# The Mediterranean circular food systems network (MedCiFoS) case-studies report

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**MedCiFoS institutions:**

This report documents the work and findings from exploratory studies conducted in four MedCiFoS countries (Morocco, Spain and Greece).

# Morocco

**Quantifying household-generated waste and waste management systems-based greenhouse gas emissions in Benguerir, Morocco.**

**Introduction**

Household waste represents disposable hazardous and non-hazardous material generated at the household level. In Morocco, an accurate understanding of the amounts of household waste is compromised by data uncertainties. Most of the available household waste data in low and middle-income countries are based on theoretical estimation rather than actual measurements (Chaher et al., 2020a; Chaher et al., 2020b). The amount of solid waste generated daily ranges between 0.3 and 0.76 kg per capita in rural and large urban areas, respectively (Hemidat et al., 2022). However, data on the composition and characteristics of generated household waste is lacking, thus creating a barrier in selecting economically feasible and socio-culturally appropriate approaches to manage and treat the waste. Despite the lack of data on the amounts of waste generated at the household level, limited municipal waste management is most likely negatively affecting the environment. In this exploratory study, we sought to quantify and characterize the amounts of biowaste waste generated by households in Benguerir. We also used generated data to estimate greenhouse gas emissions linked to the common waste management practice of dumping and compared them to those from composting and anaerobic digesters.

**Methodology**

The study was conducted in the city of Benguerir, Morocco. The city of Benguerir has a population of ~ 84 000 inhabitants. Waste generation rates were determined by collecting waste daily for at least seven consecutive days from 68 randomly selected households. The method described by Salant and Dillmann (1994) and Rea and Parker (1997) was used to determine that the 68 households resulted in a sampling error of ±12%. The households were given plastic bags to dispose of all waste generated in the different households. On each sampling day, plastic bags were collected, and the weight and number of people in the household were recorded. The amounts of waste generated during the sampling period and the number of people in the different households enabled us to calculate the average per capita waste generation rates (kg per person per day). The amounts of waste generated in Benguerir were then estimated by multiplying the average per capita waste generation rates by the number of habitats (84,000). We then determined waste composition by emptying all the bags collected on the same day on a flat and covered surface. The waste was mixed and then sorted into different waste fractions (i.e., biowaste, paper and cardboard, plastic, textiles, metals, glass and others) and weighed. The weight of each waste fraction divided by the total waste collected during the week estimates the proportion of the different waste fractions (Lenkiewicz and Webster, 2017).

Nitrogen content in the biowaste was measured using the Kjeldahl method for organic nitrogen. The total nitrogen content of the studied samples was determined according to the official methods of analysis of AOAC International (Association of Official Analytical Chemists) using a Kjeltec 2300 autoanalyzer (Hilleroed, Denmark). Samples of 0.3 g of dry organic matter powder were placed in a digestion tube with 10 mL of sulfuric salicylic acid (30:1 vw) mixture. The tubes were then placed in a Kjeldahl catalyzer and heated to 380°C for 2 hours until the samples turned hyaline. Total nitrogen was determined by distillation.

For Phosfurus and Potassium, samples (500 mg) were weighed and placed in a digestion tube for mineralization, then 7.5 mL of $HNO_3$ 65% was added. The tubes remained open for 20 min to avoid a process interruption due to a rapid increase in pressure. They were then closed, positioned inside the microwave rotor, and digested for two h at 90°C. The final volume was adjusted to 50 mL with deionized water. The final solution was quantitatively transferred to a polypropylene tube and filled up to 10 mL.

Multi-elemental trace analysis of previously digested samples was carried out using the Agilent 5110 ICP-OES (Santa Clara, California, USA). The analyzed elements were K, P. TraceCERT® mono-element ICP standards with a 1000 mg $L^{-1}$ concentration in nitric acid obtained from Merck (Darmstadt, Germany) were used. Calibration standards were prepared from stock solutions and stored at 4 °C.

*Greenhouse gas emissions estimates*

Greenhouse gas emissions were estimated using the method described by Kristanto and Koven (2019) and Manfredi et al. (2009). Precisely, greenhouse gas emissions from waste treatment were calculated using the equation

$$Emission = EF * m$$

Where *m* is the mass of solid waste (tons), and EF is the emission factor (kg of GHG/ton). The emissions factors for the different waste management methods are given in Table 1.

**Table 1. Emission factors for waste management approaches**

| Management system | Greenhouse gas | EF | Unit | Reference |
|---|---|---|---|---|
| Landfill dumping | $CH_4$ | 1000 | kg $CO_2$-eq/ton wet biowaste | Manfredi et al. (2009) |
| Anaerobic digestion | $CH_4$ | 125 | kg $CO_2$-eq/ton wet biowaste | IPCC (2006) |
| Composting | $CH_4$ | 100 | kg $CO_2$-eq/ton wet biowaste | IPCC (2006) |
| | $N_2O$ | 71.52 | kg $CO_2$-eq/ton wet biowaste | IPCC (2006) |

**Results**

*Waste generation*

The average amount of waste generated was 0.69 kg per person per day (0.59-0.80 kg per person CI 95%). For the 84,000 inhabitants of Benguerir, this translates to 58,355 kg (49,715 – 66,994 kg CI 95%) of daily waste. An average of 80% of the generated waste was food waste biowaste. Therefore, about 46,684 kg (39,772 – 53,595 kg CI 95%) of the daily waste was biowaste.

*Organic waste characterization*

Table 2: N, P, K content of the organic fraction of the waste

| Element | Avg (%) | CV |
|---|---|---|
| **N** | 2.67 | 36% |
| **P** | 0.57 | 45% |
| **K** | 1.57 | 33% |

*GHG emissions*

Using emission factors in Table 1, results on GHG emissions from municipal solid waste are given in Table 3.

Table 3: GHG emissions from different waste management approaches

| Management system | Greenhouse gas | Tonnes of $CO_2$-eq per day |
|---|---|---|
| Landfill dumping | $CH_4$ | 58 |
| Anaerobic digestion | $CH_4$ | 7.3 |
| Composting | $CH_4$ | 5.8 |
| | $N_2O$ | 4.2 |

**Discussion and implications:**

Our results on waste generation rates (0.69 kg per person per day - 0.59-0.80 kg per person CI 95%) corroborated with estimates from other studies (0.76 kg per capita per day) conducted in urban areas in Morocco (i.e., Hemidat et al., 2022; Ouigmane et al., 2018). The amounts of generated waste and the waste disposal approach (landfill dumping) resulted in high GHG emissions (58 t $CO_2$-eq per day). Our results show that adopting improved waste management strategies (i.e., anaerobic digestion and composting) can result in an over 80% reduction in GHG emissions. These findings suggest that adopting improved waste management actions presents an enormous opportunity to utilize the biowaste as a soil amendment (Table 2) and reduce biowaste-related GHG emissions. The key to increasing the adoption of improved waste management options is to raise awareness and create support systems for economically feasible and socially acceptable waste management actions.

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**Physicochemical characterization, identification of the phenolic compounds using HPLC-DAD and microbiological characterization of olive by-products in Morocco's arid and semi-arid climate.**

## Introduction

Olive cultivation and olive oil production are profoundly imprinted in the history of the Mediterranean region (Boutafda et al., 2019). The olive tree is considered the oldest and most widespread tree in the world, covering an area of more than 10 million hectares (Fraga et al., 2020). According to the International Olive Council (IOC), in 2018, the production of olives dedicated to olive oil represented 3,135,000 tons resulting in 2,751,000 tons of table olives (IOC, 2019). This tradition represents a critical asset for many countries, not only in terms of culture and health but also in terms of wealth.

In Morocco, olive growing is a fundamental component of the agricultural sector; it is at the crossroads of economic, social and environmental issues with multiple intersecting problems (MAPMDREF, 2013). The olive tree is the primary cultivated fruit sector since it represents 65% of national tree plantations (MAPMDREF, 2021). This species is present throughout the national territory because of its ability to be adapted to all bioclimatic stages, from mountain areas to arid Saharan areas (MAPMDREF, 2014). It ensures multiple functions, including the fight against erosion, the enhancement of agricultural land and the settlement of populations in marginal areas (Soulard et al., 2011). For these reasons, the national olive industry ensures an intense agricultural activity essential in the Moroccan economy by its contribution to the support of the populations of specific regions for which it constitutes one of the principal sources of income, thus making it possible to generate more than 51 million working days per annum, that is to say, the equivalent of 380 000 permanent jobs (MAPMDREF, 2021). It also ensures the supply of industrial and traditional units of olive crushing, on the one hand, and olive canning, on the other hand. Therefore, olive growing is the subject of attention and encouragement of the government by providing the necessary means and facilities to improve this sector. During the last decade, the Moroccan olive sector has benefited from the state policy of extending the areas reserved for olive growing.

