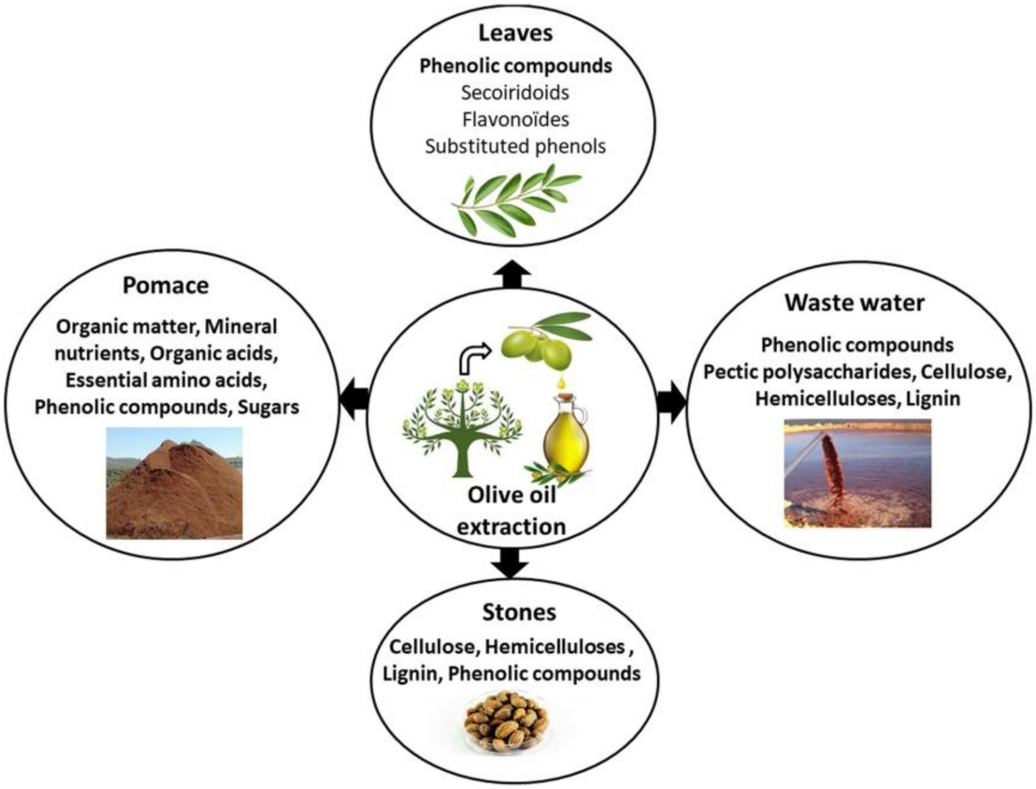

Figure 5: main components of olive oil by-product (Khaoula Khwaldia 2022)

These different byproducts are regarded as inexpensive raw materials containing bioactive molecules, which have the potential to enhance the economic value of nutraceuticals, functional food, dietary supplements, packaging materials, and pharmaceutical formulations. Figure 6 shows different applications of olive oil by-products.

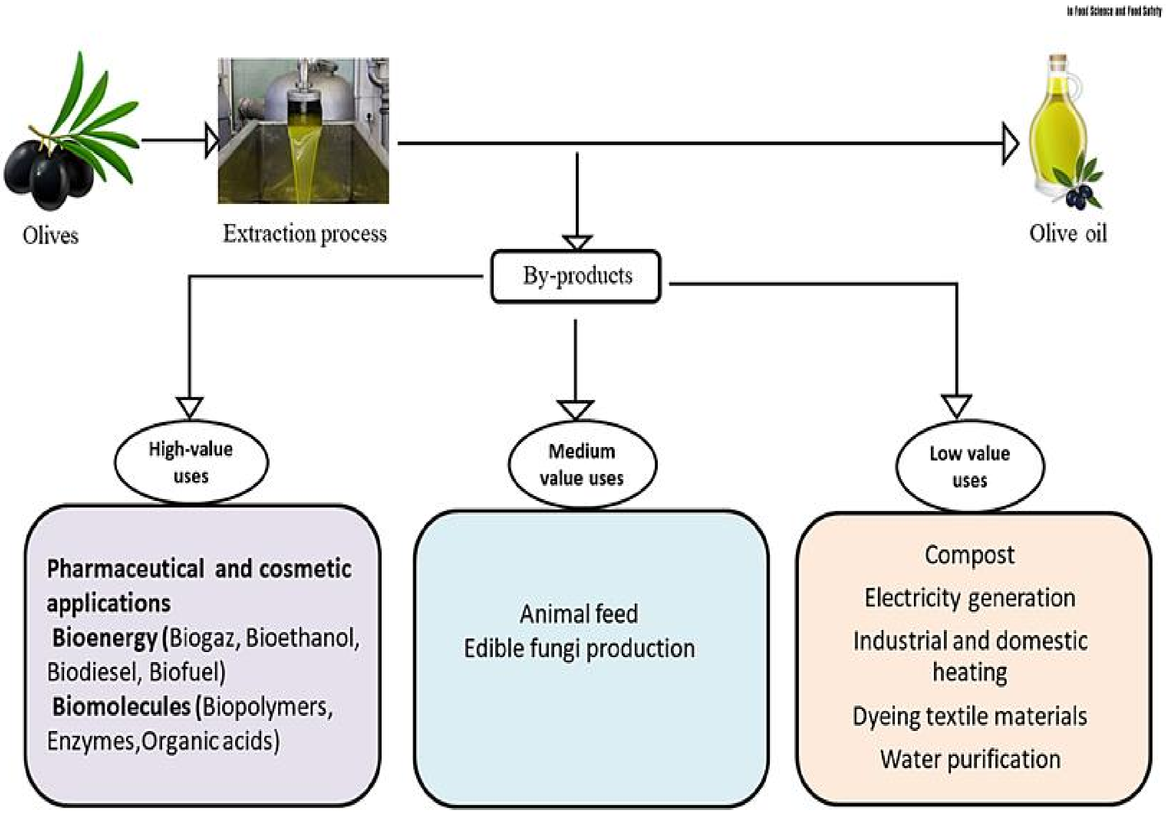

Figure 6: Diversified application of olive byproducts from the olive oil industry (Khaoula Khwaldia 2022)

Main wastes of Olive Oil Extraction

The main olive mill wastes after oil extraction are the following:

1: Olive mill solid or semi-solid waste (OMSW)

It consists of crushed olive pulp and pomace, kernel, sand and stone, leaves, wood, residual oil, and water which are approximately 550 kg per ton of olive in a three-phase extraction method. Olive pomace is made up of a lignocellulosic matrix, polyphenolic substances, uronic acids, and fatty residues. (Sarah Stempfle 2021).

2: Olive Mill Wastewater (OMWW)

It is a blend of deep brown liquid water from vegetation and the soft tissues of olive fruit, combined with water utilized at different phases of the oil extraction process. This includes water added during centrifugation, water sourced from filtering disks, and water used in washing rooms. It consists of around 800-950 kg per ton of olive during olive oil production and the remaining are olive pulp and olive oil residual (Sarah Stempfle 2021).

On the other hand, OMW is made up of water (80-83%w/w) and organic components (15–18% w/w), which include sugars, tannins, polysaccharides, phenolic compounds, organic acids, and lipids Figure 7 (Melissa G. Galloni 2022) and the remaining 2 wt.% contains inorganic matter (i.e., potassium salts and phosphates) (Shabir 2022). Specifically, phenols levels in OMWW range from 1 to 8 g·L, whereas micronutrients and mineral nutrients mainly consist of K O, and P O, which can be found in considerable amounts (2.4– 10.8 or 0.3–1.5 g·L intervals, respectively). In addition, an analysis of OMWW confirmed that it has an electrical conductivity between 5.5-1- dS/m. This wastewater contains valuable molecules with beneficial biological properties. By understanding its composition, we can develop methods to extract these molecules. This would not only reduce waste but also provide resources for new products, promoting a more sustainable and circular economic system in the olive oil industry (Melissa G. Galloni 2022).

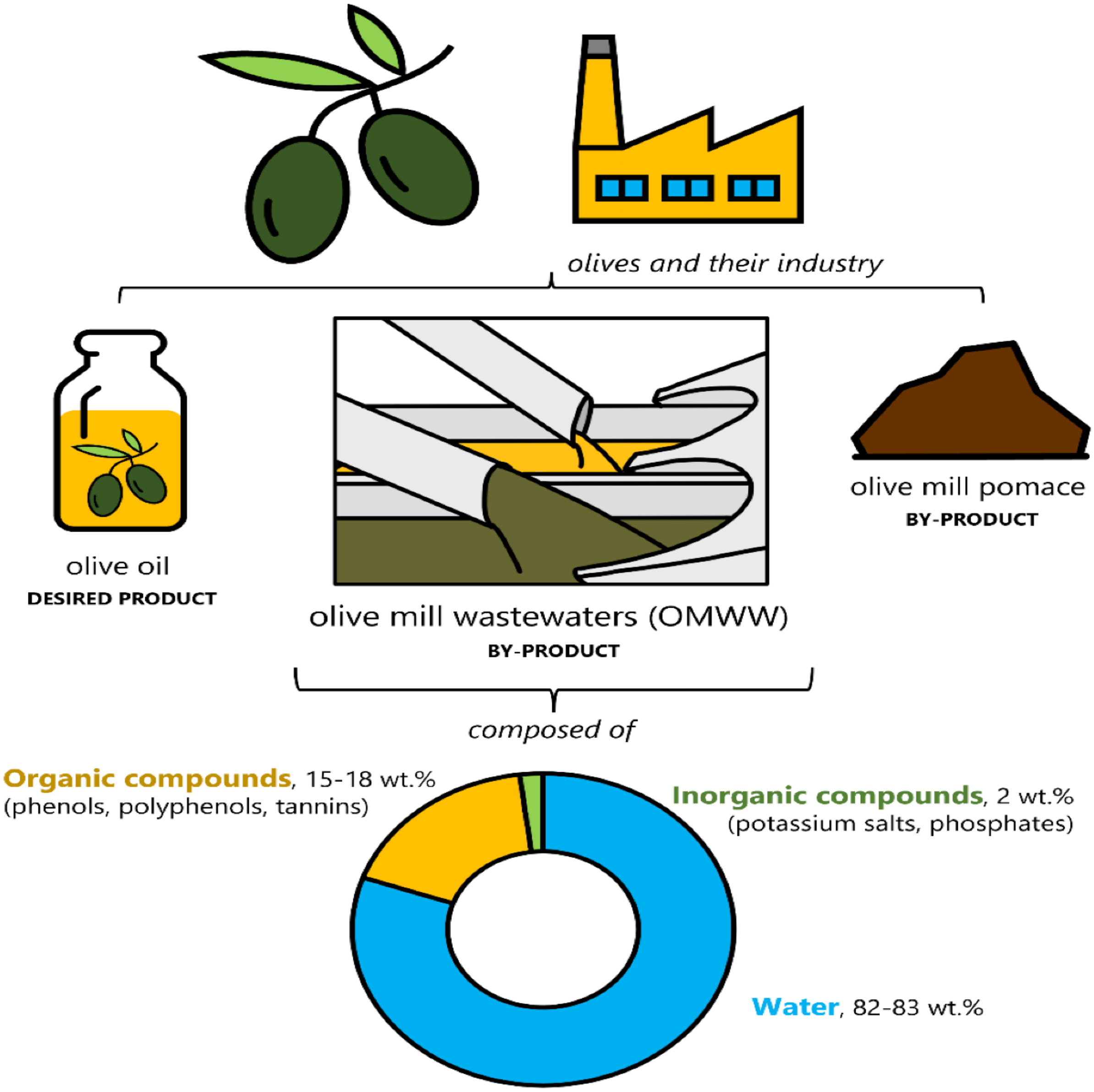

Figure 7: Main wastes of Olive Oil Extraction and its composition (Melissa G. Galloni 2022)

The worldwide production of OMWW is around 10-30 × 10^6 m^3 and 98% of that is produced in the Mediterranean basin. The ratio of olive oil production to OMWW is around 1.0: 2.5 L, which in Italy is 1.4 million m^3 among 30 million m^3 in the Mediterranean countries (Ela Eroğlu 2006, Paola Foti 2021)

The composition and characteristics of OMW usually vary depending on many factors, including the geographic location and climate, type, the degree of maturity of olive fruits, the processing procedures, and the method of oil extraction, such as batch or continuous. Table 2 shows the chemical characteristics of OMWW.

