EVALUATING ENVIRONMENTAL BURDENS AND RESOURCE CONSUMPTION IN THE OLIVE OIL INDUSTRY BY USING LCA METHODOLOGY

by

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ABSTRACT

EVALUATING ENVIRONMENTAL BURDENS AND RESOURCE CONSUMPTION IN THE OLIVE OIL INDUSTRY BY USING LCA METHODOLOGY

Türkiye is one of the major worldwide olive oil producers; thus, it is substantial to examine and evaluate the environmental impacts of its production. In this study, virgin olive oil production in Türkiye is extensively evaluated concerning its environmental impacts utilizing the life cycle assessment methodology with cradle-to-gate approach. Additionally, the environmental performance of two and three-phase extraction technologies was compared, the importance of fertilization in raw material extraction stage was assessed, the environmental impacts of valorization of waste were discussed, and the study was related to Türkiye's 2030 Climate Change and 2053 Net Zero Targets. Additionally, the impact of the use of chemicals in olive orchards is comprehensively analyzed, referencing The EU Green Deal Farm to Fork Strategy .These analyses are intended to emphasize the potential contribution of sustainable agriculture to virgin olive oil production and its environmental performance. The outcomes of the study are examined: global warming potential, abiotic depletion , eutrophication potential, and marine aquatic ecotoxicity potential impact categories. The analysis showed that the agricultural activities had the highest environmental impacts, and increasing the share of renewable energy sources in electricity generation improved the environmental performance of producing 1 kg of unpacked virgin olive oil. Furthermore, the two-phase extraction method showed more environmentally favorable results, and waste valorization processes proved crucial. Additionally, it becomes evident that Türkiye’s VOO production holds an important position in terms of environmental impacts. The study emphasize the necessity of adopting cleaner energy resources, improved agricultural practices, and optimizing industrial processes.

ÖZET

YAŞAM DÖNGÜSÜ ANALİZİ YÖNTEMİYLE ZEYTİNYAĞI ENDÜSTRİSİNDE ÇEVRESEL YÜKLERİN VE KAYNAK TÜKETİMİNİN DEĞERLENDİRİLMESİ

Türkiye, önde gelen zeytinyağı üreticisi olan bir ülke olması sebebiyle zeytinyağı üretiminin çevresel etkilerinin değerlendirilmesi önemlidir. Bu çalışmada, Yaşam Döngüsü Değerlendirmesi (YDD) metodolojisi kullanılarak zeytinyağı üretiminin çevresel etkileri "beşikten kapıya" yaklaşımıyla kapsamlı bir şekilde değerlendirilmiştir. Aynı zamanda, iki ve üç fazlı ekstraksiyon teknolojilerinin çevresel performanslarını karşılaştırmış, üretimdeki gübrelemenin önemini değerlendirmiş, atık yönetimindeki temiz enerji kullanımının çevresel etkilerini ele almış ve çalışma Türkiye'nin 2030 İklim Değişikliği ve 2053 Net Sıfır Emisyon hedefleriyle ilişkilendirmiştir. Çalışmada aynı zamanda, tarımsal süreç AB Yeşil Mutabakatı çerçevesindeki “Çiftlikten Çatala Stratejisi” stratejisine dayandırarak analiz edilmiştir. Ek olarak, atık yönetimi süreçleri ve enerji geri kazanımı süreçleri değerlendirilmiştir. Bu analizler, sürdürülebilir tarım uygulamalarının sızma zeytinyağı üretimine potansiyel katkılarını ve zeytinyağı üretiminin çevresel performansını artırmak için yapılacak önemli adımları vurgulamayı amaçlamaktadır. YDD çalışmasının sonuçları, küresel ısınma potansiyeli, abiyotik tükenme, ötrifikasyon ve sucul ekotoksisiteye olan çevresel etkileri incelenmiştir. Çalışmada, tarım, sızma zeytinyağı üretimi ve atık yönetimi aşamaları değerlendirilmiş olup en yüksek çevresel etkiye sahip olan aşamalar analiz edimiştir. Analiz sonuçları, tarım aşamasının çevresel etkilerin en yüksek olduğu süreç olduğunu, elektrik üretiminde yenilenebilir enerji kaynaklarının payının artırılmasının 1 kg paketlenmemiş sızma zeytinyağı üretiminin çevresel performansını iyileştirdiğini ortaya koymuştur. Ayrıca, 2 fazlı ekstraksiyon yönteminin çevresel açıdan daha avantajlı sonuçlar verdiği, atık yönetimi süreçlerinde enerji geri kazanımının önemli bir rol oynadığını ortaya koymaktadır. Farklı senaryolardaan elde edilen bulgular, zeytinyağı üretimi ile ilişkili negatif çevresel etkilerin azaltılması için temiz enerji sistemlerine yönelik ve iyileştirilmiş tarımsal uygulamaların benimsenmesinin ve endüstriyel optimizasyonların gerekliliğini vurgulamaktadır.

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LIST OF SYMBOLS/ABBREVIATIONS

Symbol	Explanation
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
NH_3	Ammonia
N_2O	Nitrogen oxide
P	Phosphorus
PO_4^{3-}	Phosphate
SO_2	Sulphur dioxide

Abbreviation	Explanation
AA	Acidification
AP	Acidification Potential
CC	Climate Change
EVOO	Extra Virgin Olive Oil
FAO	Food and Agriculture Organization
FE	Freshwater Eutrophication
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MI	Maturity Index
OMW	Olive Mill Wastewater
PPP	Plant Protection Products
SDG	Sustainable Development Goal
VOO	Virgin Olive Oil
YDD	Yaşam Döngüsü Değerlendirmesi
WWTP	Wastewater Treatment Plant

1. INTRODUCTION

Agriculture and food production are considered the cornerstones of sustainable development efforts. Sustainable agriculture introduces a complex system including the protection of the environment, social justice, technological advancements, and economic sustainability (DeLonge et al., 2016). In environmental perspective, it faces various difficulties in treating natural resources beyond providing global food security. Reduced water quality, increasing demand for water and energy, extension of urban areas, soil erosion, loss of biodiversity, and the effects of climate change are among these difficulties (Amalero et al., 2003). In this perspective, olive groves and olive oil production play important roles environmentally.

Olive oil is regarded as a key nutrient, with almost the entire production originating from the Mediterranean region (Joumri et al., 2023). Global olive oil production has increased notably over time. Production increased from 1.8 million tons to 3 million tons between the 1990s and 2019 and increased to 3.3 million tons in 2022 (Fernández-Lobato et al., 2024) (Joumri et al., 2023). Meanwhile, Mediterranean countries contribute nearly 95% of this production. Spain is ranked one in terms of the olive oil production country worldwide, while Türkiye ranks fifth (Fernández-Lobato et al., 2024). For the Mediterranean countries with high olive production rates, it is an important economic resource (Espadas-Aldana et al., 2019). However, production is associated with several negative effects on the environment, including depletion of resources, air emissions, climate change, eutrophication, and waste generation. In this context, the LCA methodology appears to be one of the most appropriate scientific tools since it ensures the determination of environmental hot spots throughout a product's or a service's life cycle and paves the way for identifying more sustainable and environmental options along the life cycle.

This study aims to evaluate the environmental impacts of virgin olive oil production's raw material extraction, production and end of life stages by using life cycle assessment methodology. In this context; the ecological impact of the two-phase and three-phase extraction technology along with valorization studies in waste managent, Türkiye's climate change goals and strategies for 2030 and the net zero-emission target for 2053, and the farm-to-fork strategy introduced by the EU Green Deal are investigated in relation to virgin olive oil production. Ultimately, this study intends to how environmental sustainability can be enhanced in the production of virgin olive oil.

2. LITERATURE REVIEW

2.1. Olive Oil Production

In the olive oil production chain, three leading steps are agriculture, industrial, and packaging. Agriculture is the first step, including soil management, irrigation, fertilization, pest control, and harvesting (Guarino et al., 2019). According to Tsarouhas et al., (2015) agriculture is seen as the phase that is primarily responsible for environmental impacts. The use of pesticides and fertilizers harms ecosystems due to their involvement in soil erosion and groundwater pollution. Furthermore, irrigation is the highest water consumer followed by pest control and fertilizer (Avraamides & Fatta, 2008) Subsequently, soil management is related to agricultural machinery usage and it covers harrowing, plowing, and tillage steps (Fernández-Lobato, López-Sánchez, et al., 2021). Agricultural machinery use results in energy and fuel consumption and emissions generation (Tsarouhas et al., 2015). Moreover, the application of fungicides, pesticides, and herbicides is commonplace in non-organic tree crops to safeguard olive production. The primary compounds utilized for these treatments include organophosphorus compounds, glyphosates, and pyrethroid compounds (Fernández-Lobato, López-Sánchez, et al., 2021).

Fertilization is another crucial step which is applied to the olive orchard according to soil analysis. The appropriate amounts of fertilizer are determined based on the age of the tree and the nutritional requirements of the soil (T.C. Gıda, Tarım ve Hayvancılık, 2016). Nitrogen, phosphorus , potassium, and boron stand out as the most important nutrients employed in fertilization practices (Rosati et al., 2015). Nitrogen application is one of the fundamental aspects of olive orchard fertilization due to its significant impact on plant growth (Kotsias et al., 2023), playing a crucial role in increasing olive production. However, the usage of excessive amounts of nitrogen fertilization leads to various adverse effects on both the trees and the soil (Fernández-Escobar, 2019). Potassium fertilization also plays a critical role in enhancing oil content, particularly during the hardening of the pit, presumably due to the elevated potassium requirements during this stage (Rosati et al., 2015). Additionally; potassium sulfate, urea, and mono-ammonium phosphate which is accepted as soil fertilization, boosts both average fruit weight, pulp/pit ratio, and fruit and oil yield (Toplu et al., 2009).

Another method utilized in agriculture is irrigation. Olive trees should find sufficient water in the soil during critical periods to ensure high-quality production and well-balanced growth (T.C. Gıda, Tarım ve Hayvancılık, 2016) Climate conditions, olive variety, and tree density-dependent irrigation have been observed to increase olive yield by over 100% compared to rainfed systems. Additionally, it has been observed to positively increase fruit size, oil content, and pulp/pit ratio (Lodolini et al., 2014).

There are several indicators used to determine the optimal time for harvesting olive fruits. The most prevalent method involves checking the fruit's maturity and ripeness. The assessment commonly relies on the visual determination of the maturity index (MI). The maturity index involves assessing changes in both skin and flesh color as the fruit ripens and classifying them by color scale ranging from 0 to 7 (Khosravi et al., 2021)). While 0 indicates that the skin color is deep green and the fruit is hard, 7 indicates that the skin color is all purple or black, with the flesh purple down to the pit (University of California, 2006). The ripeness and color transformation of the olive fruits are influenced by temperature, sunlight exposure, and irrigation practices (Khosravi et al., 2021). In other words, warmer temperatures during the autumn season lead to faster ripening. Consequently, November or December is considered the optimal period for harvesting (Tarımsal Ekonomi ve Politika Geliştirme Enstitisü, 2022). Moreover, if fruits are exposed to more sunlight, they will ripen more rapidly and turn purple.

To harvest olives, several methods are used in orchards. Handpicking stands out as a traditional technique. During this process, fruits can fall into picking bags or nets placed under the tree by swinging or gently stripping them from the tree branches with partially open hands. Alternatively, fruits can be dislodged onto nets by beating the branches with large sticks. Besides handpicking, olives can also be harvested mechanically (Saglam et al., 2014).

Solid wastes that are generated after harvesting are treated by applying pruning (Abdallah et al., 2021). In temperate regions where cold and frost damage are not a concern, pruning can begin as early as December. In colder climates, pruning can be carried out after the cold has passed, typically in March to April (Abdallah et al., 2021).

The second of the three leading steps of the olive oil production chain, the industrial step, covers washing, crushing, malaxation, extraction, and centrifugation. The step is also responsible for energy and fuel consumption due to the machinery systems involved (Fernández-Lobato et al., 2022).

To expound, olive oils can be produced traditionally in two or three-phase extraction technology. The traditional technique includes washing the olives, crushing them, and rinsing them with warm water to create a paste. This paste is composed of 55% olive, 20% olive oil, and 25% solids. Then the paste is pressed, in other words, olive oils are extracted by hydraulic press separating the oil from the mixture (Smoke, 2020). On the other hand, olives extracted with two or three-phase decanters are crushed with the help of centrifugal force resulting in a fine paste. Then the olive droplets are allowed to clump together. Depending on whether it is a two or three-phase process; pomace, olive pit, and wastewater are formed as waste. In the three-phase extraction technology, three times more water is consumed compared to the traditional technique (Duman et al., 2020). Thus, pomace and wastewater are formed along with olive oil. In the two-phase extraction technology, only a mixture of water and olive pomace, as well as olive oil is generated.

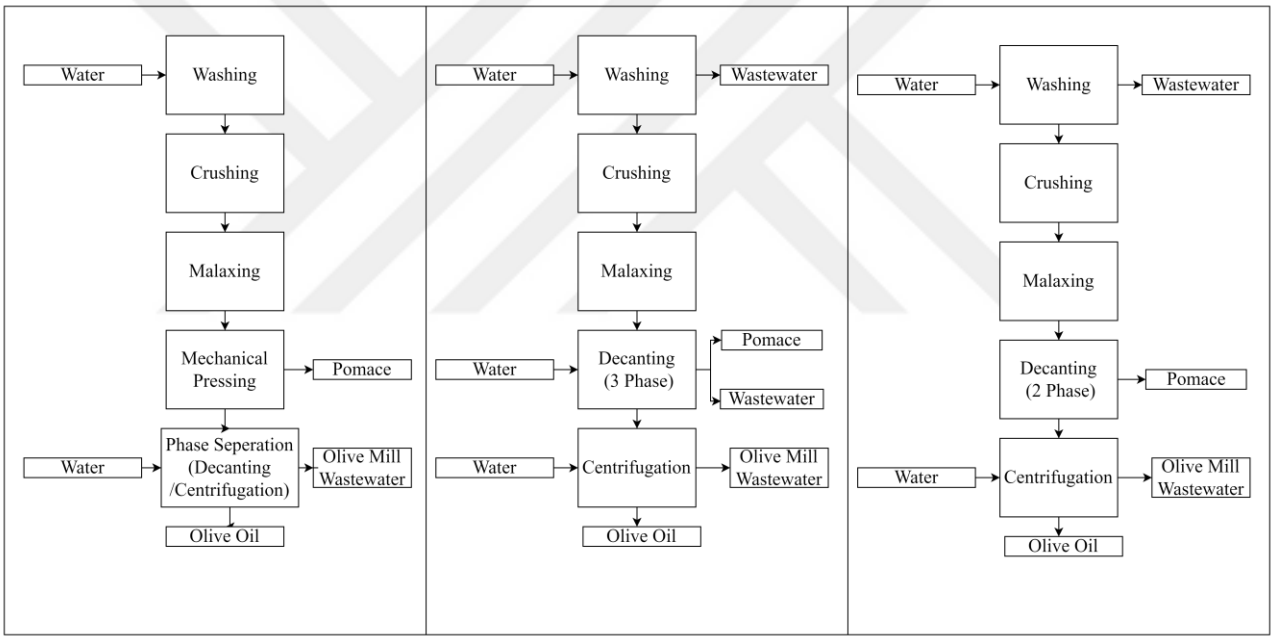

Figure 2.1. Olive Oil Production with Traditional Technique, 3 Phase Decanter and 2 Phase Extraction Technology Respectively (Fernández-Lobato, López-Sánchez, et al., 2021).

In Türkiye, to minimize the potential adverse effects of olive oil enterprises on the environment, prevent water pollution, and reduce water consumption, the "Transition to Two-Phase Production for Olive Oil Enterprises Directive" was published in 2023 by the Ministry of Environment, Urbanization, and Climate Change. Within this framework, it is expected that the amount of wastewater generated from olive oil enterprises will decrease by 75% with the transition from three-phase to two-phase production. The total pollution load from olive oil enterprises in Türkiye, which currently stands at 96 kilograms of Chemical Oxygen Demand (COD) per ton, is aimed to decrease

by 98% to 1.25 kilograms of COD per ton with the transition to two-phase production (T.C. Çevre Şehircilik ve İklim Değişikliği Bakanlığı, 2023)

2.2. Waste Management of Olive Olive Production

The significance of the waste generated during olive oil production processes in terms of the environment is considerable, as these wastes are regarded both as a resource to be recovered and as waste to be processed. The waste products generated in the olive oil industry are by-products such as olive mill wastewater (OMW) and pomace.