The Green Morocco Plan aims to increase the area under olive trees to reach 1,2 million hectares. The increase in olive production and large-scale industrialization of its processing will increase olive oil production, oil quality and farmer incomes. However, it will also increase liquid waste called olive mill wastewater (OMWW). This production of vast quantities of by-products (OMWW and pomace) leaves a significant ecological footprint (El-Bassi et al., 2021). These by-products are undesirable for the olive oil industry regarding sustainability and environmental impact, which can be more significant given the high disposal costs (Galliou et al., 2018).

Olive by-products, mainly OMWW, are often stored in evaporation ponds or discharged into natural environments, causing intense odour nuisance, soil contamination, plant growth inhibition, pollution of natural waterways, and severe effects on aquatic fauna and ecological status (Komnitsas et al., 2016). OMWWs are one of the most polluting effluents produced by agro-industries due to their high organic load and a wide range of contaminants, including phenolics, lipids, polysaccharides and tannins (Karaouzas et al., 2011; Ntougias et al., 2013). The high phenolic composition and organic content make them highly resistant to biodegradation (Zirehpour et al., 2014). OMWW shows low biodegradability and high phytotoxicity due to the presence of phenolic compounds. Similarly, reduced sugars can stimulate microbial respiration and reduce dissolved oxygen concentrations (McNamara et al., 2008). In addition, the high amounts generated in a short period aggravate environmental damage between October and March in Mediterranean olive oil-producing countries (Dermeche et al., 2013).

Many treatments of OMWW aim to reduce organic load and phenolic compounds (Dias et al., 2021). However, the challenges that are facing OMWW treatment are mainly related to (1) high organic load, olive oil mill effluents are 100-400 times more loaded with pollutants than ordinary domestic wastewater (Zaier et al., 2017), (2) seasonal operation, (3) high territorial dispersion and (4) the presence of organic compounds that are not readily biodegradable, such as long-chain fatty acids and phenolic compounds, and the high cost of treatment (Bouknana et al., 2014).

Many biological and physico-chemical treatment processes have been proposed to treat olive oil mill effluents, including storage in evaporation ponds, co-composting, flotation and decantation, coagulation oxidation with $O_3$ and Fenton's reagent, filtration, sedimentation, dilution in open evaporation ponds and incineration, ultrafiltration/reverse osmosis, chemical and electrochemical treatments, and transformation into animal feed (Barje et al., 2013; El Fels et al., 2019; Fakharedine et al., 2011; Hajjouji et al., 2008; Rahmanian et al., 2014).

This work aimed to make physico-chemical characterizations of olive by-products from olive oil crushing units according to a traditional system and modern unit. Also, the study focused on identifying the most important phenolic compounds by high-performance liquid chromatography with diode array detection (HPLC-DAD) and microbiological characterization to predict better and suggest suitable biological treatment processes.

## Materials and Methods

*Olive mill wastewater sampling*

Before sampling, a socio-economic survey was conducted on the operation and dynamics of olive oil crushing units in the study area. From two mills located in Chichaoua and Attaouia, samples were taken from traditional and modern industrial olive oil crushing characterized by three-phase and two-phase centrifugation, respectively.

*Physical-chemical characterization of OMWW*

The Physical-chemical characterization of OMWW was based on the study of the following parameters: pH, electrical conductivity (EC), suspended solids (SS), dry matter (D.M.), ash contents (AshC), total sugars content (TSC), total organic carbon (TOC), total Kjeldahl nitrogen (TKN), Proteins, lipids, chemical oxygen demand (COD), biological oxygen demand (BOD), and phenolic compounds (PC). Each analysis is repeated three times.

*Determination of phenolic compounds*

The extraction technique of phenolic compounds was developed by (Macheix et al., 1990). The determination of phenolic compounds was performed by the Folin-Cioccalteu reagent (Vasquez et al., 1974). Samples were analyzed by high-performance liquid chromatography (HPLC).

*Microbiological parameters*

Microbiological analyses of the OMWW samples were performed by viable counts on specific media.

*Greenhouse gas emission estimates*

Greenhouse gas emissions were estimated using the method described by Kristanto and Koven (2019) and Manfredi et al. (2009). Precisely, greenhouse gas emissions from waste generated from the traditional and modern systems were calculated using the equation

$$Emission = EF \times m$$

Where m is the mass of oil waste (tons), and EF is the emission factor (kg of GHG/ton). The emissions factors for the different waste management methods are given in Table 1.

***Table 1. Emission factors for waste management approaches***

| **Management system** | **Greenhouse gas** | **EF** | **Unit** | **Reference** |
|---|---|---|---|---|
| | | | | |
| dumping | $CH_4$ | 1000 | kg $CO_2$-eq/ton wet biowaste | Manfredi et al (2009) |
| Anaerobic digestion | $CH_4$ | 125 | kg $CO_2$-eq/ton wet biowaste | IPCC (2006) |
| Composting | $CH_4$ | 100 | kg $CO_2$-eq/ton wet biowaste | IPCC (2006) |
| | $N_2O$ | 71.52 | kg $CO_2$-eq/ton wet biowaste | IPCC (2006) |

**Key results**

The amounts of solid waste generated through the traditional and modern olive oil treatment systems were 1000 tons and 2500 tons, respectively. This the higher amount of waste for the modern system is a consequence of higher processing capacity, which increases by close to 100% in the modern and more advanced system. The GHG emissions associated with different soil waste management practices for waste generated by the traditional and modern system are given in Table 2.

The physico-chemical characterization of the studied olive by-products shows that olive oil waste has many highly polluting and not very biodegradable by-products. Indeed, high acidic (pH = 4.5) by-products also had high values of organic pollutants, COD and $BOD_5$ values of these OMWWs can reach respectively 212 and 75 $g.L^{-1}$, and high concentrations of phenolic compounds up to 8 $g.L^{-1}$. HPLC identified three classes of phenolic compounds: simple phenols and secoiridoidal derivatives in significant quantities, followed by phenolic acids. The analysis of the phenolic extract shows the presence of Hydroxytyrosol, Tyrosol, Caffeic acid, p-Coumaric acid and Oleuropein. The microbiological analysis shows a low microbial load with the dominance of fungi and the total absence of pathogenic microorganisms.

*Table 2: GHG emissions from solid waste management approaches*

| Management system | Greenhouse gas | Traditional | Modern |
|---|---|---|---|
| | | *Tonnes of $CO_2$-eq per milling season* | |
| Dumping | $CH_4$ | 1000 | 2500 |
| Anaerobic digestion | $CH_4$ | 125 | 313 |
| Composting | $CH_4$ | 100 | 250 |
| | $N_2O$ | 72 | 179 |

**Implications**

Our results show high GHG emissions from current solid waste management actions. We also estimate a huge potential to reduce those emissions by adopting different waste management actions. However, the lack of suitable treatment methods is currently leading mill owners to discharge these wastes into the environment without any preliminary treatment. These by-products (i.e., solid waste) are discharged into the environment without treatment, and due to their high organic matter content, they could lead to hyper-eutrophication of aquatic systems and groundwater contamination. They could also increase soil acidity and affect soil quality. Though we did not include liquid effluent in our calculations, there is urgent to treat/valorize both liquid effluent and solid waste before it is discharged into the environment.

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# Spain

**Food waste valorization in Spain.**

Extensive bibliographical consultations were conducted to learn from publicly available information. The objective of the study was initially the city of Madrid. Information, as detailed as possible, was sought, not only on the total volume of the produced waste but also on the different waste fractions. The objective was to classify them according to the type of food, their origin and their viability for composting, among other fundamental factors for future research projects.

Multiple sources were consulted. First, the information provided by the Ministry of Agriculture, Fisheries and Food was sought. The Agricultural Statistics present data on waste, but the information is disaggregated down only to autonomous communities and is not divided according to the type of food. The same occurs with the publications of the National Institute of Statistics.

More information can be extracted from the Community of Madrid Sustainable Waste Management Strategy. It provides detailed information about the Community's waste but does not carry out the analysis at the city level. Furthermore, although it breaks down the organic fraction into multiple sections, it does not do so based on the type of food.

The rest of the consulted sources with a lower scale than the national one were, again, incomplete compared to what was sought. Most divide the urban waste into a few fractions related to organic waste, usually between one and three. Nevertheless, they are never classified according to the type of food. In addition, the data is usually organized by autonomous communities, with no specific information on the City of Madrid. Therefore, we searched for information on food waste at the national level.