Table 2: Chemical characteristics of OMWW (M. Dermeche S 2018)

Parameter	Minimum	Maximum
pH	2.24	5.9
Electrical conductivity (dS/m)	5.5	10
Total carbon (%)	2	3.3
Organic matter (%)	57.2	62.1
Chemical oxygen demand (g/L)	30	320
Total organic carbon (g/L)	20.19	39.8
Total suspended solids (g/L)	25	30
Mineral suspended solids (g/L)	1.5	1.9
Volatile suspended solids (g/L)	13.5	22.9
Volatile solids (g/L)	41.9	-
Mineral solids (g/L)	6.7	-
Volatile acidity (g/L)	0.64	-
Inorganic carbon (g/L)	0.2	-
Total nitrogen (%)	0.63	-
Lipids (%)	0.03	4.25
Total phenols (%)	0.63	5.45
Total sugars (%)	1.5	12.22
Total proteins (g/L)	2.6	3.1

Aim of Thesis

Nowadays, because of the scarcity of sunflower oil, which is produced and exported by Ukraine, annual olive oil production increased dramatically. This situation increased the demand for olive oil faster than its production, which is expected to reach 3,100,000 tons in 2022. This sizeable seasonal production rate of wastewater represents a considerable hazard to the environment due to the high load of pollutants, which needs an intensive management protocol. From an economic and environmental point of view, lack of adequate management of this number of produced byproducts and wastes is vital and always has been challenging. Disposal of these byproducts in soil or waterways leads to grave issues for the Mediterranean basin (Donatella Restuccia 2022). Some of these byproducts can be considered high-value compounds and can be used at different industry levels.

Unfortunately, the treatment of OMW is still a crucial issue in the Mediterranean region that needs to be resolved due to the severe negative impact on the environment, especially land and water resources. This fact still challenges researchers and industries to present their research findings and technologies to solve OMW problems. This project aims to review the characteristics of high-value components of olive mill wastewater, and its management and application of these bioactive at different industry levels to increase the sustainability of olive oil production.

Literature Review

Criticism and Opportunity of OMWW

The Criticism of Olive Mill Waste Water

The primary waste produced from olive oil extraction processes is OMW. This wastewater had been historically discharged directly onto land, forming a black soil layer near the olive oil mills. These days, the annual quantity of OMW effluents produced in the Mediterranean countries is about 30×10^6 m^3. These effluents have become an increasing environmental challenge due to the significant increase in olive tree planting and the consequent development in olive oil production processes. For example, the shift from conventional mills using pressure to machines using centrifugal force has accompanied the production of more significant amounts of OMW (Al-Qodah, et al. 2022).

OOMW, originating from three-phase extraction systems, is a challenging dark brown liquid. It carries a unique odor, within an acidic pH range of 3.0 to 5.5 mainly because of fatty acids, and due to the presence of dissolved salts exhibits high conductivity (6 to 16 mS/cm). Additionally, OMWW shows elevated values in various pollution parameters. These include intense offensive smell, biochemical oxygen demand in 5 days (BOD_5) ranging from 40 to 95 g/L, chemical oxygen demand COD from 50 to 180 g/L, with a significant concentration of polyphenols (up to 80 g/L), which exhibit resistance to biodegradation and pose toxicity to many microorganisms, and fish toxicity at 8.7%. The average composition of OMWW is shown in Table 3 (Giada La Scalia 2017). Notably, it contains significant amounts of suspended high content of solid matter (total solids up to 20 g/L). Without proper recycling, OOMW becomes a serious environmental concern, representing a substantial source of pollution (Cancilla 2021).

As mentioned before European countries have the biggest portion of olive oil production in the world. they are generated in huge quantities in short periods of time. Although this high yield has economic and health benefits, it has a significant environmental problem due to the generation of high amounts of both solid and water waste. According to the European Community, the production of OMW is about 30 million m^3 per year. In Italy because of the widespread use of a three-phase system, the amount of OMWW is high, so there is a high demand to recycle this by-product (Giada La Scalia 2017, Cancilla 2021). In addition, the reduction of waste by-products along with the supply chain has a double benefit in terms of both environmental impact and disposal cost.

Table 3: Average physicochemical properties of olive oil mill wastewater and present compounds (Giada La Scalia 2017)

Compound	Concentration (g/L)	Parameter	**Quantity**
Ammonium	1.8	BOD_5^* (g/L)	**37.5**
Calcium	0.7	COD (g/L)	**197.0**
Magnesium	2.6	Electrical conductivity (mS/cm)	**9.2**
Potassium	5.9	pH	**4.8**
Sodium	1.7	Total dissolved salt (g/L)	**16.5**
		Water content (%)	**79.0**

- BOD5, Biochemical oxygen demand in 5 days; COD, chemical oxygen demand.

It is worth noting that the quantity of OMWW is still much lower than other types of waste, for example, domestic sewage and its production is seasonal, but in terms of pollution, each 1 m^3 of OMWW is equal to 100-200 m^3 of domestic sewage. So Improper disposal of OMWW into water reservoirs poses serious threats to ecosystems, particularly natural water bodies like groundwater resources, surface waters, seashores, and oceans. The prominent issue observed is discoloration, resulting from the oxidation and subsequent polymerization of tannins. Furthermore, OMWW contains substantial amounts of reduced sugars, high phosphorus content, and phenolic compounds, which exert toxic effects on certain organisms. This imbalance leads to the rapid development of sugar-metabolizing microorganisms to grow rapidly and adversely affect other living organisms. The increased phosphorus content accelerates algae growth, contributing to eutrophication. Even minimal exposure, equivalent to 1 liter of untreated OMWW in 100,000 liters of circulating water, can severely intoxicate aquatic organisms, including riverfish (*Gambusia affinis*) and certain types of shellfish (Evagelia Tsagaraki 2006, Antonio Fiorentino 2004).

The dispersion of OMWW and its subsequent metabolic processes have the potential to contribute to soil nutrient enrichment and may be regarded as an economical water resource. However, owing to the elevated concentration of potassium, the cation exchange capacity of the soil is likely to be altered, consequently affecting the environment for soil microorganisms, and influencing soil fertility. Additionally, adverse effects resulting from the unregulated distribution of OMWW may include the immobilization of available soil nitrogen, a decrease in magnesium levels, and alterations in soil porosity (Evagelia Tsagaraki 2006).

As Italian regulations, the disposal of OMWW onto agricultural soil is permitted up to 50 m^3/h for OMW obtained by a press system and 80 m^3/h for those with a centrifuge system. However, discharging a substantial amount of pollutants into the sewage system without any treatment is prohibited. Numerous studies indicate that such untreated discharges are responsible for toxicity in seed germination, bacteria, and aquatic organisms (Antonio Fiorentino 2004).

Opportunity of OMWW

OMWW has a double nature. While it is a strong pollutant, in the meantime it is a source of valuable components, like polyphenols, inorganic trace elements, organic matter, anthocyanins, and flavonoids. More than 30 different phenolic compounds have been detected in OMWW showing great variability both from the qualitative and quantitative point of view, depending on several factors, such as type of olive, stage of maturity, and most importantly type of production process. So it can be considered as a main natural antioxidant and pharmaceutical ingredient and it has the potential to be used as a natural food preservative (Evagelia Tsagaraki 2006).

This aligns with the growing interest in the food industry for high-quality products containing natural antioxidants and antimicrobials. Existing research on the antioxidant or antimicrobial properties of these OVW-derived phenolics would strengthen the case for their use. The study found that polyphenols extracted from olive mill wastewater have antimicrobial effects on *Escherichia coli* K-12, affecting its biofilm formation and motility. These findings suggest that it has potential as a natural product with anti-biofilm properties, which could be beneficial for food preservation and addressing biofilm-related issues in various industries (Carraro 2014). In addition, other studies show due to the high content of phenolic compounds in OMWW like simple phenols, flavonoids, and lignans it very attractive for the active packaging industry (Khaoula Khwaldia 2022). However, challenges such as extraction costs and potential regulatory need to be addressed before widespread adoption.

Olive Mill Wastewater Treatment

Olive mill wastewater is the resulting effluent from the olive oil industry that poses a significant threat of pollution effect to the environment. Although it is produced seasonally and in smaller amounts compared to other industries, the negative effects of OMW on the environment are high. A composition rich in organic matter, acidic pH, high content of phenolic compounds, high concentration of total solids, and unpleasant odor are the main characteristics of OMW turning this effluent into an environmental problem (Domingues 2021, Ahmad Jamrah 2023). OMW discharge is a significant environmental concern. Studies have shown that it can contaminate groundwater and water bodies, potentially harming public health and negatively impacting agriculture and surrounding ecosystems (Adnan I Khdair 2017). In addition, the direct, and non-treated use of OMWW can also harm crop growth. Thus, the treatment of OMW before release into the environment is an important issue.

There is still no European Union (EU) legislation regulating OMW management and reuse in agricultural soils. In the EU, each Member State is responsible for its regulations regarding the safe disposal and reuse of OMW. According to Italian legislation law N 574 OF 11/11/1996 the agronomic use of vegetation water shall be permitted within the acceptability limit of fifty cubic meters per hectare of surface area concerned in one year for vegetation water from traditional cycle mills and eighty cubic meters per hectare of surface area concerned in one year for vegetation water from continuous cycle mills (Law No. 574 1996).

There are many ways of the OMW treatment, from conventional approaches such as the physical (e.g. centrifugation, filtration, and adsorption) and biological (anaerobic digestion and anaerobic co-digestion) processes, to Chemical treatments, such as electrocoagulation, advanced membrane filtration, advanced oxidation processes (AOPs) and sulfate radical based AOPs (SR-AOPs). Figure 8 shows the different ways of OMWW treatment. (Shabir Sumera 2023, Telma Vaz 2024). Due to the complexity of the effluent, OMW may not be efficiently treated by a single process and requires a mix of technologies before reaching the required characteristics for its application.