Leaves are the initial by-product arising from the raw material extraction stage stage of olive oil production and emerging during the pruning or harvesting phases as well as during the washing stage of olives in the production stages. They account for approximately 10% of the total weight of processed olives (Rodrigues et al., 2023). It has been observed that olive leaves, which contain high levels of fiber and polysaccharides, significant protein content, and various phenolic compounds, have applications in the cosmetic sector. The application of olive leaf extracts to the skin has been shown to be safe and to exhibit strong antioxidant and antiradical activities (Rodrigues et al., 2023).

2.2.1. Olive Mill Wastewater Management

OMW exhibits distinctive characteristics including a potent odor, acidity, dark hue, and a substantial organic load, as indicated by parameters such as Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Dissolved Solids (TDS), and notably high concentrations of phenols (Al-Hmoud, 2020). Considering their environmental impact, the pollution potential of 1 m^3 of OMW is estimated to be equivalent to that of 100-200 m^3 domestic sewage. (Bettazzi et al., 2006) The untreated discharge of OMW into water bodies poses significant challenges to ecosystems. Various alternatives and combinations are implemented to treat these wastewaters and minimize their environmental impact including chemical, mechanical, physical, biological, and thermal methods (Al-Hmoud, 2020).

Table 2.1. Characteristic parameters of OMW obtained from press and three-phase process (Azbar et al., 2004).

Property Unit	Unit	Traditional Method	Three- Phase Process
pH	-	4.5- 5.0	4.7- 5.2
BOD_5	g/L	90-100	33
COD	g/L	120-130	40
Total Solids	%	12	3
Volatile Suspended Solid	%	10.5	2.6
Mineral Suspended Solids	%	1.5	0.4
Suspended Solids	%	0.1	0.9
Total Nitrogen	%	5-2	0.28
Polyphenols	%	1-2.4	0.5
Oil & Grease	%	0.03-10	0.5-2.3

In Türkiye, the regulation currently in force regarding the treatment of OMW is “Regulation on the Control of Water Pollution," published in the Official Gazette dated December 31, 2004, with the number 25687. Based on the regulation, the main parameters for OMW are given as COD, oil-grease, and pH and are provided in the Table 2.2. Thus, it is imperative to treat OMW using appropriate methods to meet the discharge standards and protection of the receiving media specified in the regulation.

Table 2.2. Regulation on the Control of Water Pollution for Olive Oil Industry (Hocaoğlu et al., 2015).

Parameter	Unit	Composite Sample 2-Hour	Composite Sample 24-Hour
COD	mg/L	250	230
Oil & Grease	mg/L	60	40
pH	-	6-9	6-9

The diverse array of components present in OMW necessitates the application of diverse technologies to mitigate pollutants that cause detrimental effects on the environment. Various methodologies, including anaerobic and aerobic biological treatment electrochemical treatment, precipitation/flocculation, treatment through combined processes, and evaporation lagoons, have been employed for OMW treatment (Erses Yay et al., 2012).

First of all, due to the high levels of COD, BOD_5, and Total phenol content in OMW, various physical methods such as centrifugation, sedimentation, filtration, adsorption, evaporation,

distillation, and aeration are employed for its treatment. Chemicals are introduced into the system to facilitate the breakdown of organic matter. One of these methods, coagulation, flocculation, and sedimentation processes, has been reported to achieve over 95% removal of oil-grease and over 40% removal of COD (Hocaoğlu et al., 2015).

Secondly, membrane processes represent one of the options utilized in wastewater treatment (Rocha et al., 2022). Through physical pretreatment and microfiltration, COD was reduced by 48%, TSS by 56%, TKN by 85%, and oil and grease by 75%. With chemical pretreatment and microfiltration, wastewater achieved removal rates of 98% for TKN, 75% for TSS, 74% for COD, and 94% for oil-grease (Hocaoğlu et al., 2015).

Thirdly, aerobic and anaerobic treatment methods, both of which are biological treatment techniques, are employed in the treatment processes. As a pretreatment step, filtration applied to the wastewater removes 60% of the organic matter. While anaerobic treatment removes 89% of the remaining COD, only 20% of phenolic compounds are eliminated(Hocaoğlu et al., 2015).

Lastly, thermal processes are known as evaporation, distillation, incineration, and pyrolysis, and the number of these processes is extensive, with the general principle across all methods being to reduce the water content of wastewater and the overall volume of waste.

In Türkiye, the methods commonly employed for the disposal of OMW include evaporation in lagoons, utilization for agricultural irrigation, and the establishment of individual expansions of factory facilities (M. Ozturk et al., 2021; Slama et al., 2021). Moreover, Turkish producers who use the 3-phase extraction technique in production result in the generation of substantial wastewater volumes, which are subsequently managed through the use of evaporation ponds (Erses Yay et al., 2012) Complementing these methods, various technical solutions are employed for OMW treatment. These encompass a range of approaches such as evaporation ponds, anaerobic and aerobic biological treatments, chemical treatment processes, filtration methods including ultrafiltration and membrane filtration, flocculation techniques, adsorption, and their synergistic combinations (Erses Yay et al., 2012).

2.2.2. Pomace Management

The olive pomace is a by-product of the VOO process consisting of olive husk, pulp, crushed olive stone, and water with a moisture content exceeding 60% and it, represent the 35–40% of the total weight of the processed olive (Rodrigues et al., 2023).

During the formation of olive oil, oil is obtained from the pomace formed during the process through extraction with organic solvents called hexane. If the pomace is processed promptly, the oil obtained can also be used for cooking. Pomace oil obtained from pomace that is not processed immediately is mostly used for industrial purposes such as soap and paint production (Hocaoğlu et al., 2015). Secondly, the main phenolic compound found in olive pomace, called hydroxytyrosol, possesses desirable biological effects such as antioxidant and anti-aging activities, as well as photoprotective, depigmenting, antimicrobial, and anti-inflammatory effects. Therefore, it is also considered as a product for the cosmetic industry (Rodrigues et al., 2023). Thirdly, pomace has the potential to be used as a fuel source following the extraction of residual oil, thanks to its high calorific value. Therefore, 55% of olive oil producers sell their olive pomace to olive pomace processing facilities. Additionally, 37% of olive oil producers utilize pomace as fuel to meet the local heating needs of the factory (Erses Yay et al., 2012). Lastly, it is possible to obtain energy from pomace through methods such as combustion, gasification, liquefaction, and pyrolysis.

The characteristics of pomace can differ based on the extraction technology utilized. Unlike the three-phase extraction technology, the two-phase extraction technology does not involve the use of water, leading to varying moisture percentages in the pomace. With the two-phase extraction method, the moisture percentage of the pomace can potentially reach as high as 70% (Rodrigues et al., 2023).

Table 2.3. Physicochemical Properties of Olive Pomace with Two Phase Extraction Technology (Fernández-Lobato et al., 2022)

Proximate Analysis (%)		Ultimate Analysis (%)	
Moisture	60- 70	Carbon	51.3
Moisture (dried olive pomace)	10-15	Hydrogen	6.4
Ash	5	Nitrogen	2.0
Volatile matter	77.4	Sulfur	0.3
Fixed Carbon	17.6	Oxygen (by difference)	35.0

Table 2.4. Physicochemical Properties of Three Phase Extraction Technology (Ramos & Ferreira, 2022).

Proximate Analysis (%)		Ultimate Analysis (%)	
Moisture	52	Carbon	55.10
Ash	2.50	Hydrogen	7
Volatile matter	80	Nitrogen	1.30
Fixed Carbon	17.6	Oxygen	33.90

The gasification process is a highly efficient thermochemical conversion technology that produces valuable syngas, containing H_2, CH_4, and CO, from solid carbon-based materials at high temperatures, along with a solid byproduct known as biochar. The resulting syngas can be utilized in gas turbines, combustion engines, or fuel cells for energy generation (M. U. Ozturk et al., 2023).

Syngas is accompanied by tar during the gasification process, which is a dense, black, and sticky liquid that can condense at low temperatures, posing a risk of clogging gas flow. This can lead to problems in equipment and engines, thereby negatively impacting the efficiency of gasification. The level of tar in syngas should be kept as low as possible, although the tolerance limits vary depending on the process and application. While tar is generally considered an undesirable byproduct of the gasification process, it has potential uses in certain industries (M. U. Ozturk et al., 2023).

Another byproduct of the gasification process is known as biochar, which contains organic carbon in stable aromatic forms. The conversion of carbon produced during gasification into CO_2 is an undesirable outcome; therefore, the high methane content in syngas and the carbon within the resulting biochar hold significant value for the process. Additionally, the reduction of CO_2 emissions during this process is a highly positive development from an environmental perspective. On the other side, it is noted that that biochar contains many beneficial elements by using wastewater treatment sludge as a raw material, and they emphasized its potential as a soil amendment or an adsorbent with the capacity to remove various pollutants from water/wastewater due to its rich nutrient content. Previous studies have highlighted the positive effects of biochar on soil fertility and health, as well as its role in the removal of pollutants from wastewater (Ramos & Ferreira, 2022).

Pyrolysis is the thermal decomposition of biomass fuel in the absence of oxygen at temperatures ranging from approximately 400 to 700 °C, characterized by an endothermic nature. This thermochemical biomass conversion process yields a variety of products, including gases, liquids (such as tar or bio-oil), and solids (char), depending on the specific pyrolysis conditions employed. Pyrolysis can be differentiated into two categories: "slow pyrolysis," which is optimized for char

production with residence times extending from minutes to days, and "fast pyrolysis," which is optimized for bio-oil production and characterized by much shorter residence times, typically on the order of seconds or minutes (Ramos & Ferreira, 2022).

2.3. Olive Oil Quality Standarts

Olive oils are governed by various standards and rules depending on location of trade (Conte et al., 2020). The standards established by the EU, the International Olive Council, and the Codex Alimentarius are the three most important ones. EU regulations are mandatory within the EU area and must be implemented by member countries without any additional procedures; however, the same regulations cannot be applied outside the EU (Conte et al., 2020).

The International Olive Council (IOC) is responsible for developing standards that can also be applied by many countries, similar to as well as the Codex Standard Founded in 1963, the IOC developed a "Trade Standard for Olive Oils and Olive Pomace Oils," which serves as a reference for all member countries. These nations are required to implement the standard within the context of international trade and are encouraged to harmonize their national regulations with the IOC's guidelines. The EU's olive oil standard is CODEX STAN 33–1981, which was reviewed in 2017. The Codex standard has a unique structure: while certain fundamental purity and quality characteristics are mandatory, adoption of a range of additional features by a member is voluntary (Conte et al., 2020).

In Türkiye, “Turkish Food Codex Communiqué on Olive Oil and Pomace Oil” was published in 2017. Within this framework, the quality of produced olives has been determined and the defined different types of olive oils that are produced, including extra-virgin olive oil, virgin olive oil, lampante olive oil, refined olive and so forth. These physical and chemical characteristics are identified by its acidity level, free acidity content, peroxide value, UV specific absorbance values (K232 and K270), indicating the pureness of olive oil, fatty acid ethyl ester (FAEE), which is related with quality of olive and sensory characteristics.

Classifying different types of oil is to define the physical and chemical characteristics of each, as well as the sensory properties of virgin oil (Alimentarius, 2001). This ensures the purity and quality of the relevant products, while safeguarding against any detriment to existing regulations. According to Regulation (EEC) 2568/91 as amended by the European Commission, classes of olive oils are rated

in accordance with quality standards based on physico-chemical and sensory characteristics. Table 2.5 is show the Turkish quality standards.

Table 2.5. Quality Standarts Based on Türkiye Issues Food Codex Communiqué on Olive Oil and Pomace Oil (Resmi Gazete, 2017)

	Crude Olive Pomace Oil	EVOO	VOO	Refined Olive Oil	Olive pomace oil	Refined olive-pomace oil	Crude Pomace Oil
Acidity Level (%)	> 2.0	≤ 0.8	≤ 2.0	≤ 0.3	≤ 1.0	≤ 0.3	≤ 1.0
Peroxide (meq O_2/kg)	-	≤ 20	≤ 20	≤ 5	≤ 15	≤ 5	≤ 15
UV spesific absorbance values (K232)	-	≤ 250	≤ 2.60	-	-	-	-
UVspesific absorbance values (K270)	-	≤ 0.22	≤ 0.25	≤ 1.25	≤ 1.15	≤ 2.00	≤ 1.70
Fatty acid ethyl ester (FAEE) (mg/kg)	-	≤ 35	-	-	-	-	-

The quality, nutritional properties, and sensory characteristics of olive oil are related to its chemical composition, which results from complex interactions between environmental, agricultural, and technological factors. These factors depend on agronomic practices, climatic conditions, harvesting applications, carriage and storage methods, and industrial technologies (Faghim et al., 2021).

Irrigation is a major application that affect quality of olive fruit. It enhances the agricultural productivity and has diverse effects on soil properties, affecting soil fertility both positively and negatively. The positive effects of soil irrigation include increased soil moisture levels and increasing organic matter content. With irrigation, quality characteristic parameters are changed: while acidity, K232, and K270 levels tend to increase; the contents of chlorophyll, carotenoids, and phenols experience a decrease. On the other hand, irrigation has minimal or no impact on the composition of fatty acids, peroxide value, and free acidity level. Consequently, these alterations can lead to a reduction in oil stability (Trabelsi et al., 2022).

Harvesting is another factor influencing the quality of olive oil. Olive fruit is harvested in two ways: traditional hand harvesting and mechanical harvesting. Hand harvesting involves manually picking the olives by hand, using large sticks to strike the branches and dislodge the fruits, and directly

plucking the fruit from the branch by hand allowing it to fall onto a picking platform. The mechanical method utilizes tree-shaking machines. Researches show that when the olives are carefully handpicked to avoid damage, there is a noteworthy reduction in free fatty, the level of peroxide, while the total polyphenol content is increased. Furthermore, it has been observed that the quality of the oil deteriorates due to the watering of the olives during harvesting (Saglam et al., 2014).

2.4. Life Cycle Methodology

Life cycle assessment (LCA) is a methodology and an analytical tool that assesses the complete life cycle of a system or a product extending from the attainment of natural resources to disposal (ISO 14040, 2006). Fundamentally, each phase of the production is considered in terms of its environmental aspects and potential impacts presenting an in-depth insight into the product's environmental footprint.

LCA is comprised of four main phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO 14040, 2006). Goal definition involves stating the study's reasons, describing the intended application, and identifying the target audience. The scope definition encompasses key parameters, functional units, system boundaries, and so on. In the inventory analysis stage, the data is collected, the inputs and outputs of a product throughout its life cycle are quantified. In the impact assessment phase, an evaluation of the importance of the potential environmental impacts of the product is made. Lastly, in the interpretation phase, findings from the stages are assessed based on the goal and the scope leading to expected recommendations. The applications include identifying environmental improvement opportunities, strategic planning or environmental strategy development, product and process optimization, design and innovation, and environmental reporting and marketing (Ouellet-Plamondon & Habert, 2015).

The availability of reliable and transparent data is crucial as LCA relies on datasets, so the availability of reliable and transparent data is essential. In cases where data is missing, having a dependable dataset becomes essential. Ecoinvent is one such dataset that fulfills this need. It provides users with transparent and consistent data spanning a wide range of products and activities globally. Moreover, it facilitates access to methodologies, flow charts, life cycle inventories, and literature references, and is compatible with commonly utilized LCA software.

Conducting a life cycle assessment study necessitates a modeling tool for the analysis of environmental impacts. To meet this requirement, Gabi was developed in 1992, by a German company. This software encompasses life cycle unit process and an impact assessment database containing data supporting various lifecycle impact assessment methodologies, and a calculator that combines the data. (Herrmann & Moltesen, 2015).

2.5. Life Cycle Assessment of Olive Oil

The LCA of olive oil encompasses all stages including agricultural activities, industrial processes, packaging, and waste management. of the supply chain to assess its environmental impact.

In LCA studies of olive oil production, the functional units commonly selectes as 1 kg to 1 ton olives and 1 liter to 1 bottle of olive oil. Besides, Software tools such as OpenLCA, SimaPro, and Gabi are commonly employed for impact assessment, while Ecoinvent, Agri-footprint, and ELCD databases are used in LCA to obtain secondary data (Rapa & Ciano, 2022). Additionally, ILCD, ReCiPe, and CML are the most widely employed methods (Rapa & Ciano, 2022). What is more to the point, the secondary data used in LCA studies are obtained from the Ecoinvent, Agri-footprint, and ELCD databases (Rapa & Ciano, 2022) .

Additionally, the scope of the LCA of olive oil production encompasses almost all the stages, including farming, olive production, packaging, and wast management (Rapa & Ciano, 2022). Likewise, Hanandeh (2015), examined agricultural activities, olive oil extraction, packaging, and waste management stages. However, Guarino et al. (2019) did not report on waste management, whereas Salomone et al. (2015) omitted the packaging step in their study. Salomone et al. (2015) and Fernández-Lobato et al. (2021) focuses solely on the agricultural and extraction stages. **Hata! Başvuru kaynağı bulunamadı.** shows the inputs and outputs used in LCA based olive oil production studies.