At this scale, the Household Food Waste Quantification Panel stands out, belonging to the "More food, less waste" strategy carried out by the Ministry of Agriculture, Fisheries and Food Environment. The Panel provides information on the waste of raw food, divided into 33 categories, and the waste of the main recipes made, with 24 categories. It does not consider other factors of interest, such as the proportion of unavoidable waste versus that which can be reduced, but it is the most complete report that has been found.

In conclusion, the current lack of information on food waste is notable, especially at scales below the national level. The possibility of carrying out a specific analysis on the City of Madrid was proposed, carrying out surveys on their consumption habits to different families, following the methodology of the National Quantification Panel. However, the idea was dismissed, given the lack of time and available resources.

**Study on the olive grove in Spain and the management of the "alperujo"**

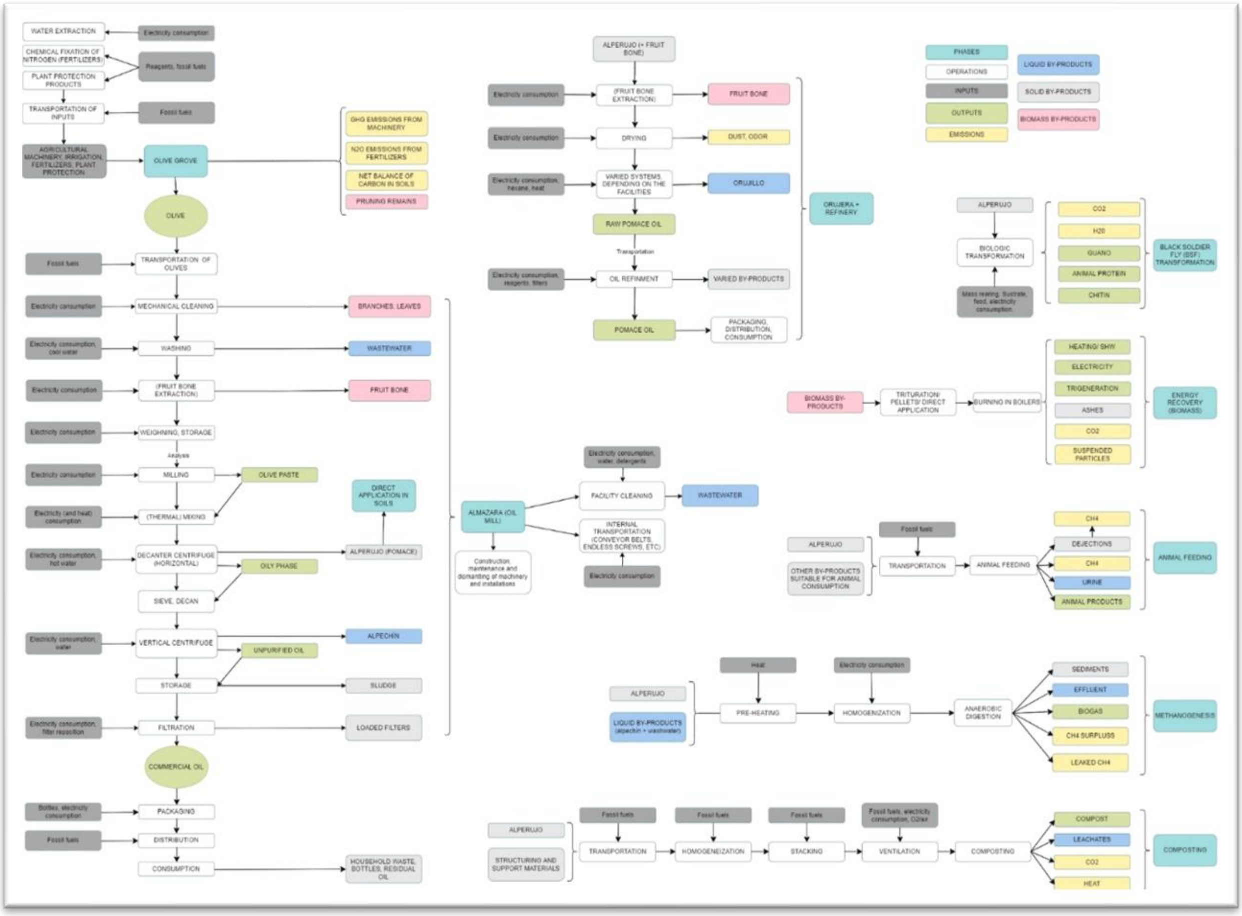
The study's objective was to carry out a life cycle analysis of the olive sector, calculate its carbon footprint, and evaluate the environmental and economic viability of the different alternatives for managing the generated waste, highlighting the alperujo.

Multiple alternatives have been proposed to analyze. In the first place, the most popular stands out: the production of refined oils in "orujeras". Energy recovery alternatives are also relevant, such as using olive bone for biomass and obtaining natural gas through anaerobic fermentation. On the other hand, composting and direct soil application are alternatives of great agricultural interest. The alperujo can also be used for animal feed. Finally, the alternative of using an insect, the "soldier fly", to process it and obtain high-quality guano, animal protein and other high-value-added products is proposed.

The alternatives were evaluated by studying the flows of mass and energy to identify the inputs and outputs of each one. The following scheme has been generated to represent them (Figure 1).

After identifying the processes involved in the sector, their quantification has been sought. Firstly, public information has been used, such as the agricultural parameters published by the Ministry of Agriculture, Fisheries and Food. Nevertheless, specialists from the different alternatives are also being contacted to obtain essential information for the analysis. The objective is to capture the data collected in the SigmaPro LCA calculation software. For this, a matrix compatible with the program has been prepared.

There are several objectives for the future, such as obtaining the remaining parameters and for the student to learn how to use the software. Once achieved, simulations will be conducted to determine the viability of the different alternatives from both an environmental and economic perspective. Once the conclusions are obtained, a technical report will be written.



WATER EXTRACTION
Electricity consumption
CHEMICAL FIXATION OF NITROGEN (FERTILIZERS)
Reagents, fossil fuels
PLANT PROTECTION PRODUCTS
TRANSPORTATION OF INPUTS
Fossil fuels
AGRICULTURAL MACHINERY, IRRIGATION, FERTILIZERS, PLANT PROTECTION
OLIVE GROVE
GHG EMISSIONS FROM MACHINERY
N2O EMISSIONS FROM FERTILIZERS
NET BALANCE OF CARBON IN SOILS
PRUNING REMAINS
OLIVE
Fossil fuels
TRANSPORTATION OF OLIVES
Electricity consumption
MECHANICAL CLEANING
BRANCHES, LEAVES
Electricity consumption, cool water
WASHING
WASTEWATER
Electricity consumption
(FRUIT BONE EXTRACTION)
FRUIT BONE
Electricity consumption
WEIGHNING, STORAGE
Analysis
Electricity consumption
MILLING
OLIVE PASTE
Electricity (and heat) consumption
(THERMAL) MIXING
DIRECT APPLICATION IN SOILS
Electricity consumption, hot water
DECANTER CENTRIFUGE (HORIZONTAL)
ALPERUJO (POMACE)
OILY PHASE
SIEVE, DECAN
Electricity consumption, water
VERTICAL CENTRIFUGE
ALPECHIN
UNPURIFIED OIL
STORAGE
SLUDGE
Electricity consumption, filter reposition
FILTRATION
LOADED FILTERS
COMMERCIAL OIL
Bottles, electricity consumption
PACKAGING
Fossil fuels
DISTRIBUTION
CONSUMPTION
HOUSEHOLD WASTE, BOTTLES, RESIDUAL OIL
ALMAZARA (OIL MILL)
Construction, maintenance and dismantling of machinery and installations
Electricity consumption, water, detergents
FACILITY CLEANING
WASTEWATER
INTERNAL TRANSPORTATION (CONVEYOR BELTS, ENDLESS SCREWS, ETC)
Electricity consumption
ALPERUJO (+ FRUIT BONE)
Electricity consumption
(FRUIT BONE EXTRACTION)
FRUIT BONE
Electricity consumption
DRYING
DUST, ODOR
Electricity consumption, hexane, heat
VARIED SYSTEMS, DEPENDING ON THE FACILITIES
ORUJILLO
RAW POMACE OIL
Transportation
Electricity consumption, reagents, filters
OIL REFINMENT
VARIED BY-PRODUCTS
POMACE OIL
PACKAGING, DISTRIBUTION, CONSUMPTION
ORUJERA + REFINERY
PHASES
OPERATIONS
INPUTS
OUTPUTS
EMISSIONS
LIQUID BY-PRODUCTS
SOLID BY-PRODUCTS
BIOMASS BY-PRODUCTS
ALPERUJO
BIOLOGIC TRANSFORMATION
Mass rearing, Sustrate, feed, electricity consumption
CO2
H20
GUANO
ANIMAL PROTEIN
CHITIN
BLACK SOLDIER FLY (BSF) TRANSFORMATION
BIOMASS BY-PRODUCTS
TRITURATION/ PELLETS/ DIRECT APPLICATION
BURNING IN BOILERS
HEATING/ SHW
ELECTRICITY
TRIGENERATION
ASHES
CO2
SUSPENDED PARTICLES
ENERGY RECOVERY (BIOMASS)
ALPERUJO
OTHER BY-PRODUCTS SUITABLE FOR ANIMAL CONSUMPTION
Fossil fuels
TRANSPORTATION
ANIMAL FEEDING
CH4
DEJECTIONS
CH4
URINE
ANIMAL PRODUCTS
ANIMAL FEEDING
ALPERUJO
LIQUID BY-PRODUCTS (alpechin + washwater)
Heat
PRE-HEATING
Electricity consumption
HOMOGENIZATION
ANAEROBIC DIGESTION
SEDIMENTS
EFFLUENT
BIOGAS
CH4 SURPLUSS
LEAKED CH4
METHANOGENESIS
ALPERUJO
STRUCTURING AND SUPPORT MATERIALS
Fossil fuels
TRANSPORTATION
Fossil fuels
HOMOGENEIZATION
Fossil fuels
STACKING
Fossil fuels, electricity consumption, O2/air
VENTILATION
COMPOSTING
COMPOST
LEACHATES
CO2
HEAT
COMPOSTING