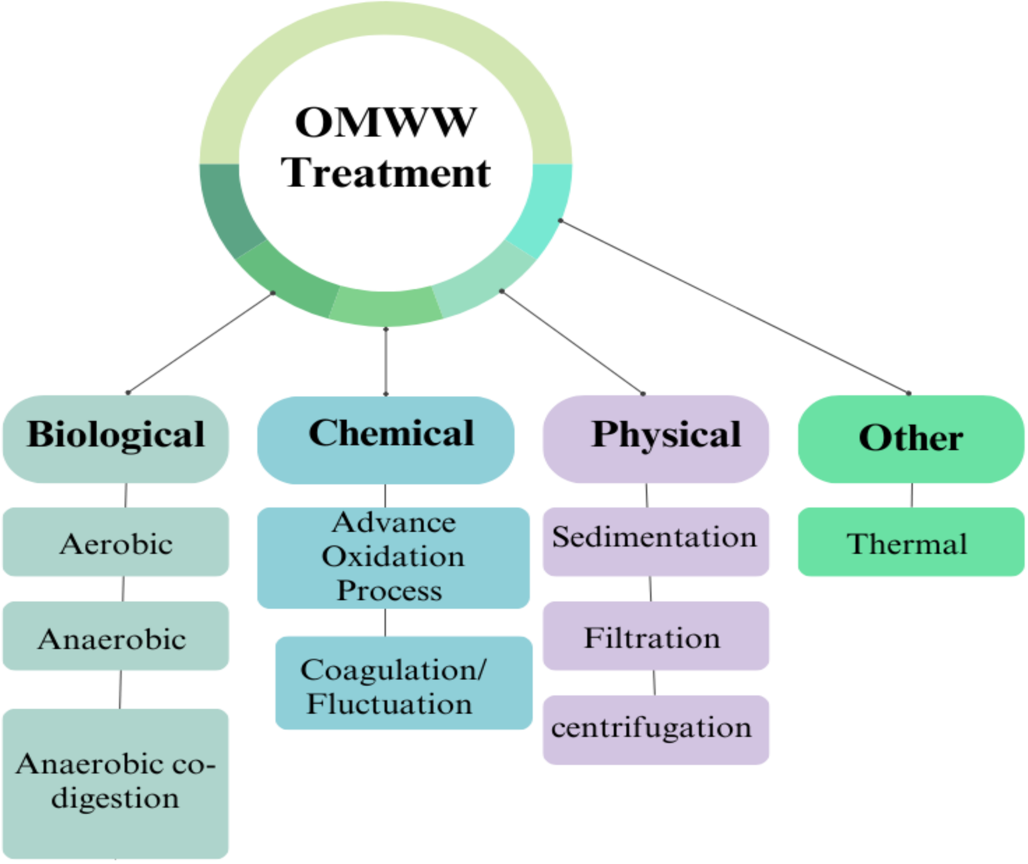

Figure 8: Different ways of OMWW treatment

Biological Treatment of OMWW

Biological methods are based on the production of proteins, and activated carbons, including, anaerobic and aerobic digestion. This reduction can be accounted for using the phenols as an energy source by microorganisms, and their incorporation (Mohamed Hafidi 2005). Biological wastewater treatment has emerged as a dominant technology due to its well-established reputation for environmental compatibility, operational reliability, and, in most cases, economic viability. This approach increases the natural biodegradation capabilities of microorganisms to remove organic matter and inorganic nutrients from wastewater streams. However, the presence of phenolic compounds in olive mill effluent (OME) poses a unique challenge, as these compounds can inhibit microbial activity. Although the biological treatment of OME requires careful selection and potential adaptation of the microbial consortium, it remains an attractive option for OME management due to its sustainability, reliability, and cost-effectiveness (Telma Vaz, 2024, Sumera Shabir 2023).

Aerobic treatment method

The aerobic treatment of OMWW appears to be efficient at reducing the level of phenolic compounds. bacteria, fungi, and protozoa play a crucial role in treatment of wastewater. Aerobic microbes such as *Geotrichum candidum, Phanerochaete chrysosporium, Pleurotus ostreatus, Bacillus pumilus*, *Aspergillus niger, A. terreus* and others have long been advocated for OMW therapy. These microorganisms feed on a variety of complex pollutants that found in the water and drastically reduce phenolic component concentration (Esteves 2021).

In aerobic treatment, specially designed containers, called bioreactors, create ideal living conditions for these microbes. These reactors provide them with the oxygen, organic matter, and nutrients they need to thrive. During this process, microbes function as decomposers, oxidizing complex organic molecules to revert them to simple forms of carbon that may be safely reintroduced to the environment (Muthusamy Govarthanan 2021, Sumera Shabir 2023).

To improve the treatment's efficiency in mitigating the wastewater's toxicity, Houda El Hajjouji 2014 suggested that aerobic treatment should be applied before the anaerobic process. They confirmed that aerobic treatment of OMWW can reduce genotoxicity (harm to genetic material) and phytotoxicity (harm to plants) of raw OMWW. Scientists believe the decrease in phytotoxicity is primarily linked to the breakdown of phenolic compounds by microbes. These phenolic compounds, particularly oleuropein and gallic acid, are known to be harmful to plant genetic material.

Anaerobic Treatment of OMWW

Anaerobic digestion (AD) has emerged as a highly effective and environmentally sustainable biochemical process for bioenergy production from organic waste biomasses. In anaerobic digestion, microorganisms convert, in the absence of oxygen, the biodegradable organic matter into biogas and digestate. It is achieved by a collection of anaerobic microorganisms, typically bacteria, under limited or no oxygen conditions.

These microorganisms have a slower rate of growth than aerobic microorganisms. In treating olive mill wastewaters, anaerobic digestion is the most often used approach. The procedure requires little energy, generates less sludge, and allows for energy recovery since methane gas is created during the last stage, which may be utilized to generate electricity (Ioannis S. Arvanitoyannis 2007, Sumera Shabir 2023).

It can be conceptually divided into four key steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, with the last being the most critical anaerobic stage (Figure 9).

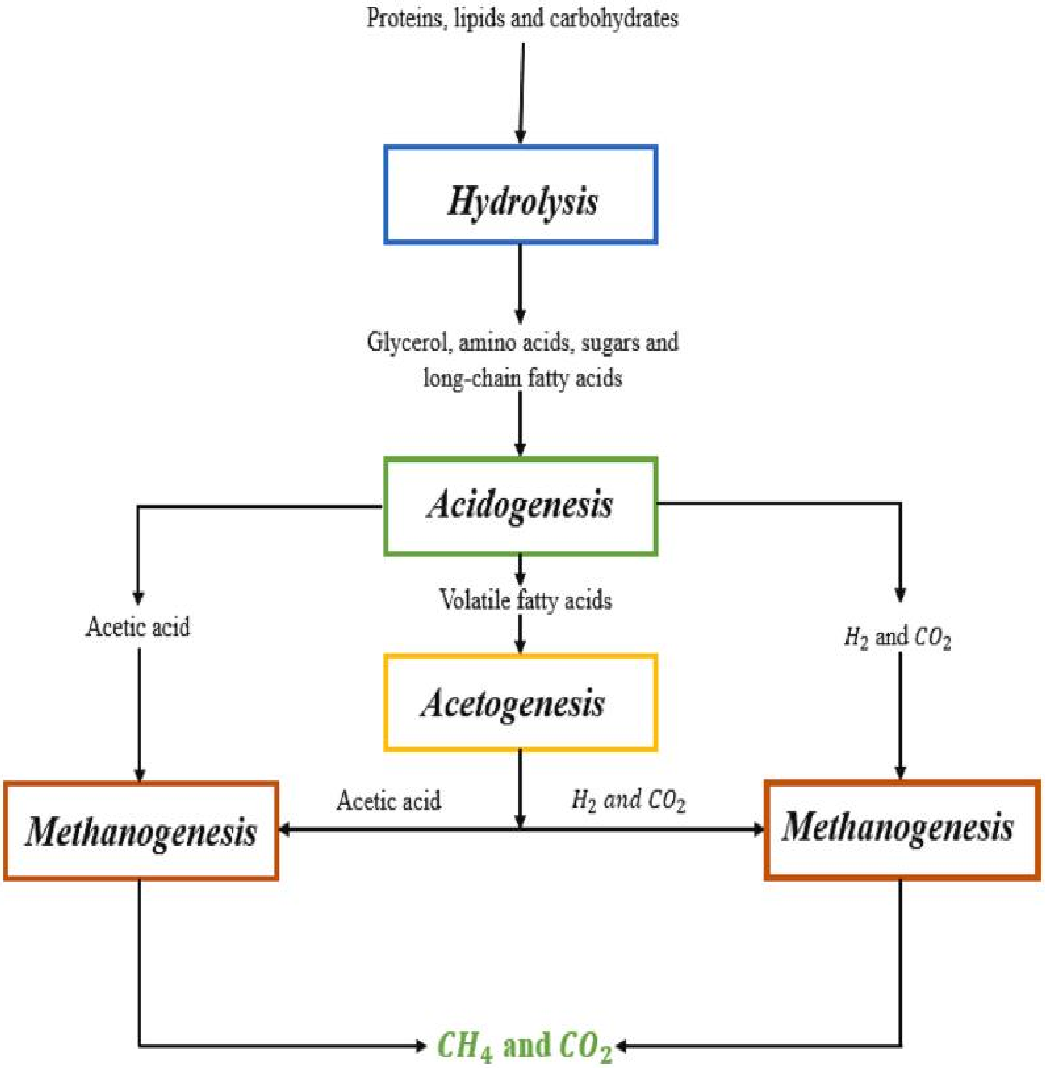

Figure 9: key steps of anaerobic OMWW treatment (Telma Vaz 2024)

The wastewater should have a balanced C/N/P ratio and a pH between 6.5 and 7.5 for an effective anaerobic bioconversion process. Biogas is a versatile fuel source composed primarily of methane (CH4) at concentrations ranging from 50% to 75%. Carbon dioxide (CO2) is another major component, accompanied by trace amounts of ammonia (NH3), siloxanes, hydrogen (H2), nitrogen (N2), and oxygen (O2) (Brisolara 2016, Liberti 2016). Biogas applications include direct utilization for fuel, utilization in co-generation systems for combined heat and power generation, and upgrading through a purification process to produce biomethane, a renewable alternative to natural gas (Telma Vaz 2024).

Each stage is run by distinct bacterial populations operating in the absence of oxygen (Fezzani B 2010). The inoculum, a critical component, establishes the initial microbial activity and shapes the overall bacterial community composition, ultimately influencing the rate and efficiency of substrate (Yan 2023). The source of the inoculum significantly impacts methane yield, process stability, and overall treatment time. Several options exist for inoculum selection, including digestate from established AD processes, sludge from wastewater treatment facilities, effluent from manure treatment operations, or even landfill leachate (Ge 2016).

Beyond biogas production, AD offers a valuable co-product: digestate. This nutrient-rich material, resulting from the anaerobic digestion process, finds application as a fertilizer in agricultural settings. Digestate application enhances soil fertility and promotes improved plant growth. Furthermore, it presents itself as an eco-friendly alternative growing medium or nutrient suspension for hydroponic vegetable cultivation (Aboelfetoh M 2022).

Aboelfetoh M 2022 investigated the impact of anaerobic digestion (AD) temperature and the ratio of olive mill waste (OMW) to dairy manure (DM), on renewable energy production and digestate quality. They also, analysis the quality of digestate as a fertilizer for the growth of faba bean. The result shows that the mixture with the ratio of 2:1:2, OMW:DM: inoculum in the anaerobic situation at 55°C generated 40% more methane than at 35°C and 252% more than at ambient temperature. In addition, different digestate concentrations affected faba bean growth. So, optimizing AD conditions and waste ratios can enhance both energy production and crop growth.

Anaerobic co-digestion

AD of crude OMWW had a lower treatment efficiency in terms of organic compound removal, biogas production, and process stability. This could be attributed to phenol toxicity towards methanogenic bacteria and nitrogen lack of these effluents, which result in an imbalanced C/N ratio required for a good anaerobic digestion process. Therefore, some research study is focused on improving AD of OMWW such as pre-treatment steps before AD to reduce toxic compound concentration. (El Gnaoui 2020). The anaerobic co-digestion (AcoD) process has been studied as an alternative to surpass some of the difficulties of mono-digestion, by combining at least two different substrates (Almeida 2021).

Moreover, the AcoD of OMWW has been proposed in order to enhance the AD performances, by mixing OMWW with other nitrogen-rich substrates, mainly animal manure, agro-industrial residues, and municipal solid waste (Azbar Nuri 2008).

In one research Azbar 2008, Investigated co-digestion of OME with other organic residues (cheese whey and laying hen litter). Co-digestion with laying hen litter significantly enhanced OME biodegradability. Over 90% increase in biogas production was obtained when digesting OME with laying hen litter. The biogas production increased only 22% when CW was used for the same purpose. This study highlights the potential of co-digestion to improve OME treatment and biogas production.

Chemical treatment of OMWW

Various less expensive chemical approaches, such as adsorption, oxidation, electrocoagulation, and photocatalytic oxidation, have been used to treat OMW, but they cannot entirely reduce the pollutant load of OMW. Hence, this method could be used in combination with other methods of OMWW treatment. Haksevenler 2014 confirmed that among the investigated chemical treatment processes, electrocoagulation, and Fenton's reagent were found more effective after pretreatment, especially in terms of total phenols removal.

Ozone, hydrogen peroxide, chlorine, chlorinated derivatives, and combinations of all of these have been investigated for OMWW treatment. Hydrogen peroxide and ozone systems are selected because of their strong oxidizing potential and the ability to operate at atmospheric pressure and temperatures without producing unwanted breakdown products (Auría Rasclosa 2014).