The raw material extraction stage represents the harvesting of olives in orchards. In the literature, all studies highlighted that the agricultural activity is the most impacting due to the use of fertilizers and pesticides. Besides, studies show that absence of synthetic fertilizers and pesticides in organic systems, lower environmental impacts were observed (Rapa & Ciano, 2022). Additionaly, Guarino et al., (2019) states that fertilization is the responsible for highest impact.

Additionally, the effects of irrigation and rainfed systems have also been investigated in the literature. In this context, it has been emphasized that irrigation leads to a reduction of 10% to 34% in freshwater eutrophication and freshwater ecotoxicity impacts (Carrasco-Pancorbo et al., 2005).

Furthermore, intensive and super-intensive land systems have been assessed. De Gennaro et al. (2012) states that intensive systems have lower impacts compared to super-intensive systems. However, other studies have suggested that increasing the intensity of a system should result in less environmental impact. The main reason is that definition of goal and scope, as well as the functional unit, have a remarkable influence on LCA results. Romero-Gámez et al. (2017) evaluate the environmental impact of traditional, intensive, and super-intensive crop systems in Spain. They conclude that improvement of olive cultivation processes could be achieved through the reduction and optimization of fertilization.

Extraction technologies are crucial for the production stage. In literature, extraction technologies are compared. According to Fernández-Lobato et al. (2021), the 3-phase system extraction technology produces the greatest environmental impact as opposed to traditional and 2-phase extraction technologies. On the other hand, Restuccia et al. (2018) compared two and three-phase extraction technologies and their results show that revealed lower environmental impact generated by the two-phase method. Furthermore, the study evaluates two scenarios, for managing pomace: composting and bio-gasification.

The majority of LCA studies have been conducted in Italy (Guarino et al., 2019). Furthermore, there are also notable LCA studies from other olive oil-producing countries such as Spain, Greece and Türkiye. Although it is possible to find other studies from Portugal, Iran, or Cyprus (Ruiz-Carrasco et al., 2023). Regarding Italy, various studies with diverse scopes are evaluated. Firstly, Guarino et al., (2019) examined the energy and environmental impact of different cropping systems, including traditional and industrial methods. Findings show that fertilizers have the highest impact within the agricultural activities. Furthermore, within the production stage, bottle production demands a excess amount of energy and the greatest environmental impact.

In Spain, most of the LCA studies focus on the environmental impact of olive orchards. Romero-Gámez et al. (2017) assessed the traditional, intensive, and super-intensive cropping systems and found that improving and optimizing fertilization practices could enhance olive growing. Secondly, Fernández-Lobato et al. (2021) conducted a comprehensive study to evaluate the environmental

effects of both raw material extraction and production stages of virgin olive oil in the Andalusia region. Another study compares two scenarios of by-products, one with gasification technology and one without. In the case of Greece, different scopes have been assessed using LCA methodology. Tsarouhas et al. (2015) conducted a comprehensive study, investigating 14 subsystems across the entire olive oil production chain. Chatzisymeon et al. (2013) applied LCA to investigate olive mill wastewater, with the former evaluating the environmental impact of three oxidation processes for treating the wastewater and focusing on the recovery of compounds from the wastewater.

In Türkiye, there is limited study on evaluating the environmental impact of olive oil production. One of the notable studies by Duman et al. (2020) was pioneering in evaluating the impact of pomace using LCA methodology. The other striking study about analysis of both the farming and the production stages through a cradle-to-gate LCA is supplied by Carrasco-Pancorbo et al. (2005). Besides, Ruiz-Carrasco et al., (2023) focus on agricultural activities in virgin olive oil production. Furthermore, there are some studies that briefly address and cover only parts of the olive oil production process. To illustrate, Özilgen & Sorgüven, (2011) assessed energy and exergy utilization and carbon dioxide emissions in the production of soybean, olive oil and sunflower using thermodynamic calculations rather than LCA methodology.

3. MATERIALS AND METHODS

The life cycle assessment (LCA) methodology based on the standards was applied to identify environmental impact points throughout the life cycle of the production process of virgin olive oil (VOO). The overall study was divided into three subsystems: the raw material extraction stage, the production stage and end of life stage. The functional unit was defined as the production of unpacked 1 kg of VOO. To evaluate the environmental impacts of the production of virgin olive oil, various scenarios were developed.

This study integrates Türkiye's ambitious climate goals for 2030 and its net zero emissions target for 2053 by analyzing scenarios focused on increasing the share of renewable energy in the electricity generation mix. Additionally, the potential effects of the Farm to Fork Strategy based on the EU Green Deal were also considered. Furthermore, the waste generated during the production of virgin olive oil is thoroughly evaluated, with different waste disposal and valorization pathways explored across the scenarios to assess their environmental implications. Altogether, the aim is to conduct a comprehensive assessment of the environmental sustainability of virgin olive oil production.

The environmental impacts of the production of 1 kg of unpacked VOO were assessed using GaBi 8.0 software. The evaluation employed the CML2001 impact assessment methodology in four different categories: global warming potential, abiotic depletion, eutrophication potential, and marine aquatic ecotoxicity potential.

3.1. Goal and Scope Definition

The main objective of this study is to analyze the environmental impacts related to the production chain of VOO. To achieve this, the analysis will be conducted with a careful focus on the raw material extraction stage, production stage and end of life stages. Additionally, it adopts a cradle-to-gate approach, encompassing various upstream and core activities associated with the production of virgin olive oil. Upstream processes involve the production of inputs and energy sources, as well as olive harvesting, while core processes contain activities within the production stage, such as oil extraction, utilization, waste management, and emission control. It's important to note that this approach excludes considerations of packaging and downstream processes, as they fall outside the scope of this study.

Functional unit (FU) is used as a reference point for quantifying the performance of a system (ISO 14044, 2006). In this study the production of 1 kg of unpacked virgin olive oil.is defined as FU.

Through this systematic evaluation, the study seeks to provide valuable insights into the comparative environmental performance of the main and alternative scenarios, thereby contributing to informed decision-making processes in sustainability and resource management.

3.1.1. System Boundaries

In the framework of this LCA analysis, three separate subsystems were described: the initial subsystem, the subsequent subsystem and end of life phase. The initial subsystem relates to the raw material extraction stage of olive harvesting, whereas the subsequent subsystem includes the production stages involved in the production of virgin olive oil. Lastly, the end-of-life phase addresses the disposal or valorization of waste generated during the production process.

In this study, where system boundaries are defined in Figure 3.1, the following processes have been excluded from consideration:

- The maintenance of agricultural machinery, including the replacement of mechanical or engine oil and other spare parts can have significant impacts, there are several data limitations associated with this process. Therefore, it has not been included within the system boundaries.
- Olive trees' ages are accepted as older than 25 years and excluded from the inventory because they are considered to have no environmental impact (Salomone et al., 2015).
- Packaging and distribution of VOO are not included within the system boundaries.
- The end of life of virgin olive oil, as well as the by-products such as char, tar, and gases are excluded from the scope of the study.
- The end-of-life management of exhausted olive pomace , crude pomace oil, digestate and final effluent is considered outside the system boundaries of this study.

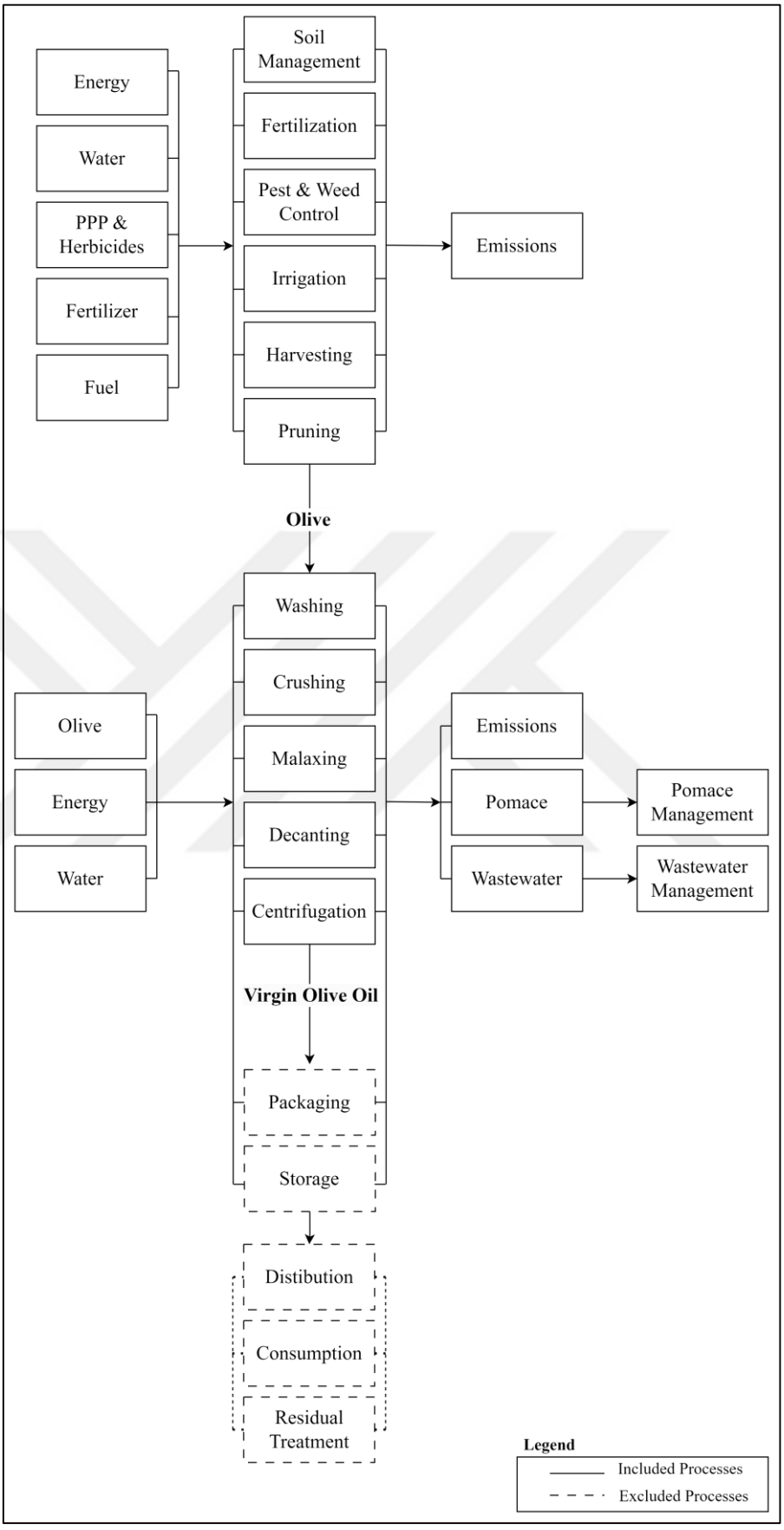

Figure 3.1. System Boundary of the virgin olive oil life cycle from cradle to gate.

The first subsystem consists of soil management, fertilization, the use of pesticides and herbicides, irrigation, cutting, and harvesting. Soil management is employed at various times to carry out operations such as harrowing, soil cultivation, plowing, and preparing the land for harvesting. Fertilization is performed to improve soil vitality and productivity. Irrigation is carried out using drip systems, with watering timed at sensitive periods to enhance both the quantity and quality of the olive yield. Additionally, pesticides and herbicides are applied to protect the crops from pests and diseases. Once the olive kernels begin to harden and oil accumulation starts, olives are harvested when the highest oil formation is achieved. Harvesting can be done through traditional manual methods or with the help of machinery.

The second subsystem, pertains to the process of producing virgin olive oil from cultivated olives. This multifaceted process is composed of distinct production units. Initially, cultivated olives are transported to the facility. Harvested olives are deposited into termed bunkers, followed by conveyance to fan-equipped sections via a conveyor system known as an elevator. Through the utilization of fans, the separation of olives from materials such as branches, leaves, and stones are facilitated. Subsequent to this, the olives are washed in a washing unit to remove dust and dirt. After washing, they are dried with the help of fans and transferred to the crushing unit. Here, the olives, along with their pits, are crushed and mashed into a paste to facilitate the extraction of oil. The olive paste, rendered into a homogenous pulp, undergoes a malaxation process within malaxers for an average duration of 20 to 40 minutes. Upon completion of malaxation, the pulp is directed to a decanter via a pumps. Within the decanter, the rotation of the olive paste separates the pomace, directing the oil and remaining contents to a centrifuge. Using pumps, the centrifugal separator further divides the denser pomace from the lighter oil fraction.

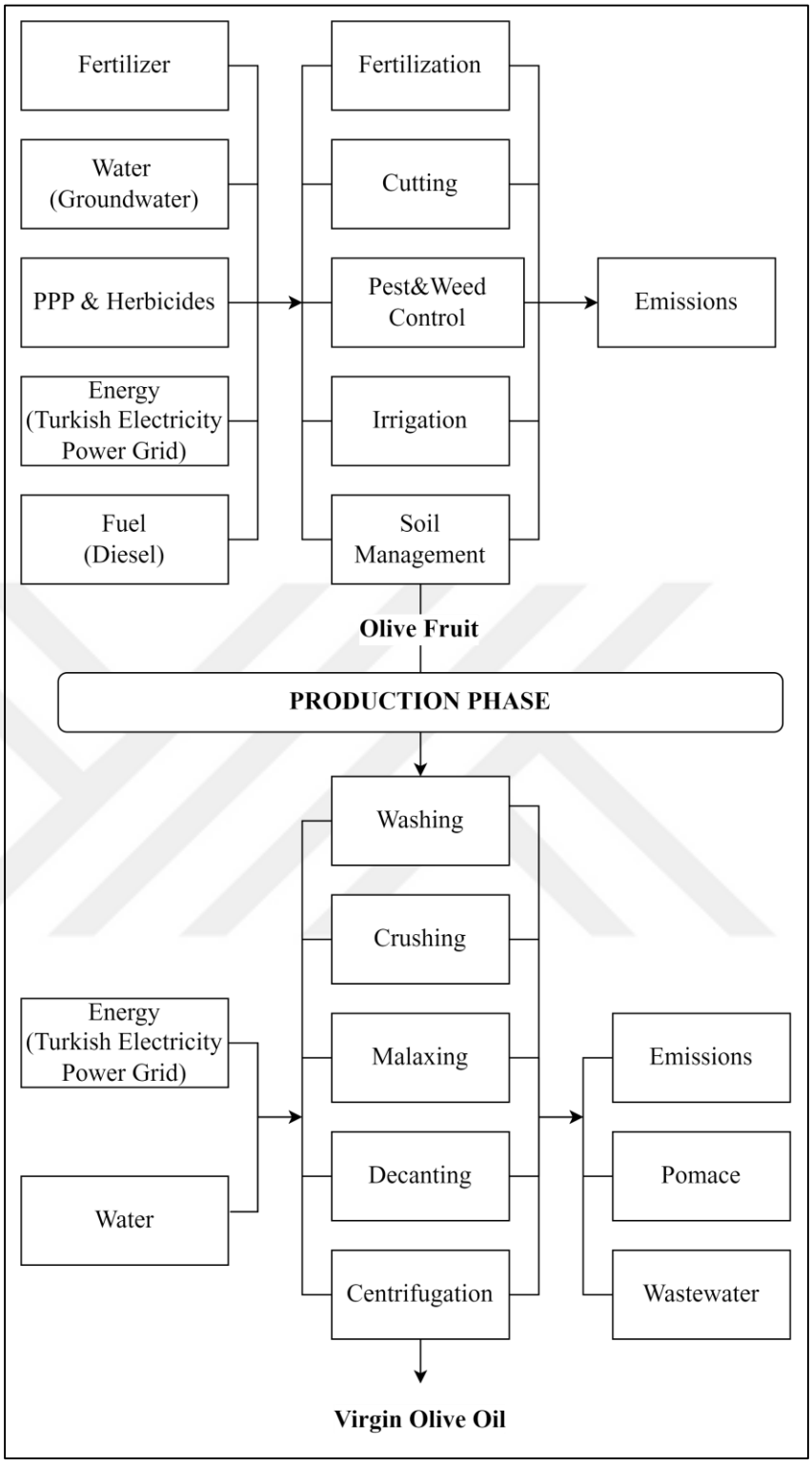

Figure 3.2. Subsystem-1(Raw material extraction stage) and Subsystem-2 (Production stage).