# Greece

# Optimizing waste stream valorization in circular olive oil production chains

## Introduction

The production of olive oil is considered one of the largest agricultural business sectors in the Mediterranean area (Banias, Achillas, Vlachokostas, Moussiopoulos, & Stefanou, 2017; Khounani et al., 2021). Worldwide, olive oil production is about 2.5 million tons per year, of which 97% is produced in Mediterranean countries (Abbattista, Ventura, Calvano, Cataldi, & Losito, 2021; Souilem et al., 2017). The biggest olive oil-producing countries are Spain, Italy and Greece, accounting for roughly 66% of the global production (Stempfle, Carlucci, De Gennaro, Roselli, & Giannoccaro, 2021). Olive oil is next to being known as a culinary speciality for its health and medicinal benefits (Donner & Radić, 2021). It is a valuable source of antioxidants and essential fatty acids in the human diet (Donner & Radić, 2021; Souilem et al., 2017). Production of olive oil has increased over the past decades due to the increasing awareness of these health benefits.

The production process of olive oil is complex and has resulted in several environmental concerns (De La Casa, Bueno, & Castro, 2021). The production of olive oil involves different processes that generate huge quantities of waste. These waste streams are not only an economic problem for producers since transport and disposal cost money but also pose serious environmental concerns due to their phytotoxicity (Abbattista et al., 2021; Souilem et al., 2017). At the same time some waste streams contain high-added value compounds such as bioactive compounds, which, once extracted, may present ingredients that can be used for food, cosmetic, and nutraceutical industries (Abbattista et al., 2021). They contain considerable amounts of valuable organic acids, fibres, proteins, carbohydrates, and, most importantly, phenolic compounds (Abbattista et al., 2021). Phenolic compounds can be used as antioxidants which have been proven to have numerous health benefits (Araújo, Pimentel, Alves, & Oliveira, 2015). During olive oil production, approximately 98% of the phenolic content of the olive fruit remains in the olive mill waste streams (Carrara, Kelly, Roso, Larroque, & Margout, 2021; Souilem et al., 2017)

The amount and physicochemical characteristics of the produced waste streams depend on the method used for the extraction and the quality of the processed fruits (Donner & Radić, 2021; Souilem et al., 2017). Depending on the extraction method, olive pomace (OP) and olive mill wastewaters (OMWW) are the main waste streams (Carrara et al., 2021; Souilem et al., 2017). OP is a heavy aqueous suspension of olive solids, which has a strong odour when released into the environment (Donner & Radić, 2021). OMWW is a highly polluting aqueous waste containing toxic components and valuable nutrients (Abbattista et al., 2021; Carrara et al., 2021; Donner & Radić, 2021). Therefore, OP and OMWW are polluting agents, with OMWW being one of the most polluting effluents produced by the agri-food industries (Souilem et al., 2017). Therefore, the waste produced in the olive oil supply chain must be reduced.

One way to potentially do that is by valorising the waste streams. Food waste valorisation converts food waste or by-products into higher-value products that contribute back to the food supply chain (Luque & Clark, 2013). Waste valorization contributes to the circular economy approach where valuable materials, once seen as waste, are recycled back into the supply chain to create new products. Valorisation of olive oil waste streams can be done in various ways (Stempfle et al., 2021).

Considering the environmental impacts of the waste streams of the olive oil production process, valorisation is expected to be environmentally beneficial (Banias et al., 2017; Paini et al., 2021). Additionally, since the waste streams consist of valuable elements, valorisation may lead to economic benefits. There is an abundance of literature that describes the options and methods available for valorisation (Paini et al., 2021; Stempfle et al., 2021), but research related to the quantification of the environmental and economic benefits is still lacking. Additionally, interrelated decisions regarding the production process influence the quality and composition of the waste streams. A decision support tool is needed to optimise the decisions associated with designing an efficient supply chain of olive oil. Such a model should combine harvest, production, and waste valorisation decisions and address questions related to how, how much, what, and when to produce to meet the demand to improve economic and environmental efficiency. This research, therefore, aims to develop such a decision support model.

## Olive oil supply chain and important waste streams

A detailed overview of the olive oil supply chain is presented in Figure 1. The supply chain begins at the olive grove. Once the olives reach the targeted maturity level, they are harvested and transported to the olive mill, where they undergo two cleaning steps to remove leaves, small branches and stones; and then washed from dust and soil (Peri, 2014a).

After the olives have been cleaned, it is time for olive milling and pitting (Leone, 2014). Milling aims to reduce the olives to a homogeneous paste by breaking the pits, skin and pulp cells. Milling affects both olive oil quality and yield. More intensive milling results in olive oils with greater bitterness and pungent characteristics and a higher content of phenolic antioxidants (Leone, 2014). After milling, the paste enters the pitting phase, which aims to remove the olive pits (Leone, 2014).

The next step in the process is olive paste malaxation (Tamborrino, 2014). Malaxation aims to make oil separation easier in the subsequent centrifugation steps. Complex physical and biochemical phenomena occur during malaxation with critical effects on the quality and yield of the oil. Malaxation is the only discontinuous operation in modern olive oil processing (Tamborrino, 2014).

After the malaxation process, the olive paste enters the centrifugal separation (Baccioni & Peri, 2014). This processing step aims to recover as much oil as possible from the olive paste. The extraction systems can be classified into two main categories: the traditional pressing process and centrifugal processes, which can either be a two- or three-phase centrifugation process (Donner & Radić, 2021; Abbattista et al., 2021; Carrara et al., 2021). The olive oil is filtered to remove any remaining suspended solid particles and micro-droplets of vegetation water. Finally, the filtered olive oil is stored and bottled. In general, three main waste streams occur during olive oil production:

- *Olive tree pruning biomass and leaves:* Olive tree pruning biomass is collected after pruning in the olive orchard (García Martín et al., 2020). Pruning leaves 25kg of waste annually per olive tree, while olive tree leaves and thin branches collected during processing comprise about 10% of the weight of olives collected for olive oil extraction (Abbattista et al., 2021).
- *Olive mill (semi-) solid waste:* Olive mill solid or semi-solid waste, also called olive pomace (OP), is the main solid waste stream of the olive oil production process comprising 35-40% of the total weight of olives processed in the olive mill. Olive pomace consists of olive stones, pulp, skins, and variable amounts of water depending on the extraction system used for oil production. To produce 200 kg of olive oil, approximately 800kg of olive pomace is produced (Abbattista et al., 2021). The two-phase extraction system results in a humid semi-solid pomace (wet olive pomace, also called alperujo) with higher moisture content (50–70%) than that of the pomace from three-phase systems (40–54%).

- *Olive mill wastewater (OMWW):* OMWW is the largest quantity of waste produced during the processing phase. The long-chain fatty acids present in OMWW represent a considerable polluting concern since they are toxic to micro-organisms and plants (Abbattista et al., 2021). OMWW is the most polluting waste generated by the agri-food industries (Khdair & Abu-Rumman, 2020). The toxicity of OMWW can be measured by the water's chemical oxygen demand (COD) (Bawab et al., 2018). On average, a three-phase extraction option is expected to produce 800-950 kg OMWW per ton of processed olives, while the two-phase extraction system produces only 250kg OMWW per ton of processed olives (Stempfle et al., 2021).