Advanced Oxidation Process Treatment

Numerous studies have explored the removal of organic contaminants using Advanced Oxidation Processes (AOPs), which can achieve the complete oxidation of organic compounds. AOPs involve oxidative processes where hydroxyl radicals (OH^-) are generated from oxidant compounds such as O_2, O_3, and H_2O_2, or other oxidants like sulphate radicals, hypochlorite, and chlorine dioxide. These processes can occur with or without a catalyst and may utilize energy sources such as electrochemical methods, artificial ultraviolet light, solar light, and ultrasounds. All these approaches, even using diverse reacting mechanisms, share the production of hydroxyl radicals (Méndez-Arriaga 2009, Mostafa 2018, Fatma Chkili 2017).

Advanced oxidation techniques, which employ a mixture of oxidants as well as oxidants combined with UV light, have emerged to boost oxidation rates. They are distinguished by the generation of the highly oxidative OH^- radical at room temperature through various photochemical and non-photochemical mechanisms. This potent radical can convert organic molecules to CO2 (Al-Bsoul A 2020). The result of OMWW treatment using ultrasound oxidation combined with advanced oxidation processes showed 59% COD removal within 90 minutes in the ultrasound/UV/TiO2 system. factors like ultrasound power, initial COD concentration, TiO2 concentration, frequency of ultrasound, and temperature are important in the system function.

Coagulation/ Fluctuation OMWW Treatment

Coagulation is a chemical process used in wastewater treatment to remove suspended solids and improve the removal of chemical oxygen demand (COD) from olive mill wastewater (OMWW) (Vuppala 2020) . In the context of OMWW treatment, coagulation involves adding coagulants (such as lime or aluminum sulfate) to destabilize suspended particles. Here’s how it works:

First Coagulation/Flocculation Step: Lime (at 8 g/L) combined with aluminum sulfate (Alum) (at 7 g/L) can remove about 10% of electrical conductivity (EC), 41% of total solids (TS), and 48% of COD.

Second Coagulation/Flocculation Step: Using 5 g/L of lime and 4 g/L of Alum, you can reduce about 37% in TS and 67% in COD.

Sludge Valorization: The resulting sludge from coagulation/flocculation can be used as a solid alternative fuel with a calorific value of 3295.79 cal/g.

Filtration: Activated carbon and fine gravels are effective filtration materials, reducing EC, TS, and COD by 51%, 37%, and 26%, respectively.

Phenolic Compounds Removal: The combined process of coagulation/flocculation and filtration achieves a global reduction yield of 97% for vanillyl alcohol, 92% for tyrosol, and 91% for vanillic acid and para-coumaric acid (Layla Fleyfel 2024, Gassan Hodaifa 2017).

Another alternative for OMW treatment is the coagulation-flocculation process based on the addition of chemical substances (aluminum sulphate ($Al_2(SO_4)_3$) and ferric sulphate ($Fe_2(SO_4)_3$) causing coagulation, precipitation, or destruction of organic load (Esteves Bruno M 2019). This type of treatment remains the most global and the least expensive compared to the mass of materials eliminated, but the presence of residual aluminum and iron can cause significant problems for ecosystems and human health, such as Alzheimer's and other diseases (Hui Xu 2017).

In conclusion, the chemical treatment of olive mill wastewater (OMWW) involves several crucial steps. Coagulation and flocculation play a pivotal role in removing suspended solids and improving the removal of chemical oxygen demand (COD) (Yamani 2019). By using coagulants like lime and aluminum sulfate, along with effective filtration methods, we can significantly reduce contaminants in OMWW. Additionally, valorizing the resulting sludge as an alternative fuel adds to the sustainability of the treatment process (El-Emam 2023). By using coagulants like lime and aluminum sulfate, along with effective filtration methods, we can significantly reduce contaminants in OMWW. Additionally, valorizing the resulting sludge as an alternative fuel adds to the sustainability of the treatment process (Abdullah 2019).

Physical Treatment

physical processes such as sedimentation, evaporation, dilution, filtration, and centrifugation have been utilized to treat OMW (Shabir S 2023).

This method reduces suspended particles, oil and grace, BOD, and COD. While these techniques offer advantages in terms of simplicity and cost-effectiveness, their application as a standalone treatment solution is limited. This is because the treated liquid may still contain a significant number of contaminants. Additionally, the process generates a separate waste stream – the precipitated material – which requires proper disposal, raising further concerns (D. El-Emam 2023). In general, to achieve satisfactory results with physical processes, they should be applied in sequence because the single-use is not able to effectively reduce organic matter content and toxicity to acceptable limits for discharge. In Table 4 some studies are summarized, where it can be found the low removal of organic matter by simple physical processes and the high removal when such technologies are applied in sequence (Telma Vaz 2024).

Table 4: Simple and sequenced physical process for OMW treatment (Telma Vaz 2024)

OMW Characteristics	Processes	Results (Removal)
After sedimentation: COD = 320 gO2L−1, BOD5 = 13.25 gO2L−1, TPh = 3.12 gL−1	Centrifugation, Filtration, Adsorption (activated clay)	Centrifugation: 22% COD, 15% BOD5, 6% TPh; Centrifugation + filtration: 25% COD, 29% BOD5, 62% TPh; Centrifugation + filtration + adsorption (with 21 gL−1 of activated clay): 71% COD, 81% TPh
COD = 148 ± 13.3 gO2L−1, TPh = 2.2 ± 0.1 gL−1	Sand filtration and Adsorption (activated carbon)	Sand filtration: 65% COD, 55% TPh; Sand filtration and adsorption: 67% COD, 95% TPh
After sedimentation: COD = 320 gO2L−1, BOD5 = 13.25 gO2L−1, TPh = 3.12 gL−1	Centrifugation, Filtration, Adsorption (activated carbon)	Centrifugation: 22% COD, 15% BOD5, 6% TPh; Centrifugation + filtration: 25% COD, 29% BOD5, 62% TPh; Centrifugation + filtration + adsorption (with 24 gL−1 of activated clay): 83% COD, 94% TPh
COD = 50.4 gO2L−1, TPh = 7.1 gL−1, TSS = 21 gL−1	Coagulation (poly diallyl dimethyl ammonium chloride), Sedimentation	Coagulation: 15% COD; Sedimentation: 31% COD, 30% TPh and 86% TSS
COD = 95 ± 5 gO2L−1, TPh = 11.5 ± 1.6 gL−1, TSS = 15 ± 4 gL−1	Sedimentation	Sedimentation: 53% COD, 78% TPh and 84% TSS
TOC = 15.5 ± 1.2 gC/L, COD = 49.2 ± 2.2 gO2L−1, BOD5 = 7.2 ± 0.5 gO2L−1, TPh = 3.36 ± 0.10 gC/L	Sedimentation (12 h)	Sedimentation: 45% TOC, 50% COD, 64% BOD5, 61% TPh
COD = 134.1 gO2L−1, TPh = 9.1 gL−1	Centrifugation, Filtration	Centrifugation: 41% COD, 52% TPh Centrifugation + filtration: 42% COD, 54% TPh

While physical treatment methods like settling can remove some larger particles from wastewater, they may not be sufficient for complex organic pollutants. However, their effectiveness can be significantly enhanced by combining them with other techniques.

Adsorption, for example, acts like a highly selective filter, attracting and trapping tiny contaminants. Coagulation and flocculation work synergistically, destabilizing and aggregating these small particles into larger, heavier flocs. These flocs then readily settle out through sedimentation, resulting in a significant reduction in both organic matter content and turbidity (cloudiness) within the treated water. This multi-step approach offers a more robust and efficient method for wastewater purification (Domingues E 2021).

(La Scalia 2017) examined two filtration methods for the treatment of OMWW. Using silicon membranes, one method effectively removed almost all (99%) of the total suspended solids and most (97%) of the oil and grease. However, it wasn't as effective at removing dissolved organic matter, as measured by COD (chemical oxygen demand) and TOC (total organic carbon).

The other method, nanofiltration, showed promise for removing dissolved organics. It eliminated around 70% of COD, a significant improvement over the membrane filtration. Nanofiltration also excelled at removing oil and grease (82%) and even most of the dissolved organic carbon (up to 99%).

An interesting economic approach combined membrane filtration with reverse osmosis to specifically target phenolic compounds, another major contaminant in OMWW. This combination reportedly reduced these phenolic components by 90%, further cleaning the wastewater (DP Zagklis 2013). Despite the fact that much research has been conducted to develop new methods for phenolic compound extraction, few economic analyses are reported in the literature to evaluate the sustainability of these methodologies.

Thermal Treatment of OMWW

Several methods have been explored for OMWW thermal treatment. Thermal process includes various techniques and methods, that all of them focused on concentrating OMWW using either an artificial heat source or a natural thermal energy source (such as the sun or air). The thermal processes include evaporation, pyrolysis, combustion, distillation, and lagoons (natural evaporation) (El Ghadraoui 2020). Here are some approaches:

1. Evaporation in Ponds (Lagoons)
2. Hydrothermal Carbonization (HTC)
3. Combined Strategy

Natural Evaporation in Ponds (Lagoons)

Natural Evaporation in Ponds (Lagoons) is one of the earliest and most common methods for OMWW treatment, particularly practiced in Morocco. OMWW is stored in lagoons where it evaporates using solar energy, especially during the summer season. This simple technique relies on natural evaporation in ambient air, utilizing significantly less energy. However, despite its simplicity, this approach has limitations and is often restricted to laboratory-scale applications (Khdair Adnan 2020, Yahia Rharrabti 2019).

COD removal rates can vary between 20% and 80% in natural evaporation lagoons. However, the waste typically remains in these lagoons for 7-8 months, necessitating extensive land areas (around 1 m^3 for every 2.5 m^3 of OMWW). Environmental issues related to these lagoons include the risk of leaks, infiltration, groundwater contamination, methane emissions from anaerobic fermentation, and the attraction of insects and unpleasant odors (Julianta Siregar 2020).

Although thermal treatment methods can reduce waste volume by 70-75%, there are significant variations in their effectiveness, influenced by factors such as olive ripeness, the extraction process, and the duration of waste storage. One major drawback of these methods is managing and disposing of the emissions generated: besides water, the distillate or condensate contains considerable amounts of volatile compounds like acids and alcohols, resulting in high acidity (pH 4-4.5), high BOD (over 4 g/L), and high COD (over 3 g/L), requiring further treatment before disposal or reuse. Additionally, the combustion of the concentrated paste releases air pollutants due to the high toxic organic load. These processes are also costly because of the significant energy requirements and the need for equipment made from corrosion-resistant materials (Volpe Roberto 2015, Christoforou Elias 2016, Hugo Perazzini 2016).

Hydrothermal Carbonization (HTC)

Hydrothermal Carbonization (HTC) is a thermochemical process that occurs at high pressure and in the presence of water. HTC transforms organic biomass components (like cellulose and lignin) into valuable carbon materials, gases, and inorganic salts. It involves hydrolysis, degradation, and polymerization. HTC reduces energy consumption compared to traditional methods. It lowers emissions and enhances carbonization efficiency. In addition, can improve water quality by adsorbing heavy metals, organic compounds, and anions (Liu Guoqing 2024, Carvalho 2022).

While HTC offers energy savings, the overall cost remains a challenge. High-pressure reactors, temperature control, and water treatment add to the expenses. Balancing these costs with the benefits of HTC is essential for widespread adoption. On the other hand, HTC aims to be sustainable, but its environmental footprint and factors including water usage, greenhouse gas emissions, and the fate of byproducts must be carefully assessed (Mirva Niinipuu 2020, Liu Guoqing 2024).

Combined Thermal Treatment

Researchers propose combining OMWW with another waste stream. The goal is to reduce energy consumption during thermal procedures. They integrate OMWW with another waste stream, such as olive husk (a solid waste from olive processing). Olive husk, rich in lignocellulosic material, is burned to generate heat. This heat is then used for the evaporation of OMWW. By combining these wastes, energy efficiency improves, leading to both energy savings and waste valorization. This approach optimizes thermal treatment while addressing environmental concerns associated with OMWW (Patrick Dutournié 2019, Ghizlane Enaime 2024).