The third subsystem pertains to the end-of-life phase and involves a chemical extraction method. The by-product generate

d during the production of virgin olive oil, known as pomace, consists of small amounts of oil and other low-value residues from the olive fruit, along with a high water content. After an energy-

intensive drying process, the dried olive pomace undergoes a solid-liquid extraction process using hexane. The products of this extraction process include crude pomace oil contained, as well as exhausted olive pomace (EOP) with a moisture content of approximately 12%, which is used as an input for industries that generate energy from biomass (Fernández-Lobato, García-Ruiz, et al., 2021). Furthermore, the oil obtained from this process is refined to produce crude olive oil, which is of lower quality than VOO. The end-of-life management of exhausted olive pomace and crude pomace oil is considered outside the system boundaries of this study.

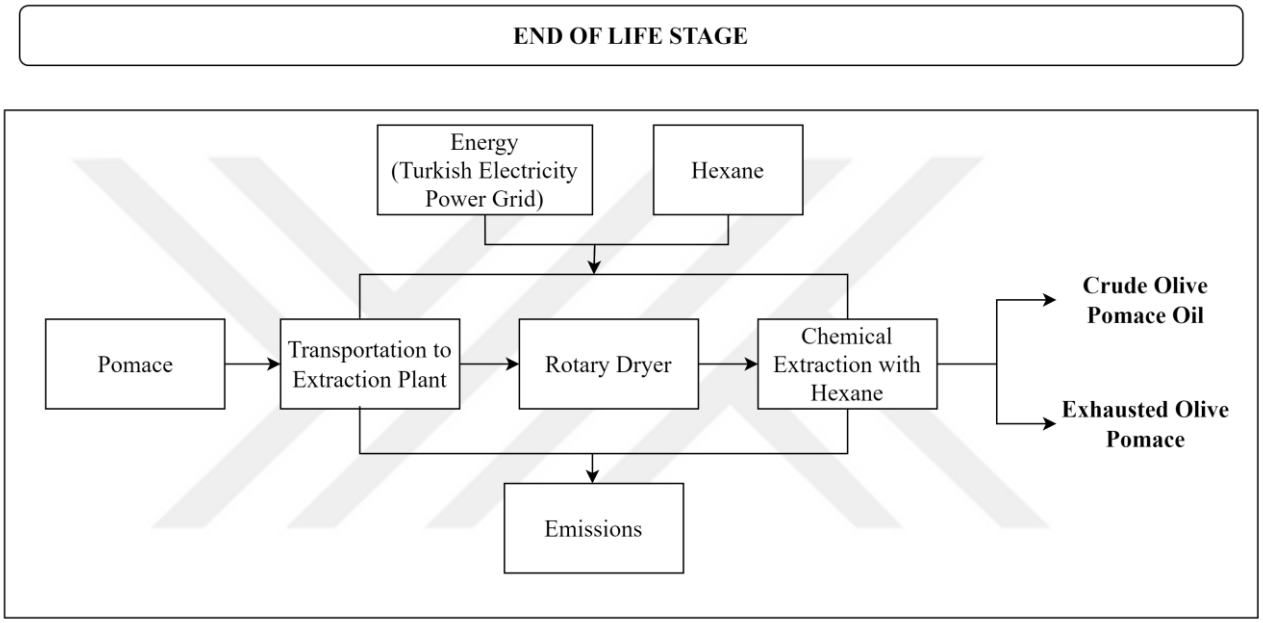

Figure 3.3. Subsystem- 3 (Chemical Extraction).

Another subsystem is related to the end-of-life stage, which incorporates the anaerobic digestion method. The anaerobic digestion method has been employed for the treatment of olive mill wastewater generated by the three-phase production technology. In this subsystem, the addition of $NaHCO_3$ to the wastewater fed into the Upflow Anaerobic Sludge Blanket (UASB) bioreactor was implemented to ensure stable reactor operation without unexpected pH fluctuations. The reactor included 6.2 liter bioreactor with double wall, to pumps for feed volumetric flow and recirculation of the UASB reactor. Specifically, 10 d and and 5 kgCOD /m3reactor/d are designed for hydraulic retention time (HRT) and organic loading rate (OLR), respectively (Manthos et al., 2023). Additionally. the system's productivity was selected to be 10.70 m^3 CH_4 /m^3 feed. The recoverable energy from the process was calculated based on the calorific value of methane, which is 39.80 MJ/m^3 CH_4 , and an energy recovery efficiency of 95% from biogas combustion(Manthos et al., 2023)

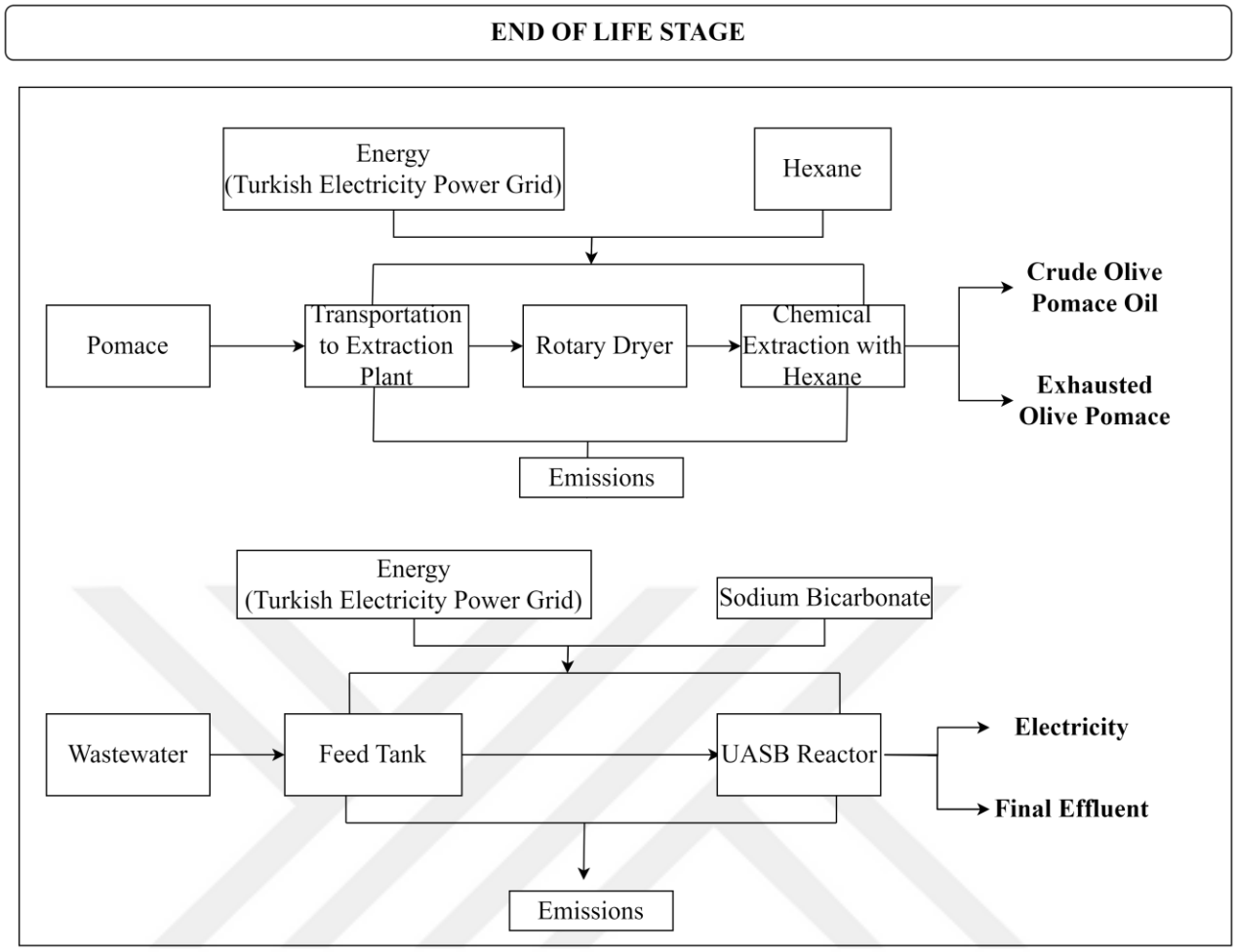

Figure 3.4. Subsystem-4 (Chemical Extaction & Anaerobic Digestion).

The fifth subsystem involves treatment of pomace with anaerobic digestion technology. This method allows on site management so the impact of transportation of pomace is minimized. By employing anaerobic digestion, pomace ,the organic by product, is converted into biogas, which can be used as a energy source. Additionally, the process reduces the volume of waste, contributing to a more sustainable waste management system. The resulting byproducts, such as digestate, can be utilized as nutrient-rich compost, further enhancing the sustainability of agricultural practices. This approach not only reduces environmental impact but also adds value to what would otherwise be discarded.

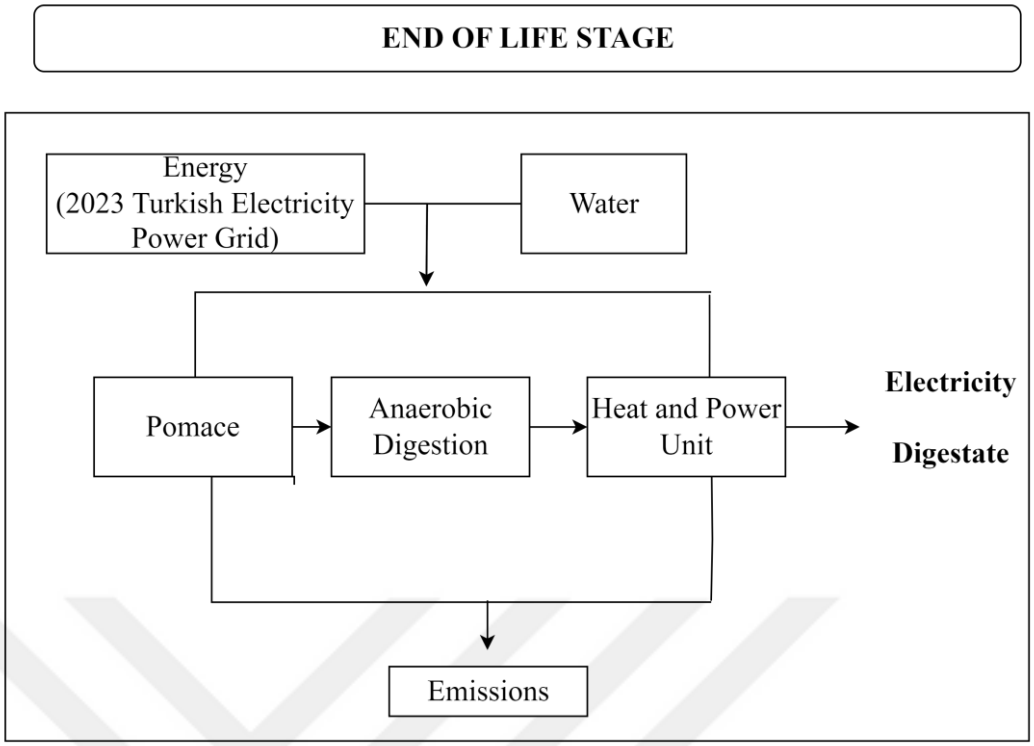

Figure 3.5. Subystem-5 (Anaerobic Digestion).

The sixth subsystem involves the treatment of olive pomace through gasification technology. This innovative method allows for the direct on-site drying of olive pomace, which is continuously produced at high rates in olive oil mills with high moisture content, instead of being transported over long distances to oil extraction plants for subsequent drying. The proposed approach involves processing this high-moisture pomace using an integrated gasification plant for combined heat and power (CHP) generation. This subsystem consists of a pelletizing machine, a downflow fixed-bed gasifier fueled by dried olive pomace pellets, a producer gas cooling and cleaning unit, a spark-ignition engine-generator set for electricity production, an auxiliary furnace, and a fluidized bed rotary drum dryer that facilitates the drying of pomece with high moisture content using the hot exhaust gases from the engine. The downflow gasifier is fed with dried olive pomace pellets and air as the gasifying agent (Fernández-Lobato et al., 2022).

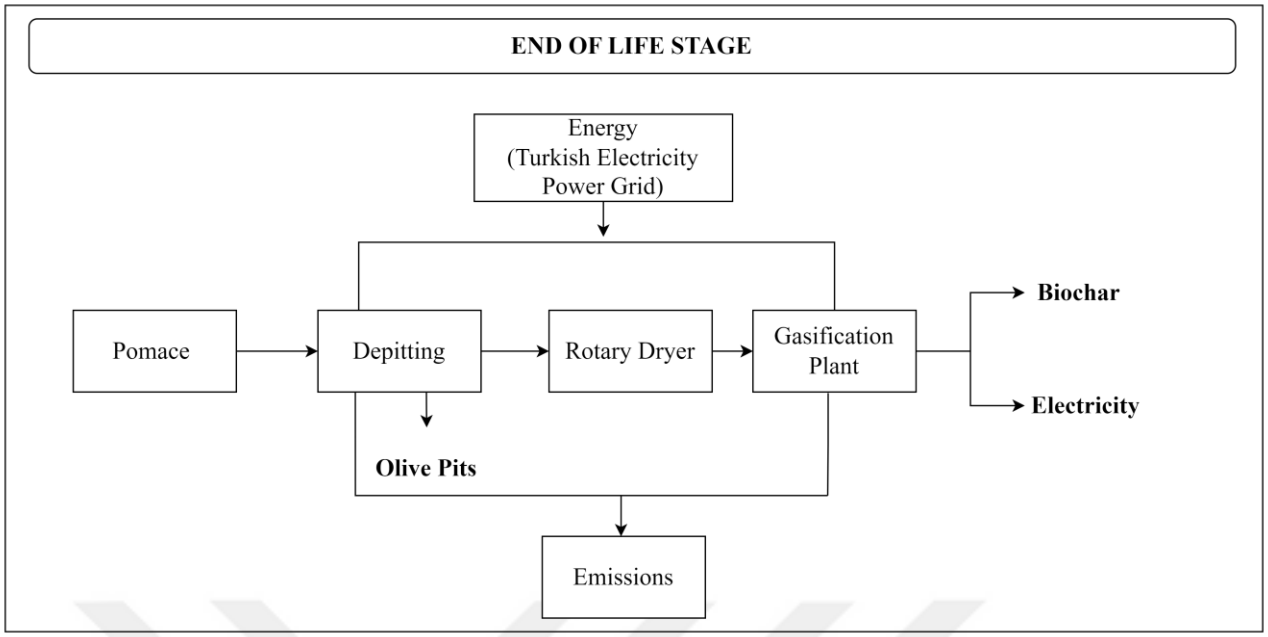

Figure 3.6. Subsystem- 6 (Gasification).

The final subsystem is the pyrolysis unit, which incorporates several key components for the processing of pomace as the raw material. The dryer unit is employed to reduce the moisture content of the biomass, preparing it for efficient pyrolysis. Crusher unit subsequently reduces the biomass into smaller, uniform particles, ensuring consistent processing. After pyrolysis, the cyclon unit separates the solid char from the produced gas. The air heat exchanger and water heat exchanger are used to cool the gases, utilizing air and water as refrigerants, respectively. Finally, the separator unit separates the gaseous products from the liquid tar, thus completing the pyrolysis process (Parascanu et al., 2018).

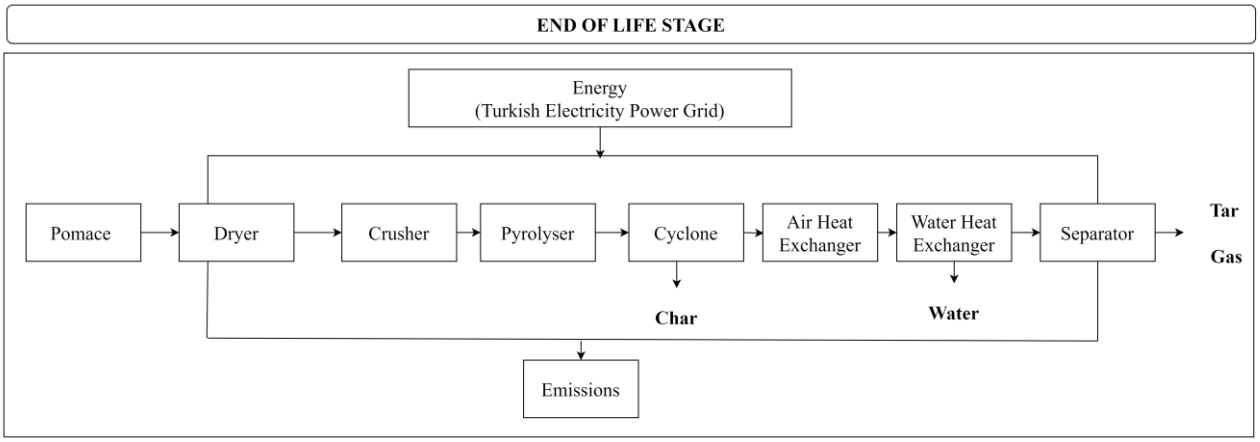

Figure 3.7. Subsystem- 7 (Pyrolysis).