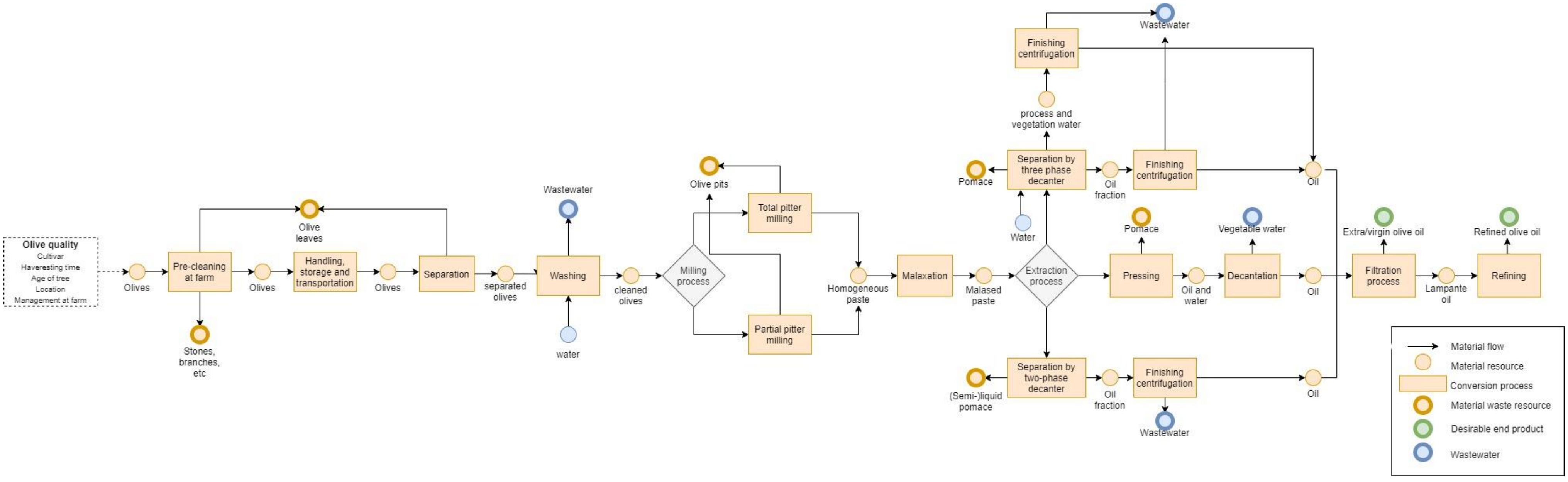



*Figure 1:graphical representation of the current structure of the olive oil production chain.*

The composition and quality of the waste streams depend on the quality of the olives and the production process. Fruit-related factors such as the cultivar and ripening stage can influence the quality of the olives. Also, the location and age of the olive trees and the management decisions on the farm, such as the use of fertilizers, can influence the physiochemical composition of olives. Decisions in the production process can substantially influence the quality of the olive oil and the waste. First, different milling methods can result in different characteristics and phenolic content. A more intense milling action results in an oil with a higher content of phenolic antioxidants, and the level of phenolic antioxidants in the waste streams is lower (Leone, 2014). Also, the malaxation time can influence the quality of the waste streams in a similar way (Tamborrino, 2014). All these decisions also influence the COD content and thus the toxicity of the waste.

## Valorisation pathways and required processing steps

Stempfle et al. (2021) performed a scoping literature review to identify all available valorisation pathways for operationalizing circular economy into the olive oil supply chain. In this literature review, 101 relevant studies were analysed. The reviewed pathways and the number of studies discussing them are summarised in Table 1. Olive mill waste (OMW) is olive mill (semi-) solid waste and olive mill wastewater.

*Table 1:Valorisation circular pathways reviewed by Stempfle et al. (2021)*

| ID | Name of pathway | No. of studies |
|---|---|---|
| **#1** | High-added value bioactive compounds recovery from olive mill waste, olive leaves, or waste cooking oil | 24 |
| **#2** | Biofuel production from pruning residues and olive mill wastes, or waste cooking oil | 23 |
| **#3** | Olive mill waste is reused as a component in the manufacture of sustainable building materials | 8 |
| **#4** | Olive mill wastewater reused for soil conditioning/fertilization/irrigation | 6 |
| **#5** | Pruning residues and olive mill waste valorised for regenerative agriculture | 6 |
| **#6** | Biochar (bio-oil, syngas) production from olive mill waste and pruning residues | 6 |
| **#7** | Olive leaves or olive cake reused for animal feed | 4 |
| **#8** | Polymeric biomaterials production from pruning residues, olive mill by-products, or waste cooking oil | 4 |
| **#9** | Olive mill waste is recycled as bio-adsorbent material for treating aqueous effluents | 3 |
| **#10** | Biofertilizers or bio-stimulants and biopesticides production from olive mill waste | 3 |
| **#11** | Treated urban/industrial wastewater reused for agricultural purposes | 2 |
| **n.a.** | Miscellanea: a collection of studies that are not focused on a specific pathway | 12 |

The two most researched waste valorisation pathways are further explained below:

### *High-added value bioactive compounds recovery from olive mill waste or olive leaves*

The most researched valorisation pathway (24 out of 101) is to recover the valuable biomolecules present in olives and that are lost for a large part in the olive mill wastes (OMWs), including both OP and OMWW, during the oil extraction process (Stempfle et al., 2021). These biomolecules consist primarily of polyphenols and other minor components such as phytosterols, tocopherols, and squalene. The molecules extraction from OMWs mainly uses physiochemical procedures or new, more sustainable physical techniques. The physiochemical procedures use organic solvents such as methanol, dichloromethane, ethyl acetate, and hexane. Physical techniques are based on membrane technologies such as microfiltration, ultrafiltration, and nanofiltration (Castro-Muñoz, Barragán-Huerta, Fíla, Denis, & Ruby-Figueroa, 2018) or reverse osmosis (Sciubba et al., 2020), followed by quick centrifugation. These physical techniques are already implemented at a large scale. Other green techniques such as microwave or ultrasound-assisted recovery of phenolic compounds are still in the testing phase but have the potential to be upscaled.

### *Biofuel production from pruning residues and olive mill wastes*

The second most researched valorisation pathway (23 out of 101) focuses on exploiting olive tree pruning biomass, OMWs, and olive oil post-consumption waste for energy production, i.e. heat, electricity, or biofuel. According to Kitchenham and Charters (2007), various conversion technologies are available for energy valorisation, with different possible outputs.

*Table 2: Bio-fuel conversion technologies for different waste streams (Stempfle et al., 2021).*

| | **Bio-fuel** | | | |
|---|---|---|---|---|
| | **Syngas** | **Electric energy** | **Methanol** | **Biogas** |
| **Pruning biomass** | Heat and power biomass plant | Combustion | | Combustion |
| **Fruit stones/pit** | Heat and power biomass plant | | | |
| **Olive pomace** | Heat and power biomass plant | | Gasification | Gasification |
| **OMW** | | | Anaerobic digestion | |

According to Stempfle et al. (2021), gasification is the most proposed and technologically ready conversion technology. Plants for gasification can be installed at the olive mills, and olive pomace is considered the most appropriate olive oil waste for feeding the gasifier plants. Figure 2 is a graphical representation of the circular olive oil production chain, including membrane processes and gasification, which appear to be the most promising valorisation options. Other valorisation options would be included in a very similar way.