Real Commercial scale of applying Filtration Treatment of OMWW in Italy

This research investigates a method to enrich olive oil with health-promoting polyphenols. They propose using a commercially available microfiltration (MF) membrane system to extract polyphenols from olive mill wastewater of a specific olive cultivar (Cerasuola). This approach aims to achieve two goals:

1. Reduce waste: OMW is a significant byproduct of olive oil production and can pose environmental challenges if not properly managed. By extracting valuable polyphenols, this method could transform OMW into a resource.
2. Enhance olive oil quality: The researchers focused on enriching olive oil from cultivars naturally lower in polyphenols (Nocellara del Belice and Biancolilla). This could create a higher-value product with potential health benefits associated with these compounds.

Furthermore, the study goes beyond the technical aspects and explores the economic viability of this approach. They analyze the cost of the MF membrane system and the potential selling price of the enriched olive oil to determine if the investment is financially sound.

They are treated by Permeare srl (Milan, Italy) and its working capacity is about 500 L/h of wastewater (Figure 10).

Figure 10: Filtration treatment of OMWW machine (La Scalia Giada 2017)

In the mill, the vegetable water produced with a low content of material in suspension (particle size exceeding 1 mm) was accumulated in one or more tanks with a capacity of 500 L. During the load into the tank, it was necessary to add the pectolytic enzymatic preparation (Permazim ZE01). The following membrane treatments were microfiltration, ultrafiltration, and reverse osmosis, as reported in Figure 11 based on (Maurizio Servili 2011) method.

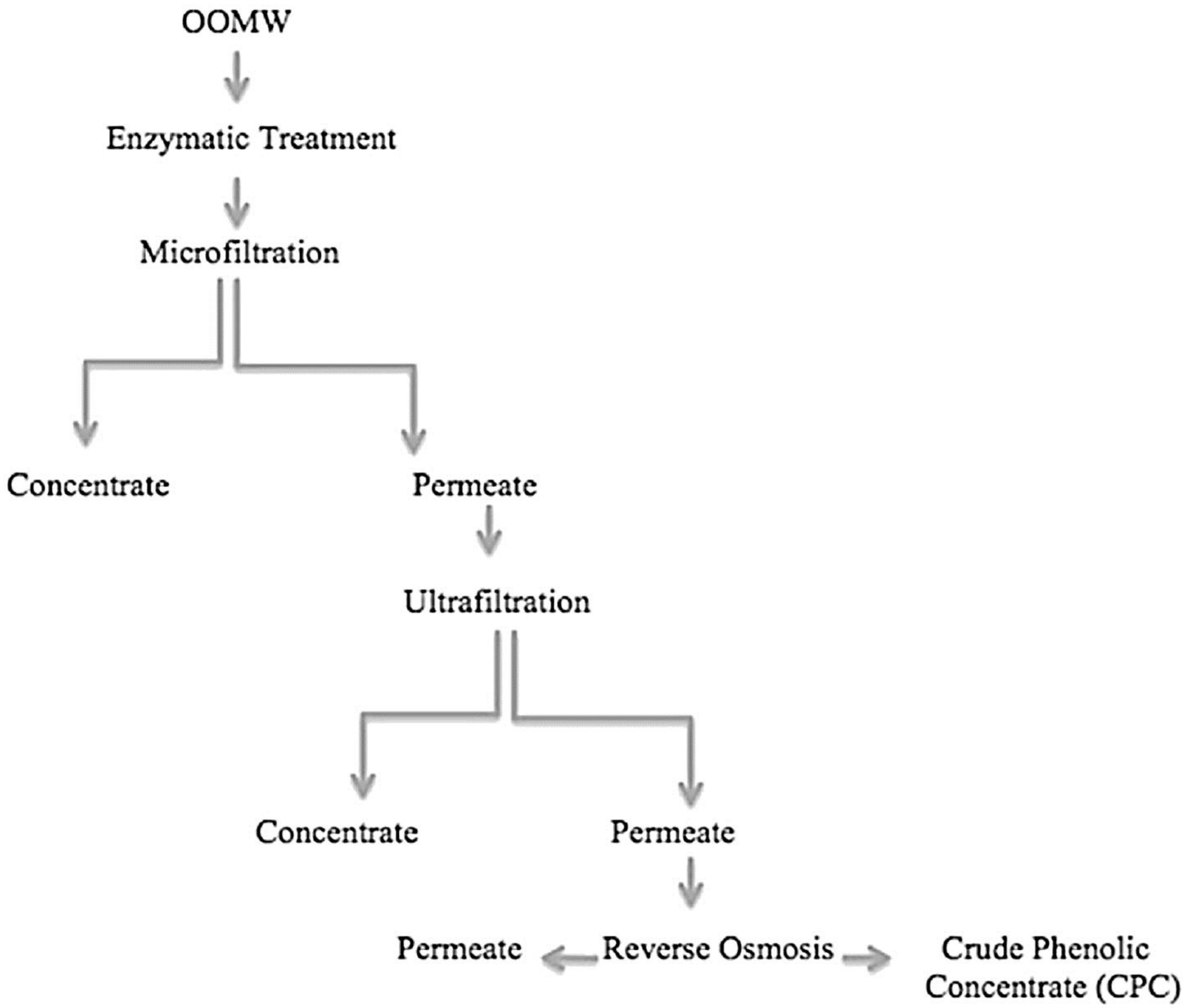

Figure 11: Phenolic Concentrate production by OOMW membrane Treatment (Servili et al 2011)

The treatment process commences with a microfiltration stage, employing a 1-micron membrane to remove any suspended solids, such as coarse particles or debris, from the OMWW. This initial filtration step utilizes a series of three membrane filters housed in tubular modules. As treatment commences, pumps transfer the OMWW from a holding tank to a dedicated processing tank.

Following microfiltration, the OMWW enters the ultrafiltration stage. Here, the focus shifts towards concentrating the larger molecules dissolved within the wastewater, effectively separating them from the cleaner water component. This cleaner water fraction, often referred to as permeate, then undergoes further concentration through a reverse osmosis system.

At the completion of the ultrafiltration cycle, the concentrated wastewater remaining in the processing tank is discharged. This concentrated stream can be directed towards additional pomace oil extraction processes, or be sent to a designated storage tank for eventual disposal. Meanwhile, the permeate from the ultrafiltration stage is transferred to a separate internal tank within the reverse osmosis system.

The reverse osmosis section houses six spiral-wound membrane modules. This stage functions by selectively extracting the remaining dissolved materials present in the permeate, resulting in a highly concentrated solution rich in polyphenols known as Crude Phenolic Concentrate (CPC). Notably, all the membranes employed in this treatment process were sourced from Permeare S.r.l. located in Milan, Italy.

The result showed that enrichment of both cultivars with 10% (v/w) of CPC during the malaxation phase, improves the phenolic concentration. However, extra addition can affect the sensory properties of EVOO negatively.

In terms of economic goals, this research showed that the system is profitable if the consumers accept a 6-7% increase in the final product price. However, the Incremental cost of enriched EVOO is feasible, with positive Net Present Value and Payback Time within four years.

Regarding to the environmental problem of OMWW, this system can reduce waste by 90%, which shows the sustainability of this system (La Scalia Giada 2017).

Present and Future Perspective of the Application of OMWW:

The drive towards minimizing waste in industrial processes, embodied by the circular economy, is leading to a shift in how olive oil production handles its byproducts. New methods are being developed to recycle and extract value from olive mill waste. This focus on waste reduction is also influencing olive oil processing techniques themselves. Innovations like stone removal, pulp dehydration, and cold pressing are creating byproducts with diverse applications in the food, cosmetics, and pharmaceutical industries.

This phrasing emphasizes the environmental motivation behind finding new uses for olive mill waste and the development of new processing techniques that generate more usable byproducts.

Byproducts generated during olive oil milling, particularly the OMW, present a unique opportunity for the industry. These residues can be categorized as "virgin" secondary raw materials due to their mechanical extraction process, free from chemical manipulation. This categorization suggests potential edibility, similar to the extracted oil, with appropriate processing or incorporation into novel food formulations (De Leonardis 2023). The inherent value of OMWW lies in its residual composition. It retains traces of oil, sugars, proteins, minerals, fiber, and phenolics, making it a prime candidate for valorization. Extensive research has explored the potential of OMW within the food industry, highlighting its applicability as a valuable ingredient, natural food antioxidant, antimicrobial and antifungal agent, and oxidative stabilizer (C. L. Fasolato Luca 2016).

However, companies are trying to recover high-value active components while reducing the toxicity of OMWW by legislation and regulatory systems. This strategy presents a dual benefit. Not only does it contribute to environmental improvements, but it also offers economic advantages through a more cost-effective and industry-friendly approach to wastewater treatment. According to research, this valorization includes extraction of valuable compounds, land, and agricultural applications, animal farming, food industries, cosmetic, and pharmaceutical industries, production of biofuels, and so on. Figure 12 shows a different use of OMWW (Doaa. 2023). Until 2021, 794 records were found on the application of OMWW, most were in the scope of environmental science such as chemical engineering, energy fuels, and agriculture Figure 13a. Also there is an increasing interest in using OMWW in the field of biotechnology Figure 13b.

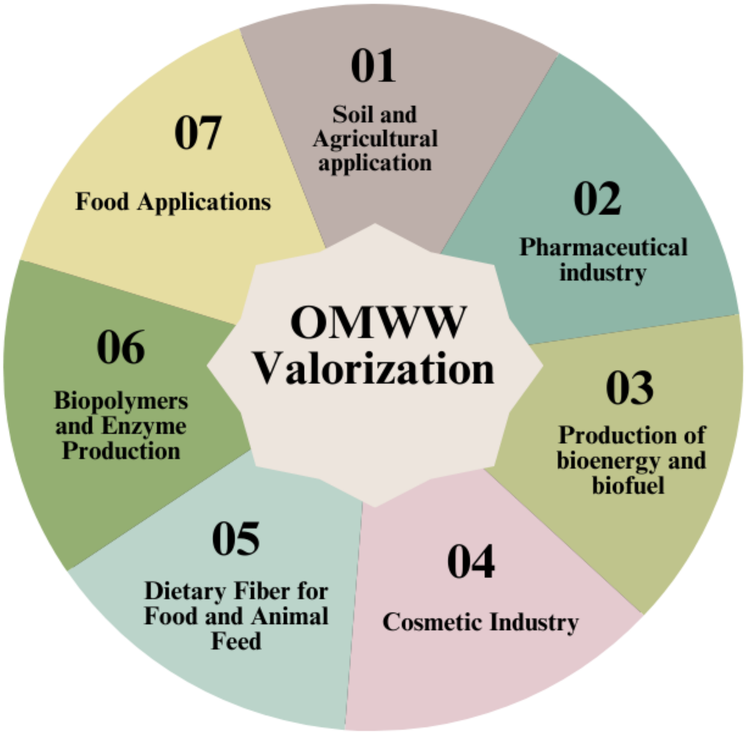

Figure 12: Valorization and different use of OMWW (Doaa 2023)