3.1.2. Data Gathering

In raw material extraction stage stage, data were collected from olive orchards in Balıkesir, Türkiye. The orchards cover an area of 50,000 m² with 1000 olive tree and yield 3000 kg of olive oil annually.

To assess fertilizer and pesticide use, site-specific soil analyzes were conducted by the Gönen Chamber of Agriculture Economic Enterprise, which operates under the Turkish Ministry of Agriculture and Forestry. According to the soil analysis, the soil type is classified as clay-loamy, with a pH 7. The available phosphorus (P_2O_5) in the soil has been measured at 4.35 kg/da, and the available potassium (K_2O) at 35.1 kg/da. Based on these findings, it is recommended to apply 1500 grams of 26% CAN fertilizer and 2 kg of DAP fertilizer per tree. Additionally, 50 kg/da of sulfur is advised. For fertilization, it is suggested that 60% of the phosphorus-based fertilizer, 50% of the potassium-based fertilizer, and 30% of the nitrogen-based fertilizer be applied during the initial fertilization, with the remaining quantities applied through drip irrigation. In this study the types and quantities of pesticides applied in the orchards were also determined through these analyses. Additonally, Water usage fuel and electricity consumption on the orchards have not been directly investigated. However, it is established that ground water is utilized and a drip there is a drip irrigation system in the orchards.

The production stage's data used in this study was sourced from an olive oil facility operating in Bursa, Türkiye. These data were generated using 2-phase and 3-phase extraction technology employed at the factory. Furthermore, specific water consumption data per unit were unavailable from the company; therefore, data were sourced from a study conducted by the Ministry of Environment, Urbanization, and Climate Change.

For end of life stage, due to the limited data obtained from the olive oil production facility, relevant literature was consulted to utilize information related to the chemical extraction (Fernández-Lobato, García-Ruiz, et al., 2021), anaerobic digestion (Manthos et al., 2023), gasification (Fernández-Lobato et al., 2022) and pyrolysis (Parascanu et al., 2018).

3.1.3. Scenario Description

Environmental impacts associated with both the current situation and alternative scenarios, as outlined in Table 3.1 comprehensively analyzed the description of scenarios, which enables the assessment of environmental effects across various stages of a VOO's life cycle.

Table 3.1. Scenario Description.

Characteristics	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Scenario F	Scenario G	Scenario H	Scenario I
Projection Year	2023	2023	2023	2023	2023	2030	2030	2053	2053
Pesticides & Fertilizer Usage	Conventional Agriculture	Conventional Agriculture	Conventional Agriculture	Conventional Agriculture	Conventional Agriculture	50% Reduction for Pesticides and fertilizers	50% Reduction for Pesticides and fertilizers	%70 Reduction for Pesticides and fertilizers	%70 Reduction for Pesticides and fertilizers
Extraction Technology	Two Phase Decanter	Three Phase Decanter	Two Phase Decanter	Two Phase Decanter	Two Phase Decanter	Two Phase Decanter	Two Phase Decanter	Two Phase Decanter	Two Phase Decanter
Waste Management	Chemical Extraction	Chemacal Extraction & Anaerobic Digestion	Anaerobic Digestion	Gasification	Pyrolysis	Gasification	Pyrolysis	Gasification	Pyrolysis
Functional Unit	1 kg Unpacked VOO	1 kg Unpacked VOO	1 kg Unpacked VOO	1 kg Unpacked VOO	1 kg Unpacked VOO	1 kg Unpacked VOO	1 kg Unpacked VOO	1 kg Unpacked VOO	1 kg Unpacked VOO

To illustrate scenarios of the study; Scenario A, comprised of Subsystem 1 (raw material extraction stage), 2 (producton stage) and 3 (end of life stage). The olives were cultivated during the raw material extraction stage, while during the production stage, the virgin olive oil (VOO) was produced using a two-phase extractiontechnology. For end of life stage, chemical extraction method with hexane has been chosen for the disposal of pomace. In this process, the pomace is transported from the production facility to a separate extraction plant for processing. As a result, by-products

such as crude olive pomace oil and exhausted olive pomace are generated. These by-products are excluded from the system boundaries and are not considered within the end of life stage of the system.

For both stages, Turkish electricity power grid mix for 2023 is used, which is as follows: 36.3% coal, 21.4% natural gas, 19.6% hydroelectric, 10.4% wind, 5.7% solar, 3.4% geothermal and 3.2% are obtained from other sources (Bağ Güllü et al., 2023).

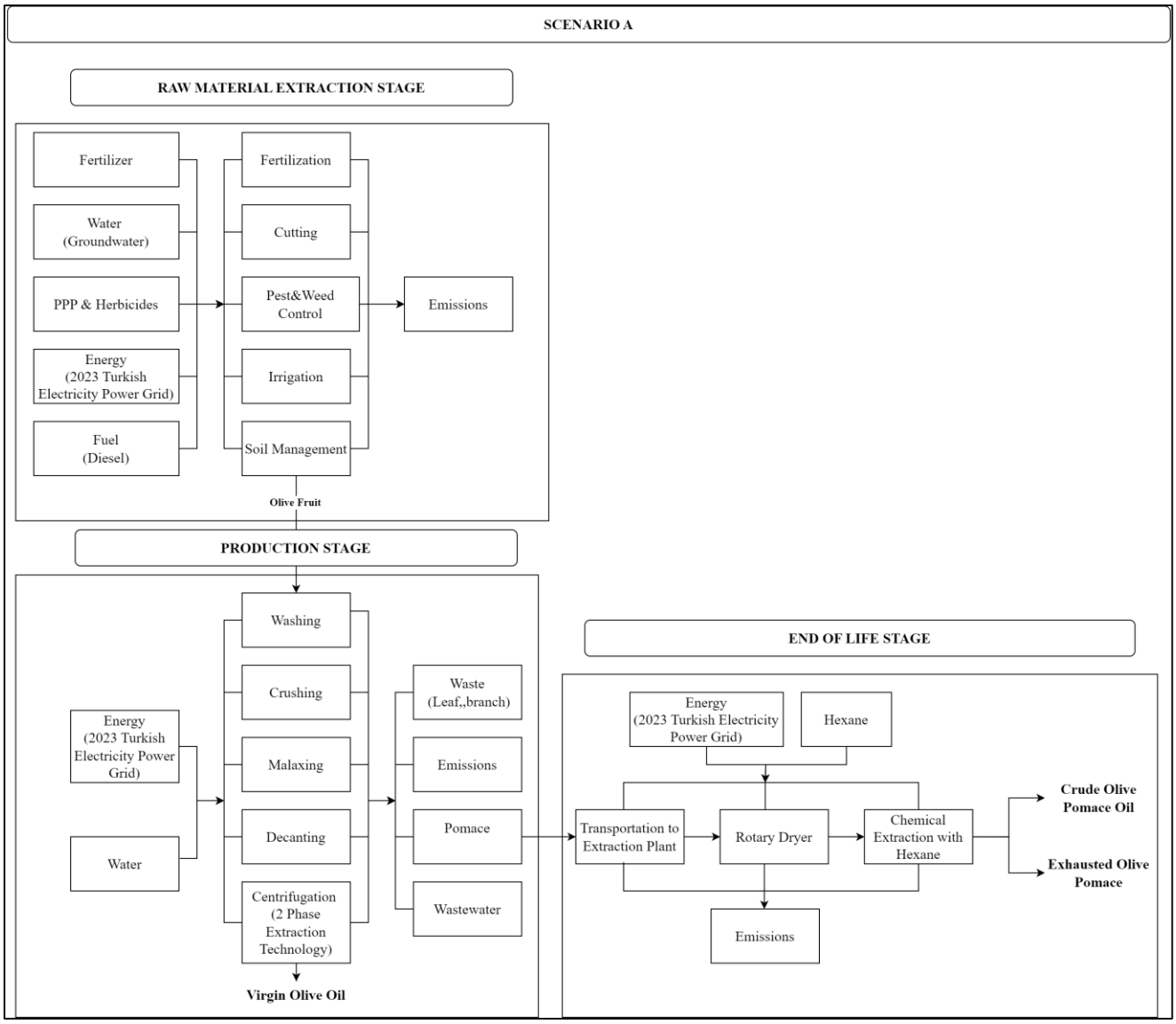

Figure 3.8. System Boundary of Scenario A: (1) Raw material extraction stage, (2) Production stage, (3) End of life stage.

Secondly, Scenario B encompasses Subsystems 1 (raw material extraction stage), 2 (production stage) and 4 (end-of-life stage). The olives are cultivated in the raw material extraction stage, and virgin olive oil is produced using three-phase extraction technology in contrast to the other scenarios. For the disposal of one of the by-products of the three-phase extraction technology, wastewater is

treated using anaerobic digestion. At the end of treatment process, biogas is produced, which is then burned to generate electricity. The generated electricity is subsequently used in wastewater treatment plant. The other by-product pomace, is disposed of in the extraction plant using chemical extraction methodology, as in Scenario A. Additionally, the 2023 Turkish electricity power grid mix is utilized for both stages, as in Scenario A.

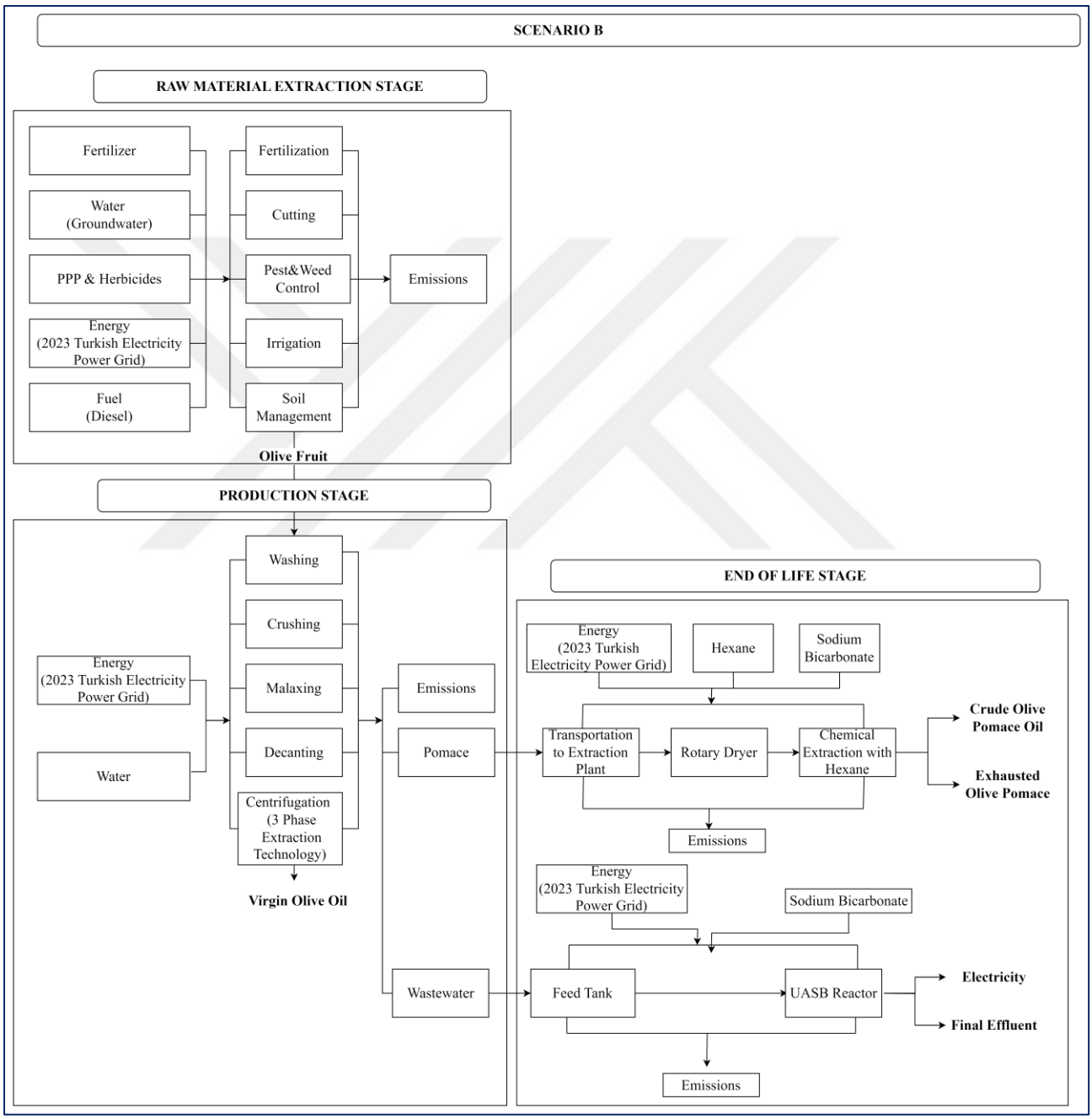

Figure 3.9. System Boundary of Scenario B: (1) Raw material extraction stage, (2) Production stage, (3) End of life stage.

Scenario C involves, Subsystem 1 (raw material extraction stage), 2 (producton stage) and 5 (end of life stage). In this scenario, the 2023 Turkish electricity power grid mix is utilized for both stages, as in Scenario A.

During the end-of-life stage, the pomace treated using anaerobic digestion technology. This technology implemented directly at the site of the production facility, minimizing the environmental impact associated with the transportation of the pomace. Anaerobic digestion converts pomace, into biogas, which can be used forself consumption, helping to power the olive oil production facility during the production stage. The byproduct are not considered within the system boundaries of this analysis.

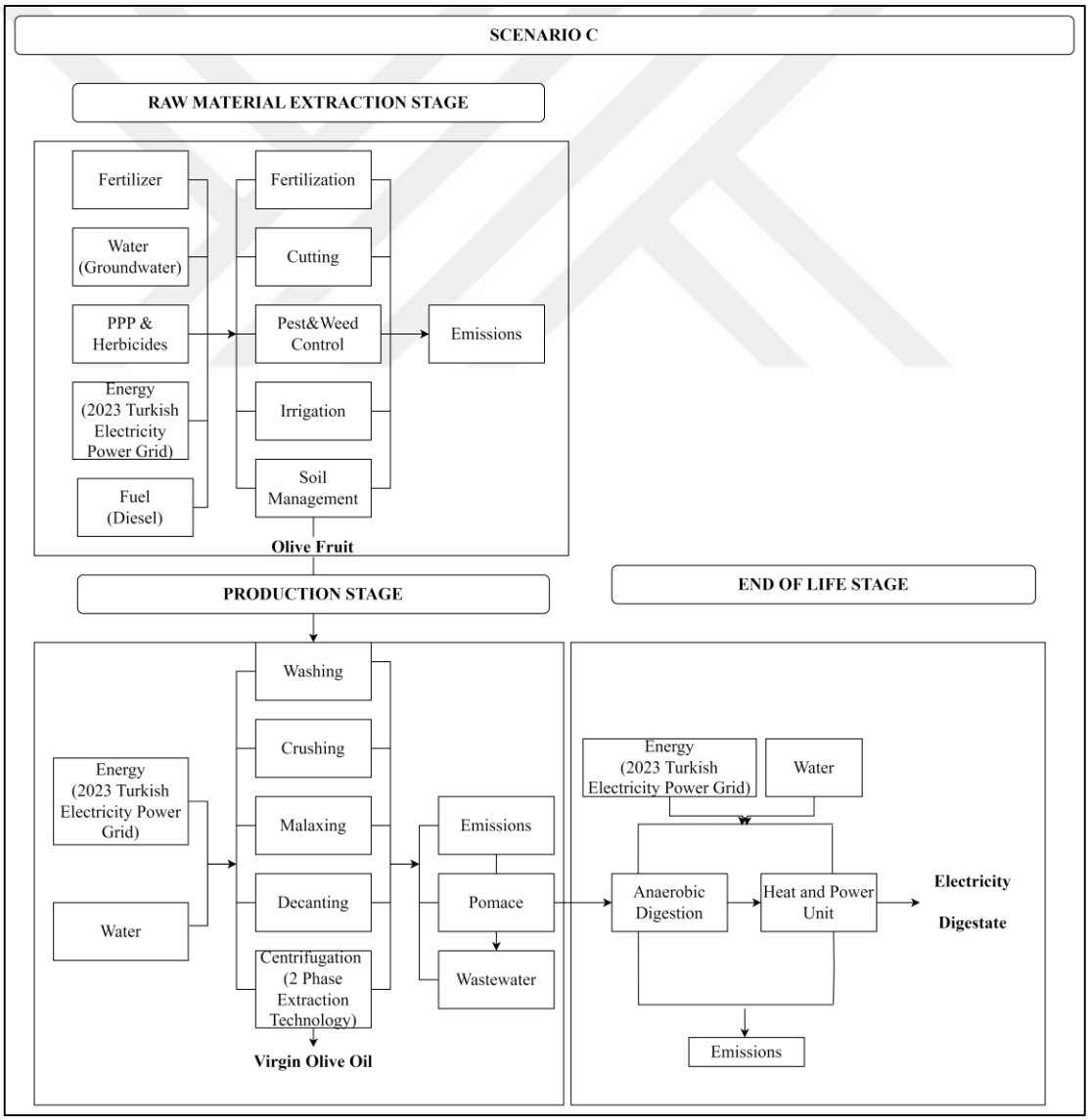

Figure 3.10. System Boundary of Scenario C: (1) Raw material extraction stage, (2) Production stage, (3) End of life stage.