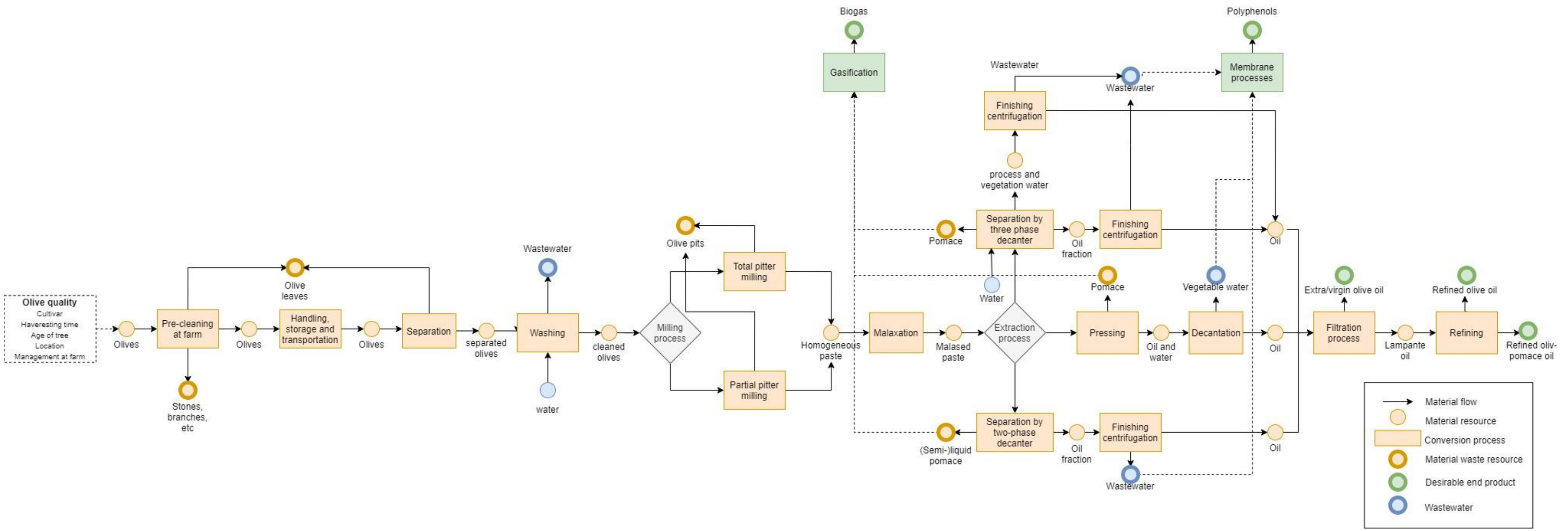



*Figure 2: graphical representation of the circular structure of the olive oil production chain.*

## Production planning model of the circular olive oil production chain.

Specific production planning and waste valorisation decisions must be optimised to identify which combination of valorisation options is the most appropriate under different bio-physical and market conditions. This section briefly describes the structure of a generic production planning model of the circular olive oil production chain. A more detailed description of the model and its mathematical formulation is the MSc thesis of Kok (2022).

A study by Taşkıner and Bilgen (2021) was used to identify the model's specific features. This study reviewed models that aim to optimise production planning decisions related to agri-food production, harvesting and processing of agricultural products. In this review, 74 papers published from January 2000 to October 2020 were reviewed, analysed, and classified based on their problem scope, model characteristics and modelling approach. This review contributed to identifying the design features of the model presented in this section.

The review also provided interesting environmental indicators for olive oil production. Such indicators are related to water use, energy use and the Chemical Oxygen Demand (COD) of wastewaters. COD is a measure of organic compounds in water and is, therefore, a measure of water-polluting charge. COD removal is often used to measure the effectiveness of valorisation options (Bawab et al., 2018).

The main decisions that are optimized at different links of the production chain and relevant constraints are presented in Figure 3. The objective is to calculate the design of the production chain that maximizes economic performance (i.e. profit) for different levels of environmental impact (i.e. COD of waste).

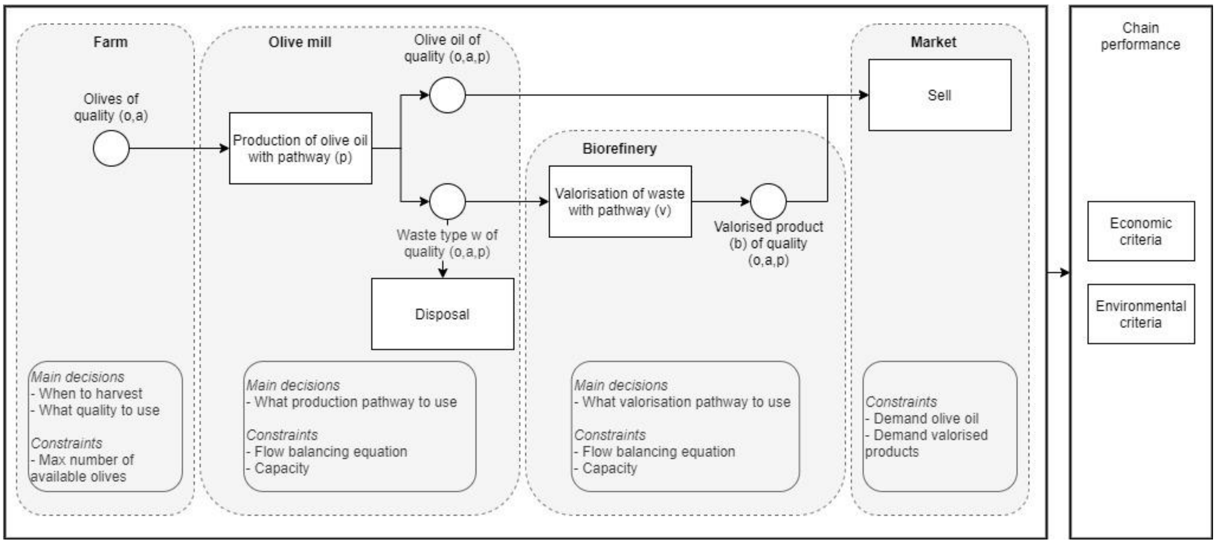



*Figure 3: Optimized decisions and constraints at different stages of the circular olive oil production chain.*

At the farm level, decisions that affect the quantity and quality of the olive fruits are made. Decisions related to how to produce and when to harvest are optimized. Different olive qualities are included and can differ because of farm management activities (e.g. irrigated vs non-irrigated production or level of use of agro-chemicals), genotypes and bio-physical conditions (soil, climate). Dynamic constraints are used to track the maturity level of the olives, and capacity constraints are used to restrict the quantity of harvested olives of different qualities to the expected produced quantities in the region. At the olive mill, decisions about how to process different qualities of olives (harvested at the farm) are optimized. Any realistic setup of the available machinery can be included as a potential processing option. For example, processing options can be defined with different grinding machinery, different malaxation times, and intensity or different water use. The quality of the produced olive oil and waste depends on the quality of the harvested olives and the selected processing option. The produced olive oil is used to meet the demand for different olive oil quality on the market side of the production chain. Waste streams of the olive mill are valorised using an optimal combination of valorisation technologies. Different valorization options result in different biomass-based products sold to the market and contribute to the profitability of the chain and the reduction of COD levels.

### Illustrative example: the circular olive oil supply chain in Greece

This section aims to demonstrate how the model can be used to optimize the circular olive oil production chain and provide information about the type of results that such models can expect. An olive production region in Greece has used a case study, while the required data is based on a literature review. In this exercise, only two popular olive oil-producing varieties are included, i.e. "Koroneiki" and "Megaritiki". Both varieties produce exceptional quality olive oil and are among the 20 cultivars covering over 90% of the olive-growing land in Greece (Kalogeropoulos & Tsimidou, 2014; Katsoyannos et al., 2015). It is assumed that all pre-harvest practices at the farm are based on current olive-producing management techniques.

For this exercise, a three-phase centrifugation olive mill was chosen because it is currently the most common olive oil extraction method in Greece, representing 80% of total production (Mylonas, Voumvaki, & Koutouzou, 2015). We explore three main processing options that differ in the malaxation temperatures. The influence of malaxation time and temperature on virgin olive oil yield, quality and composition were extensively studied by Inarejos-García, Gómez-Rico, Salvador, and Fregapane (2009). It was found that the olive oil yield and phenolic content increase with increasing malaxation temperature. Our focus was only on the two main waste streams of the three-phase extraction process: OMWW and olive pomace. The two most studied valorisation pathways i.e. gasification and membrane processes were considered. The detailed values of all model parameters can be found in the MSc thesis of Kok (2022).

Three main scenarios were explored: (i) the current situation (no waste valorisation allowed), (ii) the valorisation scenario (waste valorisation is possible) and (iii) the scenario that higher demand for high phenolic concentration olive oil was assumed. We calculated the trade-offs between profit maximization and COD minimization objectives for each scenario using the augmented ε-constraint method (Mavrotas, 2009).

## Results

The trade-offs between profitability and COD release calculated for the three different scenarios are presented in Figure 4. Allowing for the valorisation of waste streams substantially improves the production chain's economic and environmental performance.