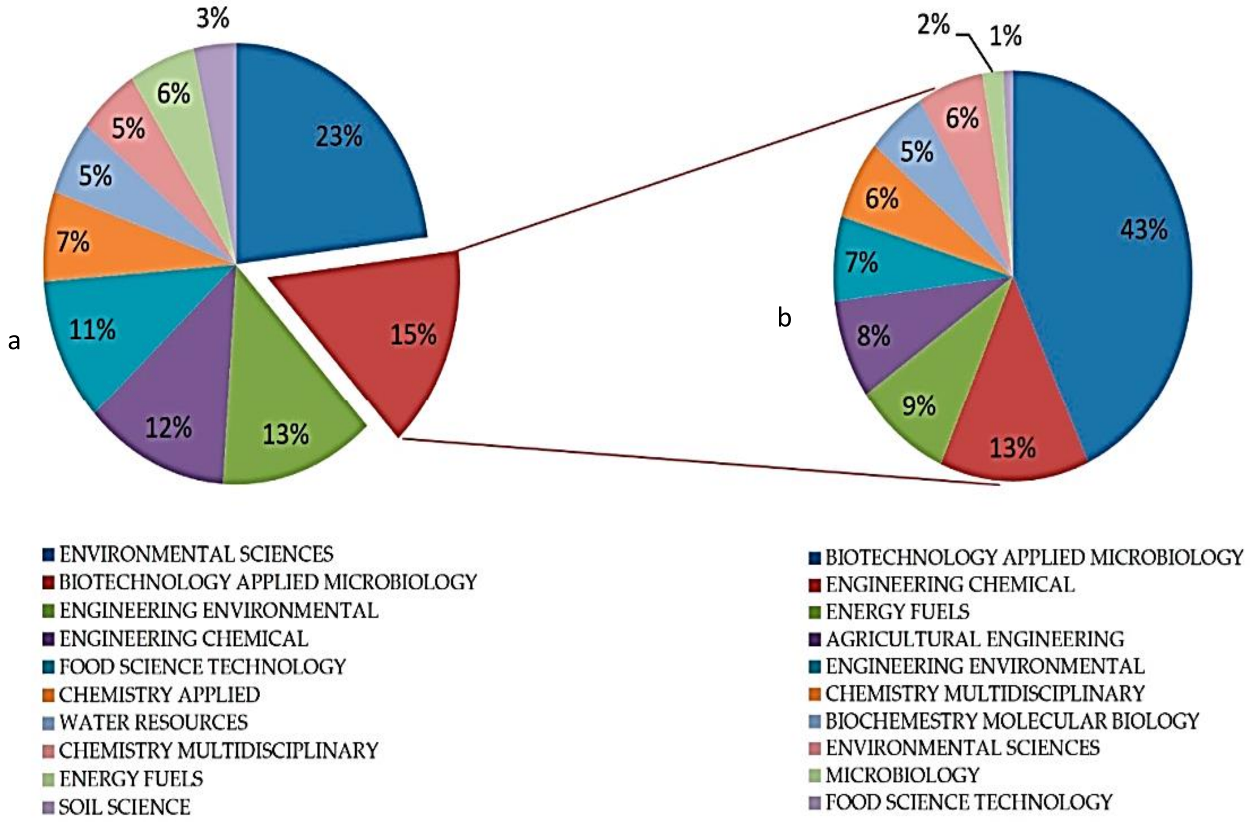

Figure 13: (a) records on OMWW found on PubMed; (b) distribution in different application areas of general records on OMWW, and specific records focusing on applied biotechnology and microbiology (Paola Foti 2021)

Olive Mill Water Waste Utilization

Soil and Agricultural Application

biopesticide and compost production

Many studies have been conducted to turn OMWW into a practical and renewable resource of organic fertilizer, compost, and also water sources for agricultural use.

Composting is a widely used process for breaking down biodegradable organic materials. It involves the controlled decomposition of these materials with exposure to oxygen. Clean and uncontaminated materials, like yard waste and food scraps, can be composted to create a valuable product named compost.

Compost offers a wealth of benefits for agriculture, horticulture, gardening, and even for nurturing indoor and outdoor ornamental plants. However, if the composting process isn't managed correctly, a lower-quality compost results. This off-grade compost can still be landfilled, as it's a stable material that won't leach harmful substances.

The magic of compost lies in its ability to improve soil health. Humic and fulvic acids, key components of compost, act as soil amendments. They stimulate microbial activity in the soil, which in turn helps plants better absorb nutrients, both natural and those added through fertilization. For optimal microbial life, compost needs moisture levels between 40% and 60%, a carbon-to-nitrogen ratio (C/N) between 25 and 30, and a presence of phosphorus and potassium (P. R. Gabriele Di Giacomo 2022).

OMWW shows promise as a biopesticide and compost ingredient. Its application to soil can stop the growth of many plant pathogens like bacteria, fungi, and weeds, potentially due to the presence of antimicrobial compounds. OMWW offers a sustainable pest management solution while utilizing a waste product from olive oil production. However, proper application methods regarding dose and timing are crucial to avoid harming crops (Paola Foti 2021).

While composting offers a well-established method for waste valorization, less explored avenues also hold promise. One such example is the agronomic application of OMWW. However, these studies suggest OMW could play a crucial role in regenerative farming practices.

This liquid byproduct of olive oil production can be spread on olive orchards itself. OMWW acts as a low-cost soil conditioner and fertilizer, offering a sustainable approach to maintaining soil health. even one of the studies demonstrates positive effects on olive production and the quality of the resulting olive oil (Magdich, Ben Rouina and Ammar 2020). Also, many olive oil-producing countries are struggling with water scarcity. Repurposing treated OMWW for irrigation represents a valuable approach to water conservation in these regions (Sarah Stempfle 2021).

However, the use of OMWW requires careful consideration, as research has identified potential drawbacks related to soil health and product quality. The application of OMWW to soil presents a double-edged effect. While it boasts a high concentration of essential nutrients, particularly potassium (K), its potential benefits are counterbalanced by several negative aspects. One major drawback is the high mineral salt content of OMWW. This, combined with its low pH (acidity), can create harsh conditions for soil health. Additionally, the presence of phytotoxic compounds, especially polyphenols, can directly harm plant growth.

The dark color of OMWW arises from the polymerization of tannins and other small phenolic compounds. One study showed that because of the direct use of untreated OMWW on wheat crops, the wheat plants showed signs of stress, with necrotic spots appearing on the leaves and a reduction in the emergence of secondary stems. However, despite these negative impacts on plant health, the final grain yield at harvest showed no significant difference compared to the control groups. This unexpected outcome suggests further research is needed to understand the complex interaction between OMW and wheat development (Semih Otlesa 2012). So, removing these phenolics through specific treatment technologies is necessary before using OMW for irrigation.

Pharmaceutical industry

OMWWs are considered as inexpensive but rich in bio-active compounds with health benefits. There are many studies about the potential use of OMWW compounds in the pharmaceutical sector.

In one study, researchers studied the potential health benefits of OMWW. Researchers in Tuscany focused on two local olive cultivars and their OMWW. They employed a liquid-liquid extraction technique to isolate dietary polyphenolic compounds, followed by analysis using high-performance liquid chromatography and mass spectrometry (HPLC/MS) to identify the specific polyphenols present.

The analysis revealed a wealth of polyphenolic compounds in the extract, with oleacein and hydroxytyrosol being particularly abundant. These specific phenolics are known for their antioxidant, antiradical, and anti-inflammatory activities, suggesting potential health benefits (Doretta Cuffaro 2023).

Recent research focused on the exciting potential of olive byproducts for developing new pharmaceutical products. Their richness in phenolic compounds, polysaccharides, and triterpenoid acids makes them prime candidates for addressing various health concerns, including gastrointestinal disorders, pain relief, appetite control, and gut microbiome modulation.

In 2018, Di and other researchers investigated the use of OMWW polyphenol for digestive problems. Their study investigated an aqueous olive pomace extract's anti-inflammatory property and its impact on human intestinal cell metabolism. The extract effectively reduced levels of IL-8, a key pro-inflammatory cytokine, suggesting potential therapeutic benefits for intestinal diseases. Additionally, the study revealed a metabolic shift towards more efficient glucose utilization, potentially explaining the appetite-reducing effects observed after consuming polyphenol-rich foods (Di M 2018).

Furthermore, other researchers suggest that extracted polar lipids may hold promise for treating inflammatory diseases like atherosclerosis. These lipids were found to inhibit platelet-activating factor, a molecule implicated in inflammatory processes.

Olive byproducts also show potential benefits for infection control. Bio-compounds like aliphatic aldehydes, identified in olive products, demonstrate antibacterial and antifungal properties against various pathogens. Also, these bio-compounds might be useful in preventing or treating infections and even offer possibilities for combating the spread of antibiotic-resistant bacteria.

In addition, some researchers highlight the wider potential of olive byproducts for human health. Compounds like tyrosol, hydroxytyrosol, oleocanthal, and oleuropein within olive mill wastewater (OMWW) exhibit a broad range of biological effects, potentially impacting processes related to diabetes, cancer, heart health, cholesterol management, neuroprotection, and even weight management (Doaa 2023).

Production of bioenergy and biofuel

Biogas, a renewable energy source similar to natural gas, is generated from the breakdown of organic matter in anaerobic fermentation. Olive mill wastewater (OMWW), rich in organic compounds that are almost 80% biomethanizable, holds immense potential for biogas production. In theory, every 1 m^3 of OMWW can create 37 m^3 of methane, as a key component of biogas.

However, a major challenge is the high concentration of polyphenols in OMWW that can hinder the normal development of biomethanization, the process by which microbes convert organic matter into biogas. Researchers are exploring innovative solutions, such as combining anaerobic treatment with an aerobic step. This two-stage approach utilizes specific microorganisms in the aerobic stage to remove the inhibitory polyphenols. This way leads to a more efficient biogas production process from OMWW (Tsagaraki 2007, Mejdi Jeguirim 2020).

Researchers are exploring a promising method to turn OMWW into biofuels. one study proposes using pyrolysis, a high-heat treatment process, to convert OMWW with olive pomace into bio-oil. This process achieves a significant 36% yield, highlighting its potential for waste valorization. While the bio-oil produced has properties generally aligning with European biofuel standards, it requires further refinement due to its water and oxygen content, and acidic nature (Mejdi Jeguirim 2020).

Some researchers explore a method different from pyrolysis that utilizes supercritical water gasification for biofuel production from OMWW. Supercritical water, achieved by heating water above its critical point (374.8°C and 22.1 MPa), becomes a powerful solvent with unique properties. In this process, OMWW is introduced to this supercritical water environment. To further enhance the breakdown of complex organic materials in OMWW and potentially increase biofuel yield and quality, catalysts are employed. The specific catalysts investigated in this article are Nickel (Ni) and Ruthenium (Ru) supported on Alumina (Al2O3). Under these conditions, with the help of the catalysts, the organic components of OMWW are broken down into a gaseous mixture. This gas mixture can then be refined into various biofuels.

The focus of the research is likely on optimizing this supercritical water gasification process with the chosen catalysts (Ni/Al2O3 and Ru/Al2O3) for biofuel production from OMWW. This optimization would involve investigating factors such as reaction temperature, reaction time, and catalyst type. By optimizing these factors, researchers aim to maximize the yield and quality of the biofuels produced.

This method presents a promising alternative approach to utilizing OMWW for biofuel production compared to traditional methods like pyrolysis. The use of supercritical water and catalysts holds the potential to improve the efficiency of the process and potentially generate higher-quality biofuels. However, further research is necessary to understand the optimal conditions for this process fully and to identify the specific types of biofuels that can be obtained from OMWW using supercritical water gasification with these catalysts (Ekin Kıpçak 2018).

Cosmetic Industry

Olive mill byproduct was developed for the skin care industry and is now widely used. It contains compounds (FAs, squalene, OLE, minerals) with biological activity (antibacterial, anticancer, antioxidant, and hydration) which could be olive mill byproducts are rich in bioactive compounds, including fatty acids (FAs), squalene, oleocanthal (OLE), and minerals. These compounds exhibit a range of biological activities in the realm of dermatology. Studies have demonstrated their potential for antibacterial activity, particularly against Staphylococcus aureus, a common bacteria associated with skin infections. Additionally, research suggests that olive leaf extracts containing OLE may play a role in mitigating hyperpigmentation by decreasing melanin production in melanoma cells. Olive mill wastewater (OMWW) extracts further contribute by potentially offering anti-inflammatory properties, as evidenced by their ability to inhibit granule release from immune cells (Charis M. Galanakis 2018).

Squalene, another key component within these byproducts, acts as a potent antioxidant, shielding the skin from the detrimental effects of solar radiation at the epidermal level. This translates to a strengthened and more resilient skin barrier, crucial for overall skin health (Asuka Kishikawa 2015). The high mineral content of olive byproducts also holds significant promise. These minerals have been identified as ideal components for promoting deep hydration, a fundamental aspect of maintaining a healthy and radiant complexion.