Scenario D involves, Subsystem 1 (raw material extraction stage), 2 (producton stage) and 6 (end of life stage). In this scenario, the 2023 Turkish electricity power grid mix is utilized for both stages, as in Scenario A.

During the end-of-life stage, the pomace generated in the two-phase production process is disposed of using gasification technology. This technology is implemented directly at the site of the production process, thereby minimizing the environmental impact associated with the transportation of the pomace. Furthermore, the gasification plant to facilitate energy generation which utilized subsequently in olive oil production facility (production stage) and gasification plant (end of life stage). However, the by-products of the end-of-life stage, namely olive pits and biochar, have not been considered within the system boundaries.

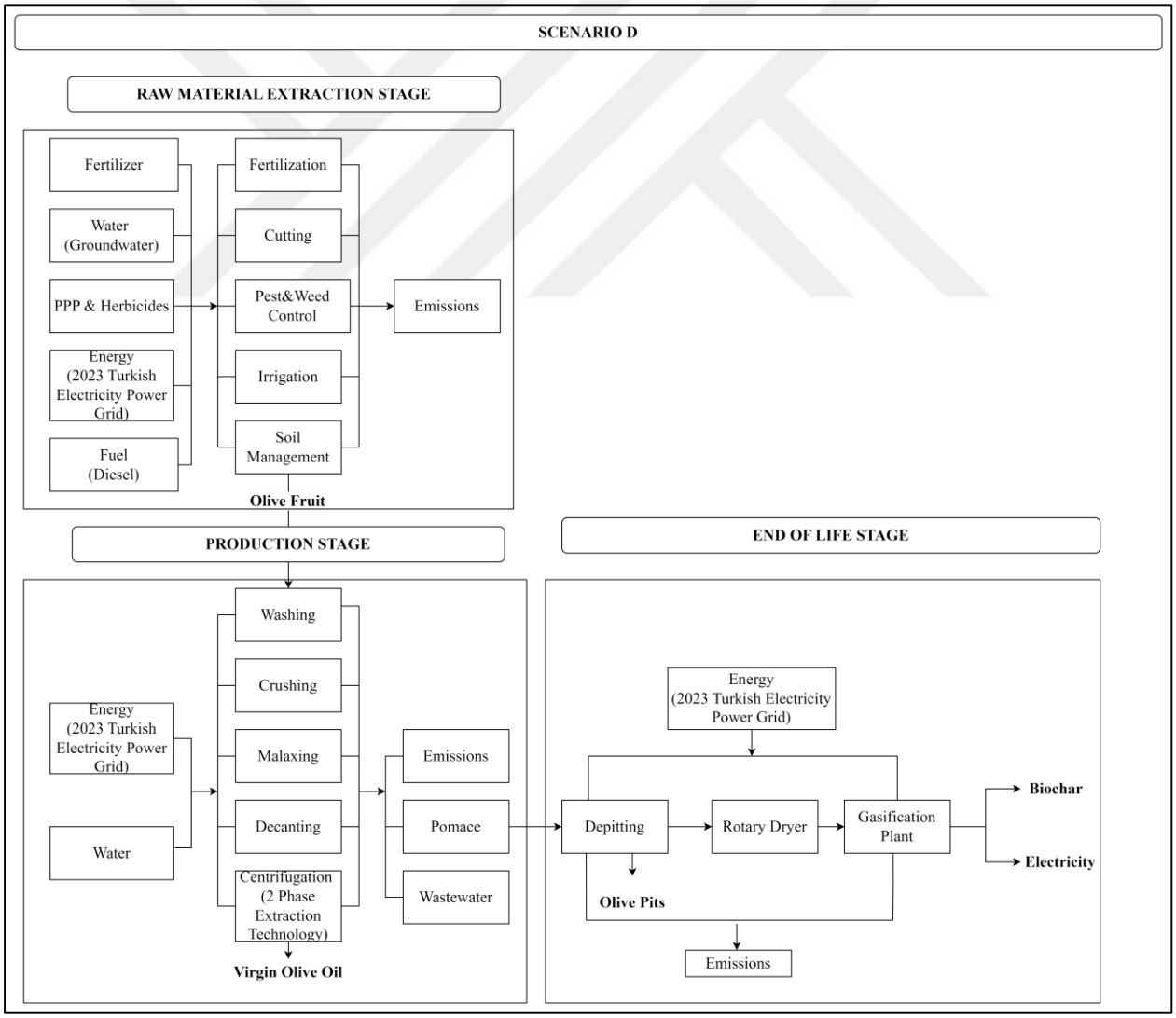

Figure 3.11. System Boundary of Scenario D: (1) Raw material extraction stage, (2) Production stage, (3) End of life stage.

Scenario E, involves Subsystem 1 (raw material extraction stage), 2 (producton stage) and 7 (end of life stage). In this scenario, the 2023 Turkish electricity power grid mix is utilized for both stages, as in Scenario A.

Unlike the other scenarios, this Scenario Donsiders the treatment of pomace in a pyrolysis facility during the end-of-life stage. It is assumed that the pyrolysis facility is located at the same site as the production stage, thereby minimizing the environmental impact associated with transportation. Additionaly, thanks to the pyrolysis plant the drying unit met their energy requirement. The by-products of the pyrolysis process, including char, tar and gas are not included within the system boundaries.

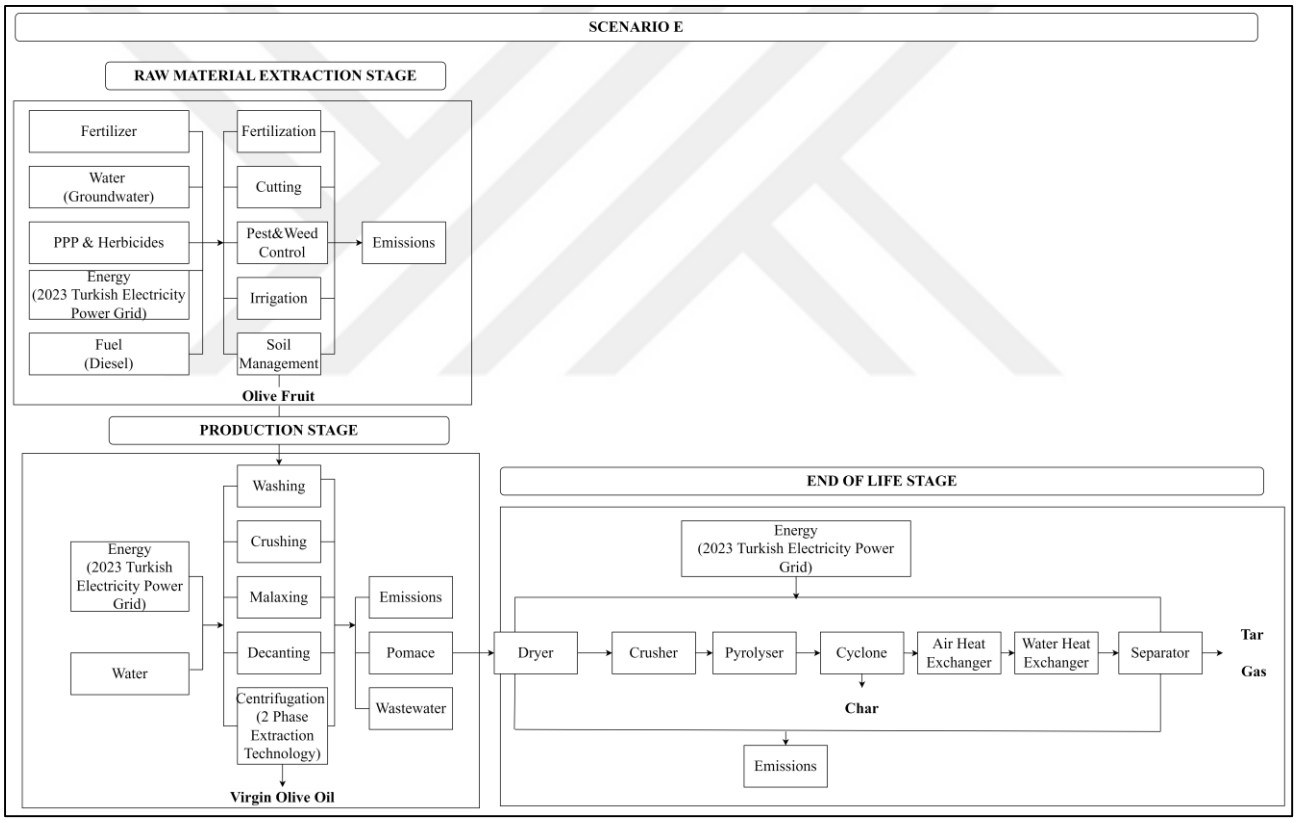

Figure 3.12. System Boundary of Scenario E: (1) Raw material extraction stage, (2) Production stage, (3) End of life stage.

Scenario F involves, Subsystem 1 (raw material extraction stage), 2 (producton stage) and 6 (end of life stage). The Scenario Iave been developed based on Türkiye's 2030 Climate Change Mitigation and Adaptation Strategy and Energy Efficiency 2030 Strategy and 2nd National Energy Efficiency Action Plan. Based on the strategies, Türkiye aims to achieve its net-zero emissions target by 2053 by increasing the share of renewable energy in its energy mix. In this context, the Turkish electricity

grid mix in 2030 is projected to consist of 16% coal, 23% natural gas, 20% hydropower, 15% wind, 12% solar, 3% geothermal, 2% biomass, and 9% nuclear energy (Bağ Güllü et al., 2023) . In this scenario, projected Turkish electricity grid mix for 2030 is used for both stages.

Additionally, in line with the EU Green Deal, The Farm to Fork Strategy, a reduction in fertilizer usage has been incorporated into the Scenario D, particularly during the fertilization phase of the raw material extraction stage. This approach aligns with the European Commission's objective to achieve a 50% reduction in the use and associated risks of chemical and more hazardous pesticides by 2030, as outlined in the EU's Farm to Fork Strategy (European Commission).

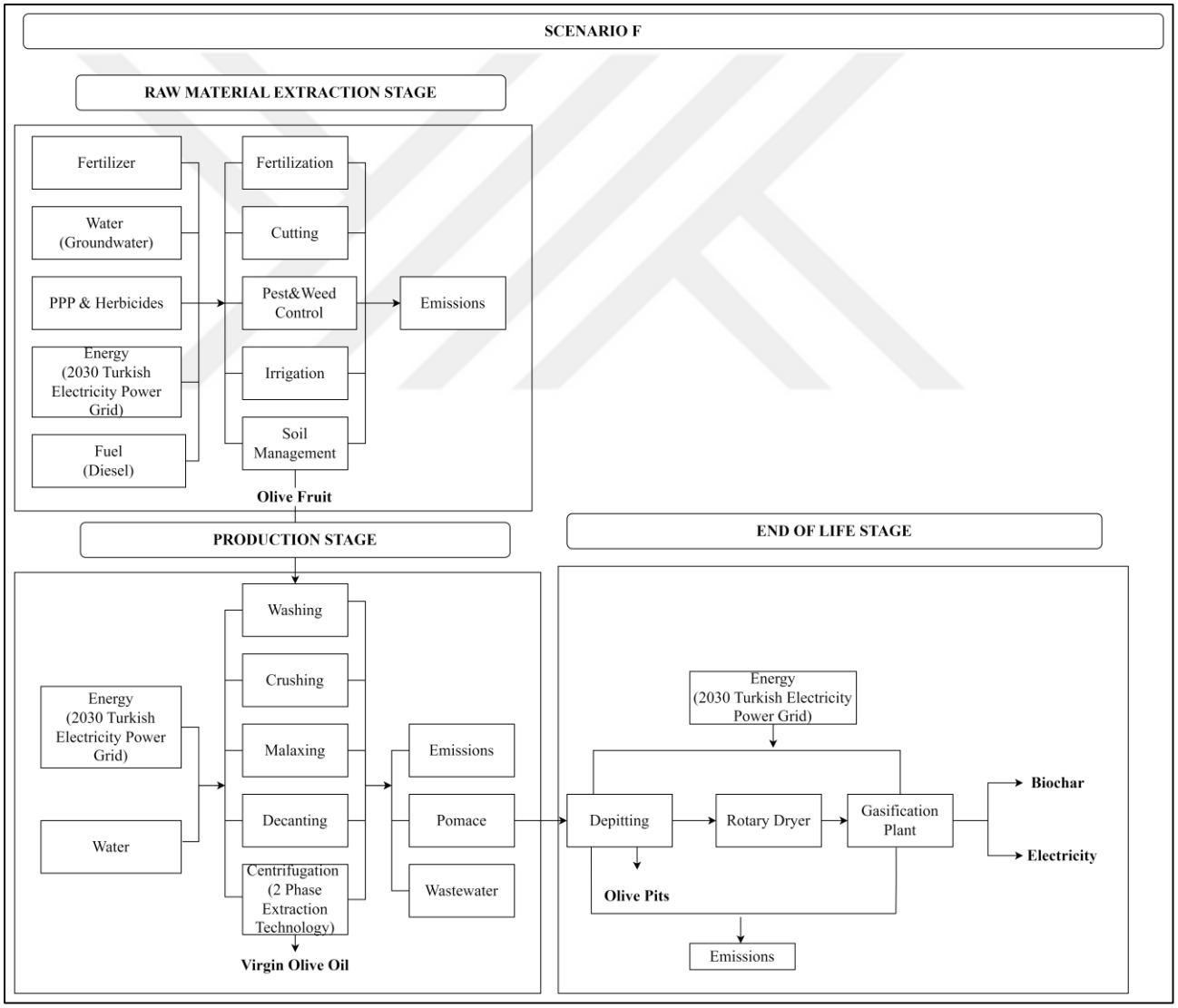

Figure 3.13. System Boundary of Scenario F: (1) Raw material extraction stage, (2) Production stage, (3) End of life stage.

Scenario G, involves Subsystem 1 (raw material extraction stage), 2 (producton stage) and 7 (end of life stage). This Scenario Iave been developed based on Türkiye's 2030 Climate Change Mitigation and Adaptation Strategy and Energy Efficiency 2030 Strategy and 2nd National Energy Efficiency Action Plan similar to Scenario F. Therefore, in both scenarios and both stages, the Turkish electricity power grid mix for 2030 is used, which is as follows: 16% coal, 23% natural gas, 20% hydropower, 15% wind, 12% solar, 3% geothermal, 2% biomass, and % nuclear energy (Bağ Güllü et al., 2023).