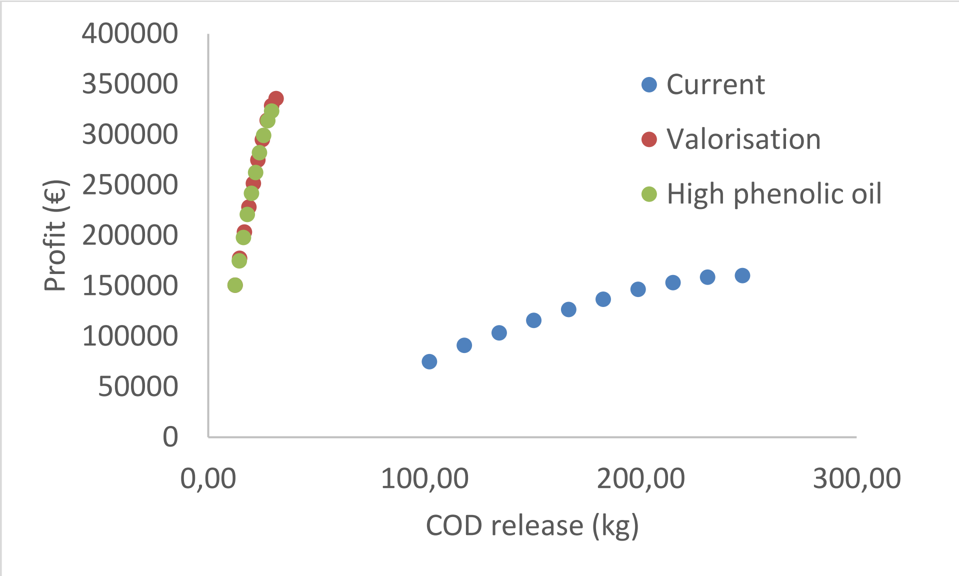



*Figure 4:Trade-off between profit and COD release for the different scenarios.*

To demonstrate the implication of different scenarios to the specific performance and decisions of the production chain, we present specific results of the extreme solutions (i.e. profit-maximizing and COD release minimizing) of the trade-off of each scenario. The economic results of the extreme solutions are explained in more detail in Figure 5 and  Figure 6.

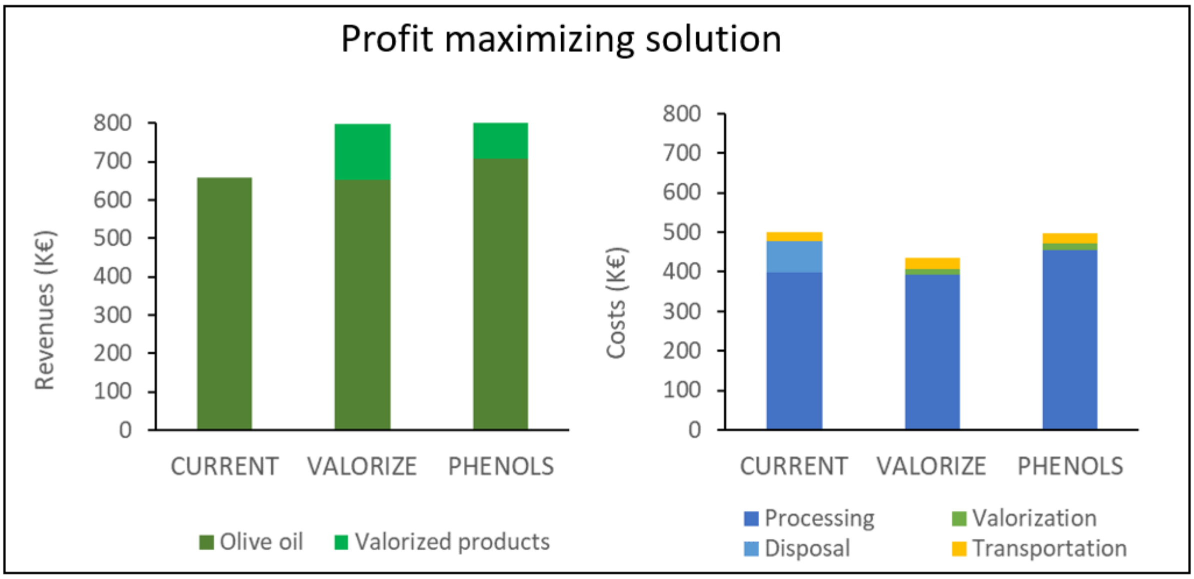



*Figure 5: Revenue and cost analysis of the profit-maximizing solution.*

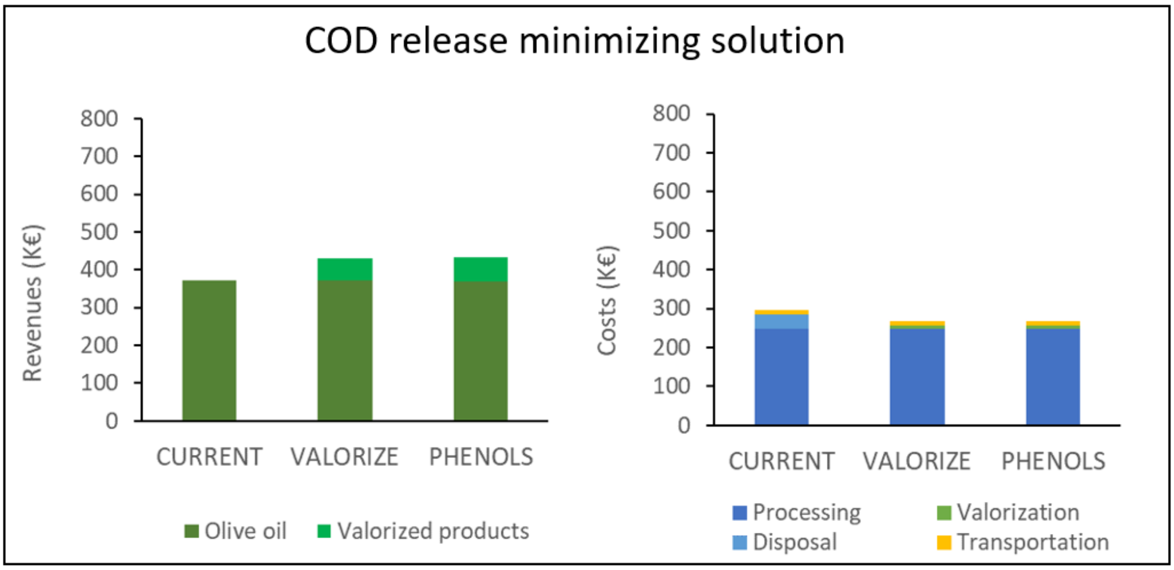



*Figure 6: Revenue and cost analysis of the COD release minimizing solution.*

In the current scenario, valorisation is not possible. As a result, all waste is disposed of, and disposal costs are imposed. These disposal costs vary from €36537 in the COD release minimization solution to €80721 in the profit maximization solution, corresponding to 12% and 16% of the total costs. In the valorisation and high-phenolic oil scenarios, it can be seen that valorisation leads to additional revenues of €144378 and €140063, respectively. Production costs are higher in the high phenolic oil scenario than in the current and valorisation scenarios. This is because the high phenolic olive oil requires higher malaxation temperatures, consequently increasing production costs. A high phenolic oil also has a higher selling price, which explains the increased revenue of olive oil sales in this scenario. The increase in production costs is higher than the increase in oil revenue in the high phenolic oil scenario, which explains why the total profit of this scenario is still lower than the profit in the valorisation scenario.

Figure 5 shows the profit breakdown with COD minimisation, with (a) showing the costs and (b) the revenue. It can be seen that the breakdown looks quite similar in all scenarios. Oil production is the same in every scenario, with valorisation being the only difference between the current and the valorisation and high phenolic oil scenarios.

The harvesting plans for profit maximisation and COD minimisation solutions in all three scenarios are shown in Figure 7 and Figure 8. Olives are harvested before week 8 of the harvesting period. For all scenarios, approximately 90% of the total quantity of olives is harvested before week 5 of the harvesting period. The largest quantity of olives in every scenario is harvested at maturity level 4. Earlier harvested olives have lower olive oil yields, higher phenolic concentration, and lower processing costs, resulting in olive oil sold at higher prices. This higher selling price is why early harvested olives are chosen for the profit maximisation harvesting plans. Maturity level 4 has the best balance between yield, production costs and selling price.