Production of Dietary Fiber for Food and Animal Feed

Dietary Fiber for Food

Dietary fiber is the edible plant cells that remain and include lignin, polysaccharides, and other compounds that are resistant to digestion by human enzymes. These include powdered cellulose, fat substitutes, microcrystalline and pectic material that produced gelling agents, as well as potential fermentation substrates yielding specific saccharides. Fiber-rich diets are beneficial to health, and their intake has been linked to a lower risk of numerous cancers. Olive mill byproducts, a rich source of olive cell wall polysaccharides, have emerged as a promising feedstock for various high-value applications (N. M.-M. Dermeche S 2013). Researchers have explored the addition of isolated phenolic compounds as novel functional components to enhance the health attributes of milk (Aliakbarian B 2015).Similarly, in the meat industry, the use of phenolics derived from agricultural byproducts presents an environmentally friendly approach to food preservation. Studies have shown that purified phenolic extracts from olive vegetation water can effectively inhibit the growth of foodborne pathogens in fresh Italian sausages (Fasolato Luca 2016).

Valorization of olive by-products extends beyond the traditional olive oil industry, with promising applications emerging in the dairy, winery, and meat sectors. Notably, hydroxytyrosol (HT), a key phenolic compound, exhibits antibacterial properties, suggesting its potential as a substitute for sulfur dioxide in winemaking. Research in the dairy sector is investigating the ability of olive by-product phenolics to mitigate the Maillard Reaction, a process that can negatively impact product quality. Incorporating olive mill wastewater (OMWW) phenolic powder into raw milk before ultra-pasteurization inhibited the formation of off-flavor compounds during heat treatment (Otero P 2021). This approach has the potential to improve both the nutritional value and sensory characteristics of dairy products.

One study in Japan examined the potential of incorporating OMWW into the fermented Total Mixed Ration (TMR) that was used for dairy cows. The focus was on the impact of OMW on nutrient content, overall quality, and the bacterial composition of the TMR.

The findings suggest that 5-10% OMW in TMR formulations offers several benefits. It demonstrably enhances the quality parameters of the feed and increases the content of polyphenols, recognized for their health-promoting properties. Importantly, these improvements occur without changing the core nutrient profile of the TMR. However, exceeding this 10% threshold leads to elevated lipid content, exceeding recommended levels for cow diets.

Regarding the bacterial composition of the TMR, OMW supplementation had a minimal effect, except a noticeable increase in the abundance of Weissella, a bacterial genus (Zhao 2023). This research provides valuable insights into the potential of OMW as a sustainable feedstock for livestock. Its utilization could contribute to effective waste management within the agro-industrial sector while potentially improving the nutritional value of animal products.

Dietary Fiber for Animal Feed

Researchers are investigating the use of OMWW as a dietary supplement for animals. OMWW contains polyphenols, which promise to improve animal health and reduce reliance on livestock antibiotics. The study suggests that these polyphenols may benefit animals by boosting the immune system, promoting gut health, and offering antioxidant and anti-inflammatory properties.

In one study, OMWW extract showed promise in reducing *Salmonella* bacteria in pig intestinal cells. This indicates a potential protective effect for pig intestines. Overall, these findings highlight the potential of OMWW polyphenols as feed additives to enhance animal health and well-being (Flavia Ferlisi 2024). Further research is needed to confirm these benefits in live animals.

Biopolymers and Enzyme Production

OMWW has emerged as a valuable resource for various bioprocesses, offering a cost-effective cultivation medium for diverse microorganisms. Studies have demonstrated its potential for the production of enzymes like; lipases, laccases, Mn-peroxidases, pectinases, biopolymers like polyhydroxyalkanoates, and algal biomass (Paz A 2021). For instance, fungal strains like *Panus tigrinus* and *Cryptococcus albidus var. albidus* can be cultivated on OMWW to produce laccases, Mn-peroxidases, and pectinases, respectively. Similarly, *Candida cylindracea* and *Yarrowia lipolytica* are effective producers of lipases when grown on OMWW, with applications in the dairy, pharmaceutical, and detergent industries. Additionally, thermostable fungal cultures like *Rhizomucor pusillus* and *Rhizopus rhizopodiformis* have been successfully employed for lipase production using olive cake as a substrate. Beyond enzymes, OMWW holds promise to produce specific biomolecules. reported the use of OMWW to cultivate *Bacillus aryabhattai* Bao3 for L-asparaginase production. Furthermore, OMWW can serve as a sole nutrient source for strains of *Paenibacillus jamilae*, promoting their growth and exopolysaccharide production, thus contributing to waste valorization and detoxification (Foti P 2021).

Use of Olive-Oil Mill Wastewater in Food Applications

Application of OMWW on beverage

Olive mill wastewater, is emerging as a sustainable source of powerful bioactive compounds for functional beverages. Rich in phenolics, these compounds have been extensively studied and linked to a range of health benefits (Nicola Caporaso 2017). Some researchers explore the exciting potential of OMW in the development of functional beverages. They delve into the characterization of the phenolic profile of OMW, emphasizing the connection between these compounds and their health-promoting properties. Then they explored the possibilities of utilizing OMW in functional beverage development.

Research suggests that OMW phenolics are not only safe for consumption but also highly bioavailable, meaning the body can readily absorb their health benefits. Given the numerous reported biological activities of OMW phenolics, the article emphasizes the potential positive impact on public health through the development of OMW-enriched beverages(Foti 2022). These beverages might contribute to a reduction in the prevalence of cardiovascular disease and chronic degenerative illnesses. Overall, the research presents a case for utilizing OMW as a sustainable and valuable resource for the functional beverage industry. Its rich phenolic content, coupled with its safety and potential health benefits, positions OMW as a promising ingredient for creating innovative and health-conscious beverages (Hanaa Zbakha 2012).

Recycling and utilizing this waste offers a two-fold advantage: generating additional income and reducing environmental impact. Researchers investigated a fermentation process using specific strains of bacteria and yeast (*Lactiplantibacillus plantarum,* *Candida boidinii, and Wickerhamomyces anomalus*) to transform fresh OMWW. The study monitored changes in phenolic content and hydroxytyrosol concentration throughout the fermentation process (Zbakh H 2012, Visioli Francesco 2003). Furthermore, the fermented OMWW was evaluated for its antioxidant, anti-inflammatory, and cell permeability properties using various biological assays. Fermentation demonstrably enhanced the antioxidant and anti-inflammatory activity of the OMWW. Additionally, the fermented OMWW displayed increased permeability in a cell line model, suggesting the potential for enhanced absorption within the body. Overall, the study successfully demonstrates the effectiveness of the fermentation process in creating a novel functional beverage from OMWW (Foti 2022). This approach offers a sustainable solution for waste management within the olive oil industry while creating a potentially health-promoting beverage product. However, these results gained from the laboratory scale and its commercial scale, acceptability, and consumer preference should be studied (Zbakh H 2012).

High bioavailability of soluble phenols has been repeatedly demonstrated, especially that of hydroxytyrosol which is absorbed 100% by humans (Visioli Francesco 2003). Furthermore, olive phenolic compounds show low toxicity up to 2000 mg/L concentration, not any undesirable effect if compared to synthetic antioxidants, like the BHT. So, some researchers investigate the potential of transforming OMWW into a novel functional beverage with health-promoting properties. There is a beverage in China called “Olive wine” which is produced by fermentation of OMW by adding sugar to it. sugar addition in the OMW is needed because they have an insufficient sugar level to obtain a satisfactory level of alcohol. This beverage demonstrated excellent in vitro free radical scavenging capacity and, in vivo, beneficial effects on malondialdehyde (MDA) levels in mouse liver (Qian Yao 2016).

Researchers also have successfully created a novel "olive vinegar" using OMW as a raw material. This innovative vinegar stands out for its unique characteristics: it remains permanently clear, unlike some traditional vinegar that can become cloudy, possesses a distinctive vinous-red color, and is free of any unpleasant odors. The production process achieves an acetic acid level of up to 4% through two methods (De Leonardis A 2019). One method involves a double fermentation process, where an alcoholic fermentation using a *Saccharomyces cerevisiae* starter is followed by an acetic fermentation. Alternatively, the process can rely on spontaneous acetification, where naturally occurring bacteria convert the alcohol to acetic acid without any additional starter cultures being added (De Leonardis A 2018).

The resulting olive vinegar is rich in both mineral compounds and phenolic substances, particularly hydroxytyrosol, a well-known antioxidant.

Oil/ Emulsion Stability

OMWW has antioxidant properties that can be efficient in retarding the oxidative deterioration of edible oils. Many vegetable oils, particularly those rich in unsaturated fatty acids, face challenges related to chemical and sensory stability. This vulnerability to oxidation, driven by their unsaturated fatty acid profile, is a major factor limiting the shelf life of products containing these oils. Synthetic antioxidants have traditionally been used to combat this issue, but concerns regarding potential toxicity have led to consumer rejection and stricter regulations (Federica Flamminii 2021). As a result, there's a growing focus on exploring natural alternatives, with research actively investigating the use of phenolic antioxidants recovered from olive industry byproducts as a sustainable and potentially safer solution.

Some researchers isolated and characterized the antioxidant compounds from OMW, demonstrating superior free radical scavenging activity compared to ascorbic acid (AA), a common commercial antioxidant. The study found that OMWE had a more potent antioxidant activity (IC50 0.32 µg/ml) compared to ascorbic acid (AA) (IC50 1.91 µg/ml). To evaluate the protective effects of OMWE in real-world applications, sunflower, and rapeseed oils were supplemented with both OMWE and AA. The oils were then subjected to accelerated storage conditions (60°C) for four weeks, while key parameters like fatty acid composition, phytosterol content, and tocopherol levels were monitored (Hamza El Moudden 2020). The results revealed that OMWE treatment significantly slowed down the oxidative deterioration of the oils compared to the control group. While both OMWE and AA exhibited a decrease in phytosterols and tocopherols over time, the OMWE treatment demonstrably decreased these losses by nearly half compared to the controls.

In 2020 a group of researchers also worked on the selective extraction of phenolic compounds from OMWW for food enrichment. The research focused on evaluating the efficacy of a phenolic extract (50 mg/L) obtained from OMWW using XAD-7-HP resin (to recover phenolic compounds from olive mill wastewaters) as a natural antioxidant in sunflower oil. Ultra-high-performance liquid chromatography identified hydroxytyrosol (834 mg/100 mL) as the most abundant phenol in the extract. To assess the impact of fortification on oxidative stability, researchers monitored physicochemical parameters (refractive index, peroxide value, and oxidative resistance to degradation) and antioxidant activity (DPPH, ABTS, and ORAC assays) in the fortified oil over 90 days of storage at two different temperatures (Manuel Suárez 2011).

The results demonstrated a remarkable 50% enhancement in the oxidative stability of the fortified oil compared to the control group throughout the storage period. This significant improvement was independent of storage temperature, suggesting its potential for broader application.

In another work, the antioxidant activity of phenolic compounds of OMWW was examined on lard. Lard, a traditional and flavorful fat derived from pork, has long been in culinary applications. However, its preservation typically relies on methods like curing with nitrites or salting, which raises health concerns due to potential nitrate conversion and high sodium content (Stefano Bovolenta 2008). This study proposes a novel and potentially health-promoting approach to lard preservation: the utilization of Olive Mill Wastewater phenolics.

The natural antioxidants in OMWW act as a defense system, combating free radicals harmful molecules that damage lard's fat cells and contribute to spoilage. The research explores the possibility of incorporating OMWW phenolics into lard during processing. Through a sustainable extraction process employing ethyl acetate, the valuable phenolic compounds are isolated from OMWW. These extracted phenolics are then introduced into the lard, significantly enhancing its oxidative stability. This approach equips the lard with natural antioxidants to fight off free radicals and prevent spoilage. This translates to a demonstrably extended shelf life for lard, potentially reducing waste and paving the way for a "novel food" option with a potentially healthier profile due to the presence of beneficial antioxidants.