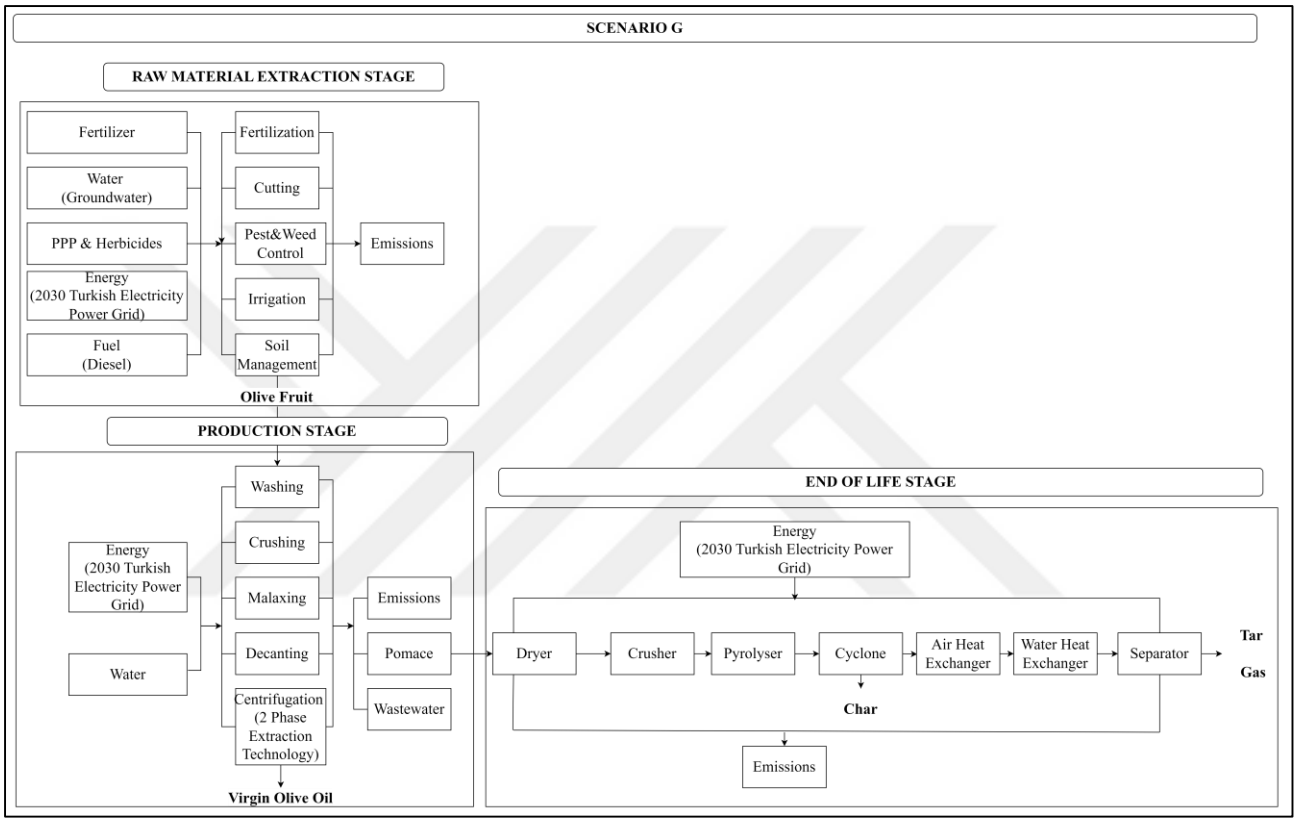

Figure 3.14. System Boundary of Scenario G: (1) Raw material extraction stage, (2) Production stage, (3) End of life stage.

Scenario H, includes Subsystem 1 (raw material extraction stage), Subsystem 2 (production stage), and Subsystem 6 (end-of-life stage). While Scenario H bears similarities to Scenario F, it only differentiates itself by incorporating energy sources aligned with Türkiye's 2053 Net Zero Emission Target. This approach aims to reflect the Türkiye’s commitment to Net Zero Target by 2053. Specifically, by 2053, the electricity power grid mix is projected to consist of 38% solar energy, 39% wind energy, 3% biomass, 9% hydroelectric, 4% nuclear energy, 1% gases with carbon capture and storage (CCS), and 4% natural gas. Furthermore, it is anticipated that coal-based electricity production will be entirely phased out after 2035, marking a significant step towards decarbonization and the transition to renewable energy sources.

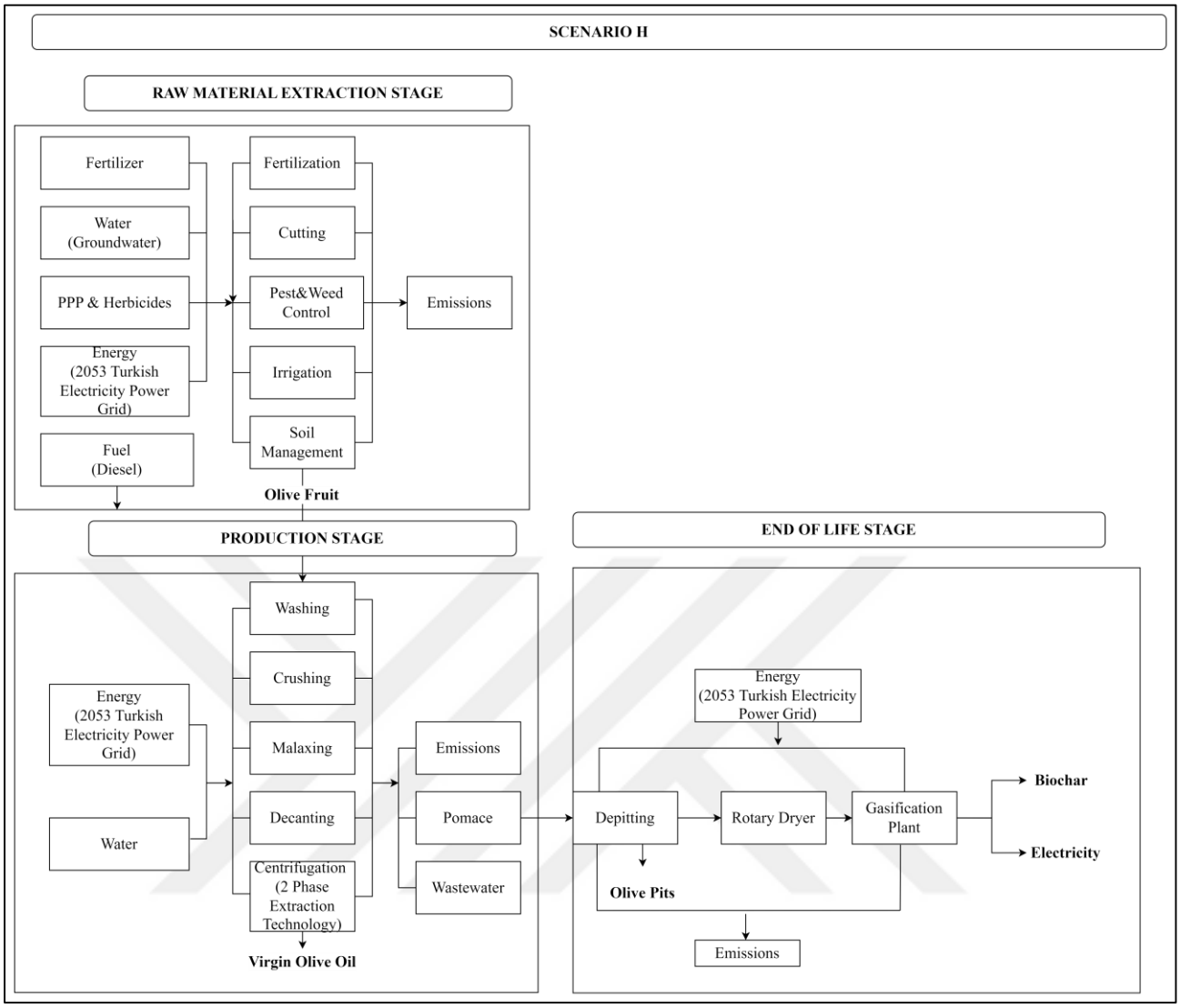

Figure 3.15. System Boundary of Scenario H: (1) Raw material extraction stage, (2) Production stage, (3) End of life stage

Scenario I involves, Subsystem 1 (raw material extraction stage), 2 (producton stage) and 7 (end of life stage). Scenario I shares similarities with Scenario G, it only distinguishes itself by incorporating energy sources aligned with Türkiye's 2053 Net Zero Emission Target. Based on the targets, Turkish electricity power grid mix is as follows: 16% coal, 23% natural gas, 20% hydropower , 15% wind, 12% solar, 3% geothermal, 2% biomass and 9% obtained from nuclear energy (Bağ Güllü et al., 2023).

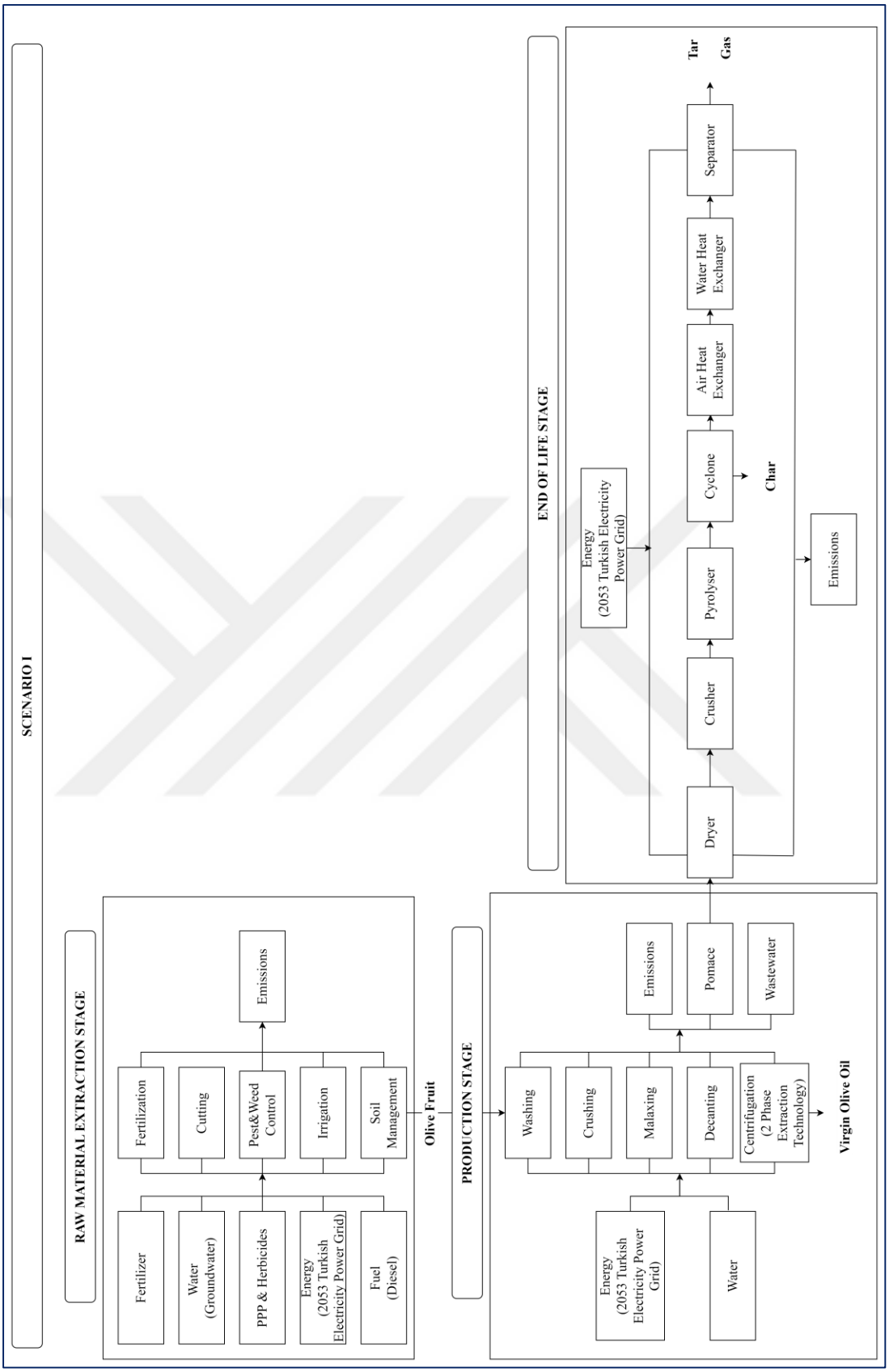

Figure 3.16. System Boundary of Scenario I: (1) Raw material extraction stage, (2) Production stage, (3) End of life stage

In Table 3.2 Turkish electric power grid mix is presented for each scenario.

Table 3.2. Scenario Basis: Turkish Electric Power Grid Mix.

Characteristics	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Scenario F	Scenario G	Scenario H	Scenario I
Projection Year	2023	2023	2023	2023	2023	2030	2030	2053	2053
Extraction Technology	Two Phase Decanter	Three Phase Decanter	Three Phase Decanter	Two Phase Decanter	Two Phase Decanter	Two Phase Decanter	Two Phase Decanter	Two Phase Decanter	Two Phase Decanter
Coal and Lignite (%)	36.3	36.3	36.3	36.3	36.3	16	16	-	-
Natural Gas (%)	21.4	21.4	21.4	21.4	21.4	23	23	4	4
Hydropower (%)	19.6	19.6	19.6	19.6	19.6	20	20	9	9
Wind Power (Onshore and Offshore) (%)	10.4	10.4	10.4	10.4	10.4	15	15	39	39
Solar Energy (%)	5.7	5.7	5.7	5.7	5.7	12	12	38	38
Geothermal Energy (%)	3.4	3.4	3.4	3.4	3.4	3	3	2	2
Biomass (%)	-	-	-	-	-	2	2	3	3
Nuclear Energy (%)	-	-	-	-	-	4	4	9	9

3.2. Life Cycle Inventory Analysis and the Key Assumptions

The life cycle inventory (LCI) analysis denotes the pivotal stage wherein data concerning the input and output of a product system throughout its life cycle are systematically collected and calculated (ISO 14044, 2006). The section provides a detailed explanation of the data collected, computed, and the underlying assumptions for each subsystem and scenario within the study.

In this study, the required data for the raw material extraction stage stage, including soil analysis, were obtained from a 50,000 m² olive orchard located in Balıkesir, Türkiye, and also from literature. Furthermore, data on the production stage was collected from an olive oil production facility located in Bursa, Türkiye and were further enriched with information derived from literature. moreover, the necessary data for the end of life stage were sourced from literature. The required data and their sources are summarized in Table 3.3.

Table 3.3. The Inventory Data Sources for The Subsystems.

Stage	Processes	Required Data	Data Sources
Raw material extraction stage stage	Irrigation	Water Consumption, Electricity consumption	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
	Soil Management	Fuel consumption	GaBi 8.0 software, Survey (Orchards located in Balıkesir)
	Plant protection products (PPP)& Herbicides	Water consumption, pesticides and herbicides usage	GaBi 8.0 software, Survey (Orchards located in Balıkesir)
	Harvesting	Fuel consumption	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
	Cutting	Fuel consumption	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
	Fertilizers	Fertilizer consumption, water consumption	GaBi 8.0 software, Survey (Orchads located in Balıkesir)
Production stage	Washing	Electricity consumption, water consumption	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye
	Crushing	Electricity consumption	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye
	Malaxing	Electricity consumption, resource consumption	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye
	Decanting	Electricity consumption	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye
	Centrifugation	Electricity consumption, water consumption	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye, Literature review
End of life stage	Chemical Extraction	Hexane consumption, electricity consumption,	GaBi 8.0 software, Scientific Papers (Fernández-Lobato, García-Ruiz, et al., 2021)
End of life stage	Anaerobic Digestion for Olive Mill Wastewater	Sodium bicarbonate consumption, Electricity consumption, Biogas generation, Electricity generation	GaBi 8.0 software, Scientific Papers (Manthos et al., 2023)
End of life stage	Anaerobic Digestion for Pomace	Water consumption, Electricity consumption, Biogas generation, Electricity generation	GaBi 8.0 software, Scientific Papers (Batuecas et al., 2019)
End of life stage	Gasification	Electricity consumption, biochar generation, electricity generation	GaBi 8.0 software, Scientific Papers (Fernández-Lobato et al., 2022), (Ramos & Ferreira, 2022)
End of life stage	Pyrolysis	Electricity consumption, char, ,tar and gas generation	GaBi 8.0 software, Scientific Paper (Ramos & Ferreira, 2022)

Soil management in olive production encompasses various agricultural machinery and operations utilized throughout the raw material extraction stage stage, each contributing to fuel consumption. The harvesting process involves machinery that shakes the olive trees, causing the olives to fall into nets placed beneath the trees. These nets are then systematically collected by machinery and transported to the production facility for virgin olive oil extraction. Irrigation plays a critical role in maintaining the olive trees, with groundwater being pumped to the trees, a process that requires electricity sourced primarily from the Turkish electricity power grid. Fertilizer application is conducted based on soil analysis specific to the orchard, ensuring that the proper quantities of nutrients, typically phosphorus, potassium, and nitrogen, are applied either directly to the soil using a broadcaster or mixed with irrigation water. In some cases, fertilizers may also contain ammonium, potassium, and urea. The application of plant protection products (PPP), including fungicides, insecticides, and herbicides, is carried out at various times throughout the year to protect the trees. These chemicals are applied either directly to the soil, mixed with irrigation water, or sprayed onto the plants using field sprayers. The cutting phase involves the use of fuel-powered machinery, including chainsaws to trim tree branches, as well as branch windrowers that cut and gather low-hanging branches, adding them to the organic material for disposal or further processing. Typically, the cutting process takes place once a year, following the harvest in irrigated olive orchards.

The data required for the processes involved in the production stage were obtained from a production facility located in Bursa, Türkiye. It is assumed that there is a distance of 100 km between the olive orchard and the production facility. This facilityconsist of several which are contributing to the extraction of the virgin olive oil.

The first unit is washing, where small branches and leaves are removed from the olives, and their surface dust is cleaned. The next step crushing, involves the mechanical breakdown of the olives, including their pits, into a paste. During malaxing, this crushed paste is further mixed, and its temperature is gently increased to optimize the extraction process. In the decanting unit, the oil is separated from the olive pomace, the solid residue left after oil extraction. Finally, in the centrifugation stage, the remaining liquid paste is subjected to centrifugal forces to separate any residual oil from the solid remnants, ensuring the maximum yield of olive oil.