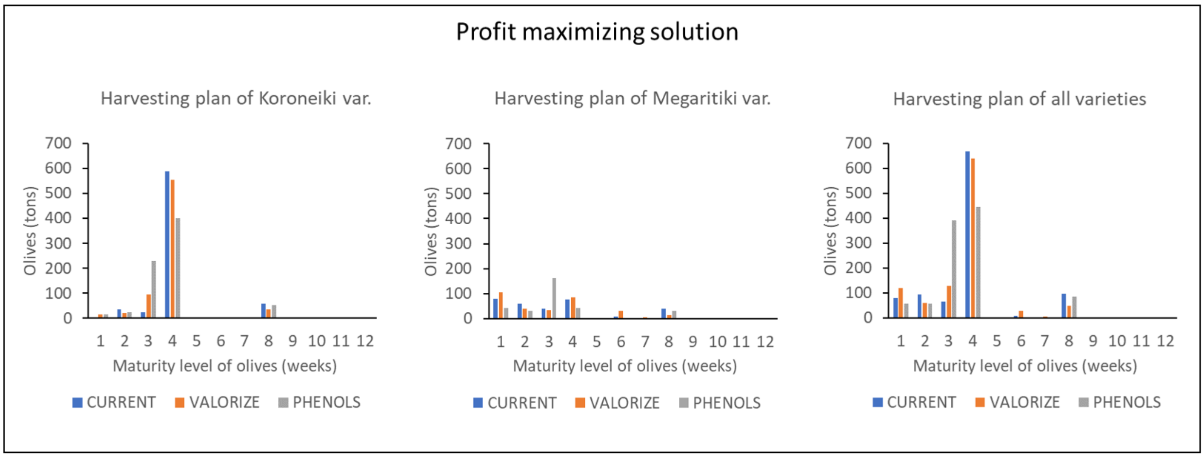



*Figure 7: Optimal harvesting plan of the Koroneiki and Megaritiki variety in the profit-maximizing model run.*

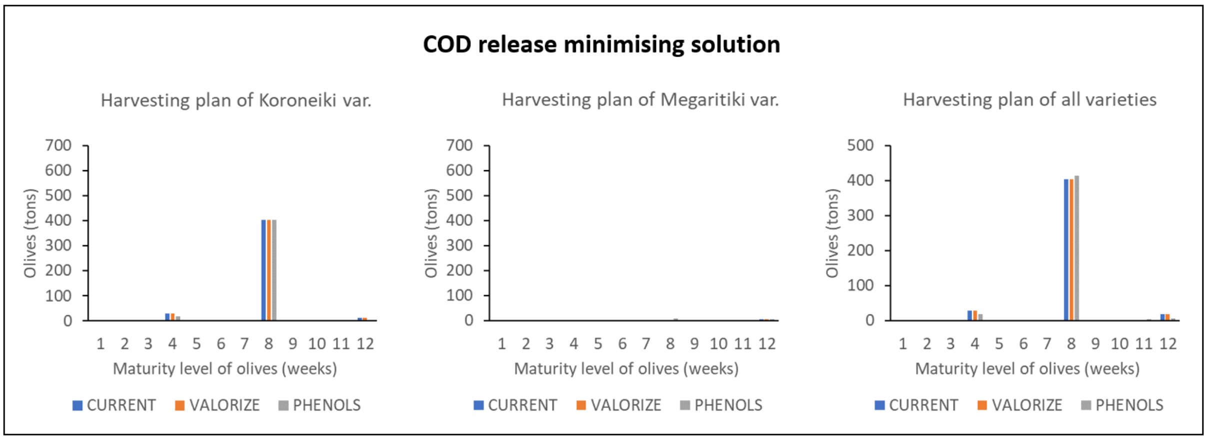



*Figure 8: Optimal harvesting plan of the Koroneiki and Megaritiki variety in the COD minimizing model run.*

The harvesting time differences between the current and valorisation scenarios are marginal. It can be seen that when valorisation is used, there is a slight preference to harvest at maturity levels 1, 3 and 6 compared to maturity levels 2, 4 and 8 in the current scenario when valorisation is not possible. Marginally higher maturity levels are preferred in the valorisation scenario, even though the phenolic content of those olives is lower (therefore, the phenolic content of the olive oil and waste is also lower). When there is a demand for high phenolic oil in the third scenario, the harvesting plan changes, the largest quantity is still harvested at maturity level 4, but instead of having one prominent peak, it can be seen that a large quantity is also harvested at maturity level 3. This direction towards maturity level 3 is because the phenolic content of olives is higher at this maturity level. With COD minimisation, olives of a higher maturity level are preferred, as seen in Figure 6b. The phenolic content of olives and the waste's phenolic content decrease when the maturity level increases. Consequently, the COD content of the waste is also lower when olives with a higher maturity level are used.

The calculated quantities of olive oil produced with different processing options in profit maximisation and the COD release minimisation model runs are presented in Figure 9 andFigure 10. It can be seen that when profit is maximized, in the current and valorisation scenarios, the processing is done mainly at the lowest malaxation temperatures. This is because, at this temperature, the production costs are the lowest. In the higher phenolic oil scenario, production is performed at 28°C and 40°C. This is because higher malaxation temperature leads to more polyphenols in the oil. At the same time, more polyphenols in the oil mean less waste and, therefore, less COD in the waste. This is why a high malaxation temperature is preferred for COD minimisation, as shown in Figure 10.

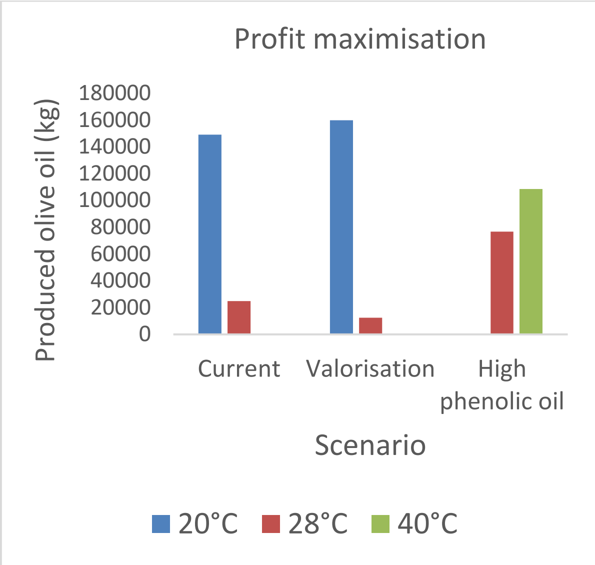



*Figure 9: optimal level of olive oil production in different malaxation temperatures in the profit maximization model run.*

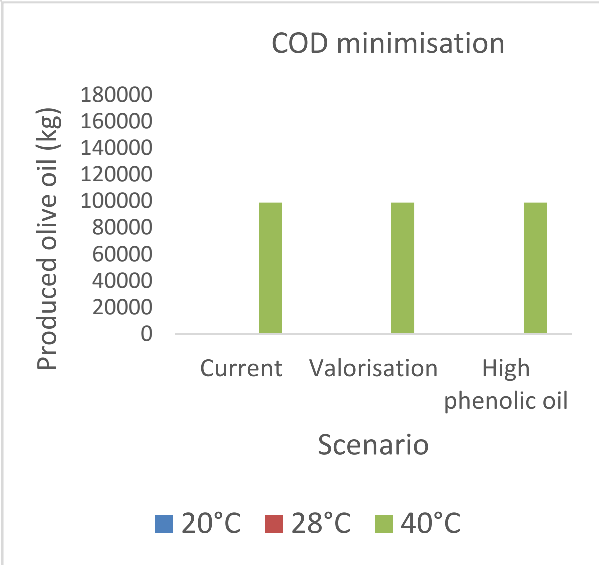



*Figure 10: optimal level of olive oil production in different malaxation temperatures in the COD release minimization model run.*

Since the two profit maximization and COD release minimization are conflicting objectives in all scenarios, the trade-offs can be calculated using multi-objective optimisation (more information on the method can be found in the MSc thesis of Kok, (2022)). The trade-offs between the two objective functions in all scenarios are presented in Figure 4. There is a clear difference between the set of solutions of the current scenario and the valorisation and high phenolic oil scenarios, which is caused by the opportunity to valorise waste streams.

## Discussion and conclusions

The model developed in this research can optimise interrelated decisions of olives production, harvesting, processing and valorisation. The model can generate insights that contribute to designing a circular olive oil production chain. We demonstrated how the model could accommodate different qualities of olives and evaluate alternative processing and valorisation options. Moreover, we showed how the model could be used to calculate trade-offs between key sustainability performance indicators.

From the results of the illustrative example, we clearly showed that waste valorisation is economically and environmentally beneficial. We showed that valorisation could increase profitability and decrease the release of COD to the environment. Sensitivity analysis showed that waste valorisation is beneficial even in worst-case scenarios. We evaluated two promising valorisation options, but more options can be explored, improving closing all cycles.

The results of the illustrative example also demonstrate the impact of the relation between the oil quality and the waste quality. Higher malaxation temperatures are preferable when both high phenolic oil is wanted and when COD release is minimised because a higher malaxation temperature leads to more phenolics in the oil and therefore less in the waste, which results in a lower COD content of the waste. The model can take this relationship between oil and waste into account. The highest malaxation temperature was chosen when COD release was minimised and therefore concluded to be the most "environmentally friendly" option. Even though this may be the case for COD release, more factors can influence the chain's environmental impact in practice.

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