The proposed approach offers a twofold benefit. Firstly, it promotes the sustainable utilization of a by-product (OMWW), transforming waste into a valuable resource for food preservation. Secondly, by harnessing the inherent antioxidant power of OMWW phenolics, lard can potentially be preserved without resorting to traditional methods with potential health drawbacks (V. M. Antonella De Leonardis 2007). This research shows a more sustainable and potentially health-conscious approach to lard preservation, offering exciting possibilities for the future of this traditional cooking fat.

However, some studies analyzed the effect of OMWW phenolic extracts on the stability of oil-in-water emulsion. Interestingly the result of this research was vice-versa. This study investigated the effects of adding spray-dried OMWW polyphenols to a model olive oil-in-water emulsion by adding whey protein isolate as an emulsifier. Researchers monitored the emulsion's physical and chemical stability during accelerated storage (40°C for 30 days).

While the OMWW extract didn't significantly improve physical stability (creaming, particle size, viscosity), it did influence the formation of oxidation products. higher polyphenol concentrations led to increased oxidation products, suggesting potential binding with the whey protein isolate used as an emulsifier.

These findings suggest further research is needed to understand how OMWW extracts interact with other emulsion components and their overall impact on stability.

Milk and dairy products:

Dairy products are a heterogeneous group of products. Milk from ruminants is a food and a raw material for dairy products such as cheese, cream, butter, and fermented milk. Milk and dairy products are good sources of protein and essential amino acids, vitamin A, riboflavin, vitamin B12, calcium, and iodine. Milk, yogurt, and cheese are the foods with the highest amounts of calcium (Holven Kirsten 2024). Thermal modification is one of the most widely used food processing techniques. Traditional heating methods used in food processing, especially for heat-sensitive products, may lead to unintended loss of quality (Jialun Hu 2024). Especially, the Maillard reaction resulted in the production of brown compounds by reaction between sugar and amino group. Therefore, it is urgent to preserve the nutritional value, taste, and appearance of milk as much as possible.

The main purposes of milk processing are to inactivate the pathogens or their induced toxins and improve the final products' digestibility, bioavailability, and shelf life (V. M. Antonella De Leonardis 2023).

(Servili 2011) studied the fortification of milk beverages with OMWW phenolic extract at the concentrations of 100 and 200 mg/L, fermented by the addition of starter cultures. These Fermented Milk Beverages (FMB) were compared with the control sample. The result showed that the fermentation process proceeded successfully for all three beverages (control, FMB100, and FMB200), which means that the addition of OMWW phenolic compounds did not interfere with the fermentation process. In addition, Sensory evaluation of the addition of olive phenolics did not negatively impact the flavor profile. Encouragingly, both FMB100 and FMB200 displayed an increase in a health-beneficial compound. This study shows that adding phenolic compounds to OMWW can fortify and create a novel healthy dairy product.

Beyond the direct addition of OMWW into dairy products, supplementing the diet of dairy sheep with these components presents an alternative approach. This dietary manipulation can demonstrably influence the final characteristics of cheese produced from the sheep's milk. Researchers fed two groups of sheep either a standard diet or one supplemented with spray-dried olive mill wastewater (SDP) for nine weeks. While the basic composition of the cheese made from both groups' milk remained similar, the cheese from the SDP-fed sheep showed improved antioxidant properties. This cheese also contained higher levels of beneficial polyphenols, suggesting these compounds might contribute to the observed health benefits (Raffaella Branciari 2020). This research opens a new avenue for exploring how manipulating animal diets can influence the health-promoting qualities of the food products we get from them.

Likewise, another study explored olive cake (a source of beneficial polyphenols) as a feed supplement for dairy cows producing Provola cheese. Like the sheep cheese, cheese from cows fed olive cake displayed a healthier fatty acid profile (higher unsaturated and conjugated linoleic acids) and increased protein content.

This study also revealed a distinct volatile profile (potentially influencing aroma and taste) and a decrease in spoilage microbes (likely due to polyphenol inhibition) in the olive cake cheese. Importantly, core cheese microbes remained unaffected (Francesco Maria Calabrese 2023).

These findings further support the use of olive byproducts in dairy farming, promoting potentially tastier, healthier, and more shelf-stable cheeses while reducing environmental impact, particularly relevant in regions like Sicily where waste disposal is a challenge.

Meat and Fish

Meat and meat products are important foods in the human diet, but there are concerns about their quality and safety. The advances in science allowed the discovery of nitrate (NO_3^-) first, and then nitrite (NO_2^-), as actual ingredients involved in cured meat products preservation. NO_2^- salts, and NO_3^- salts, such as those of sodium and potassium, are typical food preservatives used in meat processing. Both can inhibit the growth of microorganisms, delay the onset of rancidity, produce cured meat flavor or smell, and stabilize the meat's red color (Yin Zhang, 2023; Mohamed A. Sorour, 2023).

The beneficial effects of adding nitrates and nitrites to meat products are the improvement of quality characteristics and microbiological safety. However, several studies have indicated that nitrates and nitrites intake should be limited owing to their potential carcinogenic effect on humans (Milad Daneshniya 2023). Therefore, the consumer demand for natural or nitrate and nitrite-free meat products remains high. There is a need to find alternative natural plant material that provides alternative antioxidant and antimicrobial activities since they are noncarcinogenic and reliable; they can substitute or reduce nitrates and nitrites with minimal or no quality compromise of sensory attributes and shelf-life (Milad Daneshniya 2023). Hence Mercatante, Poli et al. (2022) investigate a method to create healthier cured meat products by replacing nitrites with natural antioxidants derived from olive processing by-products. They found that sausages formulated with these olive antioxidants exhibited a similar taste and improved shelf life compared to those made with conventional nitrites. This indicates that olive-based antioxidants could be a viable strategy to achieve healthier processed meats while reducing reliance on nitrites.

In addition, Dario Mercatante et al. (2024) found that OVW phenolics reduced the formation of harmful cholesterol oxides in stored cooked beef patties and reduced its negative impact. Another research on the quality of beef hamburgers showed that enriching that with phenolic extracts can improve the quality and shelf life of the final product by reducing fat breakdown, cholesterol oxidation, and optimized color changes (Barbieri 2021) the same result was observed in the research of Fasolato et al. (2016) on fresh pork sausage. These phenols act as a natural preservative for sausages; they exhibited antimicrobial activity against harmful bacteria and appeared to reduce fat breakdown.

A similar function of OMWW extract was observed in fresh salmon steak quality during storage. Researchers evaluate the antioxidant and antimicrobial effects of a phenolic extract from olive vegetation water on fresh salmon steaks stored at 4°C under a modified atmosphere. The results showed that the phenolic extract increased the microbiological quality and antioxidant concentration and decreased the lipid oxidation of salmon steaks during storage conditions (Dino Miraglia 2016).

Bakery

Bakery products are a wide variety of foods, such as bread, biscuits, crackers, snacks, breadsticks, and others. Some bakery products are consumed worldwide, while others are specialties typical of limited geographical areas prepared according to ancient recipes. The extreme variability of bakery products is due to ingredients and baking technology. Commonly, basic ingredients are wheat flour and water, but other ingredients may be employed in specific recipes, such as no-wheat-cereal flour, oil/fat, salt, eggs, and others. As regards baking technology, the main differences are the leavening conditions, leavening agents, kneading method, cooking temperature, and moisture of the final product (Antonella De Leonardis V. M., 2023; Marta Mesias, 2023).

Bakery products, like many other food items, are susceptible to spoilage during storage. This deterioration can be categorized into three primary mechanisms: physical, microbial, and chemical.

- Physical spoilage; through the loss of desirable sensory attributes, such as original color, crispness, and textural integrity (S.P. Cauvain 2010).
- Microbial spoilage; is primarily driven by the growth of fungal species like *Penicillium, Aspergillus, Cladosporium, and Neurospora*, although some bacteria like *Bacillus subtilis and Bacillus licheniformis* can also contribute (Vermelho 2024).
- Chemical spoilage; particularly relevant for oil-containing bakery products, arises from lipid oxidation. This process, initiated by oxygen exposure during kneading and high cooking temperatures, leads to the formation of peroxides, followed by the development of rancidity and off-flavors (S.P. Cauvain 2010).

The nutritional value of bakery products can be improved by different strategies including the use of by-products as ingredients (Maroua Boubaker, 2016). Enrichment and fortifying bakery products with bioactive compounds of OMWW not only provides health benefits but also can be an effective tool to delay the lipid oxidation process and slow down the formation of off-flavors, thus extending the shelf life of the product (Larissa Slongo Faccioli, 2021).

Enrichment of bakery products like pasta and bread with OMWW showed that adding OMWW slightly improved the chemical quality of the bread dough and spaghetti while not negatively affecting the sensory characteristics of the final product (Annamaria Cedola 2020). In addition, one study investigate the effect of the potential of utilizing olive oil byproducts as a functional ingredient to enrich gluten-free breadsticks. The study focuses on phenolic-rich extracts derived from olive leaves (OL) and OMWW, aiming to enhance the nutritional profile and shelf-life of the product. Fortified gluten-free breadsticks exhibit increased moisture content and a softer texture compared to the control group while the nutritional value and shelf life of breadsticks enhanced (Conte 2021).

However, Mattia Di Nunzi et al. (2020) showed that simply adding healthy ingredients doesn't guarantee the expected benefits. How the ingredients are processed and interact with each other can significantly affect how the body absorbs and utilizes them.

Conclusion

The management of Olive Mill Wastewater (OMWW) presents both significant challenges and potential opportunities. OMWW, a byproduct of olive oil production, is characterized by its high organic content and the presence of valuable compounds such as polyphenols, nutrients, and organic matter. Traditionally, the focus has been on detoxification and disposal, but this approach is often impractical and costly, particularly for small-scale producers.

Current treatment methods for OMWW include biological, chemical, physical, and thermal processes, each with distinct advantages and drawbacks. Biological methods, while effective, often require dilution due to the high strength of OMWW. Chemical methods can efficiently remove pollutants but may generate hazardous byproducts. Physical methods, such as filtration and membrane separation, are effective but energy-intensive. Thermal methods, though capable of significantly reducing waste volume, pose concerns regarding energy consumption and air emissions.

One of the primary concerns with traditional disposal methods, such as evaporation lagoons, includes the substantial land area required and the environmental risks of leakage, groundwater contamination, methane emissions, unpleasant odor, and the disposal of emissions, including volatile chemicals that require further treatment due to their acidity and high biochemical oxygen demand (BOD) and chemical oxygen demand (COD) levels.

Despite the advances in OMWW treatment technologies, the industry still faces issues related to the high energy and equipment costs, as well as the need for materials resistant to corrosion.

Furthermore, the utilization of OMWW represents a promising area of research and application. By harnessing the beneficial properties of OMWW, it can be converted into a range of useful products. For instance, OMWW can be processed into natural fertilizers and soil conditioners, enhancing agricultural productivity and soil health. The phenolic compounds found in OMWW exhibit strong antioxidant properties, making them valuable for the pharmaceutical and cosmetic industries. Additionally, OMWW can be used as a substrate for the production of biopolymers and biofuels, contributing to the development of sustainable materials and energy sources as well as food industry sections like meat, dairy products, bakery, and so on.

The thesis highlights the necessity for a comprehensive approach to OMWW management that balances environmental protection with economic feasibility. By integrating treatment methods that allow for resource recovery and the development of valuable products, the olive oil industry can progress towards greater sustainability. This research emphasizes the potential for OMWW to be viewed not just as waste but as a resource, promoting a circular economy within the olive oil production sector.

Personal Comment about the Future of OMWW Management

The future of OMWW management lies in innovative and sustainable practices that transform this byproduct into an asset. By adopting advanced treatment technologies and exploring diverse applications, the olive oil industry can significantly reduce its environmental footprint while enhancing its economic viability. This approach aligns with global sustainability goals and offers a promising pathway for the olive oil industry to contribute to a more sustainable and resilient agricultural sector.

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