Table 3.4. Required Data for Subsystems for FU.

Stage	Processes	Input / Output Data	Value	Selected Flow from GaBi 8.0	Data Sources
Raw Material Extraction Stage	Irrigation	Water Consumption	0.506 m^3	Ground water [Water]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
		Electricity consumption	0.498 kW/h	Electricity [Electric power]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
	Soil Management	Fuel consumption	0.06 L	Diesel [Refinery products]	GaBi 8.0 software, Survey (Orchads located in Balıkesir)
	Plant protection products (PPP)& Herbicides	Water consumption	0.004 m^3	Ground water [Water]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
		Pesticides	0.0546	Pesticides, unspecified [Pesticides to agricultural soil]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
	Harvesting	Fuel consumption	0.0215 L	Diesel [Refinery products]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
	Cutting	Fuel consumption	0.0027 L	Diesel [Refinery products]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
	Fertilizers	Water consumption	0.506 m^3	Ground water [Water]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
		Urea	0.665 kg	Carbamide (urea) [Organic intermediate products]	GaBi 8.0 software, Survey (Orchards located in Balıkesir)
		Phosphorus Pentoxide	0.072 kg	Phosphorus-pent-oxide [Inorganic intermediate products]	GaBi 8.0 software, Survey (Orchards located in Balıkesir)
		Potassium sulfate	0.585 kg	Potassium sulphate (agriculture) [Agro chemicals]	GaBi 8.0 software, Survey (Orchads located in Balıkesir)
		Diamonium Phosphate (DAP)	0.667 kg	Diammonium phosphate (agrarian) [Agro chemicals]	GaBi 8.0 software, Survey (Orchards located in Balıkesir)
		Calcium Ammonium nitrate	0.5 kg	Calcium ammonium nitrate (agrarian) [Agro chemicals]	GaBi 8.0 software, Survey (Orchards located in Balıkesir)
		Ammonium Sulphate	0.833 kg	Ammonium sulphate [Inorganic intermediate products]	GaBi 8.0 software, Survey (Orchads located in Balıkesir)
Production Stage	Washing	Electricity consumption	0.005 kW/h	Electricity [Electric power]	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye

		Water consumption	0.0007 m^3	Water for industrial use	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye
		Wastewater Generated	0.0007 m^3	Water (waste water, untreated)	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye
		Solid Waste	0.35 kg	Waste (solid) [Waste for disposal]	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye
	Crushing	Electricity consumption	0.031 kW/h	Electricity [Electric power]	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye
	Malaxing	Electricity consumption	0.029 kW/h	Electricity [Electric power]	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye
		Resource consumption	0.0024 Nm^3	Natural gas Türkiye [Natural gas (resource)]	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye
	Decanting	Electricity consumption	0.0087 kW/h	Electricity [Electric power]	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye
		Generation of pomace with high moisture content	2.55 kg	Pomace [Waste for disposal]	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye
	Centrifugation	Electricity consumption	0.064 kW/h	Electricity [Electric power]	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye
		Wastewater Generation	0.00035 m^3	Water (waste water, untreated) [Production residues in life cycle]	GaBi 8.0 software, Survey of the Olive Oil Production Facility in Türkiye
End of Life Stage	Chemical Extraction	Hexane Consumption	0.006 kg	Hexane (n-hexane) [Organic intermediate products]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022) and (Fernández-Lobato, García-Ruiz, et al., 2021)
		Dried Olive Pomace Generation	1.136 kg	Dried Olive Pomace [Waste for disposal]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022) and (Fernández-Lobato, García-Ruiz, et al., 2021)
		Exhausted Pomace Generation	0.963 kg	Exhausted Olive Pomace [Waste for disposal]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022) and (Fernández-Lobato, García-Ruiz, et al., 2021)
		Electricity Consumption	0.076 kg	Electricity [Electric power]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022) and (Fernández-Lobato, García-Ruiz, et al., 2021)
		Olive Pits Generation	0.384 kg	Olive Pits [Waste for disposal]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022) and (Fernández-

					Lobato, García-Ruiz, et al., 2021)
		Crude Pomace Oil Generation	0.173 kg	Exhausted Olive Pomace [Others]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022) and (Fernández-Lobato, García-Ruiz, et al., 2021)
	Gasification	Dried Olive Pomace Generation	0.75 kg	Dried Olive Pomace [Waste for disposal]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022)
		Olive Pits Generation	0.15 kg	Olive Pits [Waste for disposal]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022)
		Biochar Generation	0.42 kg	Biochar [Waste for disposal]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022)
		Electricity Generation	1.96 kWh	Electricity [Electric power]	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022)
	Pyrolysis	Electricity Consumption	0.12 MJ	Electricity [Electric power]	GaBi 8.0 software, Scientific Paper (Parascanu et al., 2018)
		Air Generation	2.55 kg	Air [Operating materials]	GaBi 8.0 software, Scientific Paper (Parascanu et al., 2018)
		Tar Generation	1.65 kg	Tar [Particles to fresh water]	GaBi 8.0 software, Scientific Paper (Parascanu et al., 2018)
		Gas Generation	0.28 kg	Gas[Operating materials]	GaBi 8.0 software, Scientific Paper (Parascanu et al., 2018)
		Char Generation	0.53 kg	Char [Waste for disposal]	GaBi 8.0 software, Scientific Paper (Parascanu et al., 2018)
	Anaerobic Digestion for OMW	Water Consumption	0.0087 m^3	Water for industrial use [Operating materials]	GaBi 8.0 software, Scientific Paper (Manthos et al., 2023)
		Sodium Bicarbonate Consumption	0.000011 kg	Sodium bicarbonate [Inorganic intermediate products]	GaBi 8.0 software, Scientific Paper (Manthos et al., 2023)
		Energy Consumption	0.0012 MJ	Electricity [Electric power]	GaBi 8.0 software, Scientific Paper (Manthos et al., 2023)
		Biogas Generation	0.13 kg	Biogas [Biomass fuels]	GaBi 8.0 software, Scientific Paper (Manthos et al., 2023)
	Anaerobic Digestion for Pomace Management	Water Consumption		Water for industrial use [Operating materials]	GaBi 8.0 software, Scientific Papers (Batuecas et al., 2019
		Energy Consumption		Electricity [Electric power]	GaBi 8.0 software, Scientific Papers (Batuecas et al., 2019
		Biogas Generation		Biogas [Biomass fuels]	GaBi 8.0 software, Scientific Papers (Batuecas et al., 2019

The following assumptions have been made during the preparation of the LCI.

Table 3.5. Key Assumptions.

Key Assumption	Activity	Resource
Transportation of olive	The distance between the olive orchards and the olive production facility is accepted as 100 km.	
Transportation of pomace	Olive oil production plant and pyrolysis and gasification plants are situated in the same location, therefore pomace transportation is not considered. On the other hand, the distance between olive oil production plant and chemical extraction facility is accepred 50 km.	(Ramos & Ferreira, 2022)
Olive to olive oil	5 kg of olives are needed to produce 1 kg of virgin olive oil	(Batuecas et al., 2019).
Waste	Pruning waste, waste from orchards, is commonly distributed to local farmers within a 1 km radius to be used as animal feed and dried to serve as an energy source	(Fernández-Lobato, López-Sánchez, et al., 2021)
Emissions	Emissions to air and water are calculated using the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories. In the raw material extraction stage, similar to the production stage, emissions are calculated following the guidelines established by PEFCR. Also, based on Brentrup et al,(2000) and Özilgen & Sorgüven, (2011) studies emissions are assumed.	(Brentrup et al, 2000) (Özilgen & Sorgüven, 2011)
End of life of by-products	End use and end of life for refined olive oil, char, tar, and syngases are excluded.	(Ramos & Ferreira, 2022)
Electricity Mixture	The electricity generated from gasification and biogas technologies has the same composition as the electricity power generation mix defined in the scenario.	

Table 3.6. Inventory Analysis for Substage Basis for FU.

LCA Stage	Process Category	Unit Operation	Input/ Output	Parameter	Unit	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Scenario F	Scenario G	Scenario H	Scenario I	Data Sources
Raw Material Extraction Stage	Agricultural Activity	Irrigation	Electricity Consumption	Electrical Energy	kWh	0.498	0.498	0.498	0.498	0.498	0.498	0.498	0.498	0.498	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
			Water Consumption	Groundwater	m^3	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
Raw Material Extraction Stage	Agricultural Activity	Fertilization	Fertilization Consumption	Urea	kg	0.665	0.665	0.665	0.328	0.019	0.328	0.019	0.665	0.019	GaBi 8.0 software, Survey
				Diammonium Phosphate	kg	0.667	0.667	0.667	0.328	0.019	0.328	0.019	0.667	0.019	GaBi 8.0 software, Survey
				Phosphorus Pentooxide	kg	0.072	0.072	0.072	0.036	0.022	0.036	0.022	0.036	0.022	GaBi 8.0 software, Survey
				Potassium Sulphate	kg	0.585	0.585	0.585	0.289	0.176	0.289	0.176	0.289	0.176	GaBi 8.0 software, Survey

				Ammonium Sulphate	kg	0.833	0.833	0.833	0.417	0.249	0.417	0.249	0.417	0.249	GaBi 8.0 software, Survey
			Water Consumption	Groundwater	m^3	0.506	0.506	0.506	0.506	0.506	0.506	0.506	0.506	0.506	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
Raw Material Extraction Stage	Agricultural Activity	Pest and Weed Control	PPP and Weed Consumption	PPP and Weed	kg	0.055	0.055	0.055	0.028	0.164	0.028	0.164	0.028	0.164	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
			Water Consumption	Water	m^3	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
Raw Material Extraction Stage	Agricultural Activity	Soil Management	Fuel Consumption	Diesel	L	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)

Raw Material Extraction Stage	Agricultural Activity	Cutting	Fuel Consumption	Diesel	L	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
Raw Material Extraction Stage	Agricultural Activity	Harvesting	Fuel Consumption	Diesel	L	0.0215	0.0215	0.0215	0.0215	0.0215	0.0215	0.0215	0.0215	0.0215	GaBi 8.0 software, Scientific Paper (Fernández-Lobato, López-Sánchez, et al., 2021)
Production Stage	Industrial Activity	Washing	Electricity Consumption	Electrical Energy	kWh	0.0005	0.0015	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	GaBi 8.0 software, Survey
			Water Consumption	Water	m^3	0.0007	0.72	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	GaBi 8.0 software, Survey
			Wastewater Generation	OMW	m^3	0.0007	0.72	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	GaBi 8.0 software, Survey
			Wastewater Generation	Solid Waste	kg	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	GaBi 8.0 software, Survey
Production Stage	Industrial Activity	Crushing	Electricity Consumption	Electrical Energy	kWh	0.0031	0.009	0.0031	0.0031	0.0031	0.0031	0.0031	0.0031	0.0031	GaBi 8.0 software, Survey
Production Stage	Industrial Activity	Malaxing	Electricity Consumption	Electrical Energy	kWh	0.0029	0.0083	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	GaBi 8.0 software, Survey
Production Stage			Natural Gas Consumption	Natural Gas	Nm^3	0.0024	0.0018	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	GaBi 8.0 software, Survey

Production Stage	Industrial Activity	Decanting	Electricity Consumption	Electrical Energy	kWh	0.0087	0.0745	0.0087	0.0087	0.0087	0.0087	0.0087	0.0087	0.0087	GaBi 8.0 software, Survey
			Water Consumption	Water	m^3	-	3	3	-	-	-	-	-	-	GaBi 8.0 software, Survey
			Pomace Generation	Pomace	kg	4.5	2.55	4.5	4.5	4.5	4.5	4.5	4.5	4.5	GaBi 8.0 software, Survey
Production Stage	Industrial Activity	Centrifugation	Electricity Consumption	Electrical Energy	kWh	0.0065	0.0553	0.0065	0.0065	0.0065	0.0065	0.0065	0.0065	0.0065	GaBi 8.0 software, Survey
			OMW Generation	OMW	m^3	0.0004	0.45	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	GaBi 8.0 software, Survey
End of Life Stage	Wastewater Generation	OMW Generation	OMW Characterization	COD before treatment	kg/m^3	-	127.23	-	-	-	-	-	-	-	GaBi 8.0 software, (Manthos et al., 2023)
End of Life Stage	Wastewater Generation	OMW Generation	OMW Characterization	COD after treatment	kg/m^3	-	47.41	-	-	-	-	-	-	-	GaBi 8.0 software, (Manthos et al., 2023)
End of Life Stage	Wastewater Management Activity	Anaerobic Digestion	Water Consumption	Water	m^3	-	0.0087	-	-	-	-	-	-	-	GaBi 8.0 software, Scientific Paper (Manthos et al., 2023)
			Sodium Bicarbonate Consumption	Sodium Bicarbonate	kg	-	0.42	-	-	-	-	-	-	-	GaBi 8.0 software, Scientific Paper (Manthos et al., 2023)
			Energy Consumption	Electrical Energy	MJ	-	6.3	-	-	-	-	-	-	-	GaBi 8.0 software, Scientific Paper

															(Manthos et al., 2023)
			Biogas Generation	Biogas	kg	-	1.12	-	-	-	-	-	-	-	GaBi 8.0 software, Scientific Paper (Manthos et al., 2023)
			Electriciy Generated	Electricity	MJ	-	4.87	-	-	-	-	-	-	-	GaBi 8.0 software, Scientific Paper (Manthos et al., 2023)
	Pomace Management Activity	Anaerobic Digestion	Water Consumption	Water	L	-	-	9	-	-	-	-	-	-	GaBi 8.0 software, Scientific Papers (Batuecas et al., 2019
	Pomace Management Activity	Anaerobic Digestion	Biogas Generation	Biogas	L	-	-	9.45	-	-	-	-	-	-	GaBi 8.0 software, Scientific Papers (Batuecas et al., 2019
	Pomace Management Activity	Anaerobic Digestion	Electriciy Generated	Electricity	kWh	-	-	0.37	-	-	-	-	-	-	GaBi 8.0 software, Scientific Papers (Batuecas et al., 2019
	Pomace Management Activity	Chemical Extraction	Hexane Consumption	Hexane	kg	0.006	0.003	-	-	-	-	-	-	-	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022) and

															(Fernández-Lobato, García-Ruiz, et al., 2021)
			Dried Olive Pomace Generation	Dried Pomace	kg	1.136	0.644	-	-	-	-	-	-	-	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022) and (Fernández-Lobato, García-Ruiz, et al., 2021)
			Exhausted Pomace Generation	Exhausted Pomace	kg	0.963	0.546	-	-	-	-	-	-	-	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022) and (Fernández-Lobato, García-Ruiz, et al., 2021)
			Electricity Consumption	Electrical Energy	MJ	0.076	0.043	-	-	-	-	-	-	-	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022) and (Fernández-

															Lobato, García-Ruiz, et al., 2021)
			Crude Pomace Oil Generation	Crude Pomace Oil	kg	0.173	0.098	-	-	-	-	-	-	-	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022) and (Fernández-Lobato, García-Ruiz, et al., 2021)
	Pomace Management Activity	Gasification	Dried Olive Pomace Generation	Dried Pomace	kg	-	-	-	0.75	-	0.75	-	0.75	-	GaBi 8.0 software, Scientific Paper (Ramos & Ferreira, 2022)
			Biochar Generation	Biochar	kg	-	-	-	0.42	-	0.42	-	0.42	-	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022)
			Energy Consumption	Electrical Energy	kWh	-	-	-	0.15	-	0.15	-	0.15	-	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022)

			Electricity Generation	Electricity	kWh	-	-	-	0.88	-	0.88	-	0.88	-	GaBi 8.0 software, Scientific Paper (Fernández-Lobato et al., 2022)
	Pomace Management Activity	Pyrolysis	Energy Consumption	Electrical Energy	kWh	-	-	-	-	0.12	-	0.12	-	0.12	GaBi 8.0 software, Scientific Paper (Parascanu et al., 2018)
			Air Genertaion	Air	kg	-	-	-	-	2.55	-	2.55	-	2.55	GaBi 8.0 software, Scientific Paper (Parascanu et al., 2018)
			Tar Generation	Tar	kg	-	-	-	-	1.65	-	1.65	-	1.65	GaBi 8.0 software, Scientific Paper (Parascanu et al., 2018)
			Gas Generation	Syngas	kg	-	-	-	-	0.28	-	0.28	-	0.28	GaBi 8.0 software, Scientific Paper (Parascanu et al., 2018)
			Char Generation	Char	kg	-	-	-	-	0.53	-	0.53	-	0.53	GaBi 8.0 software, Scientific Paper (Parascanu et al., 2018)

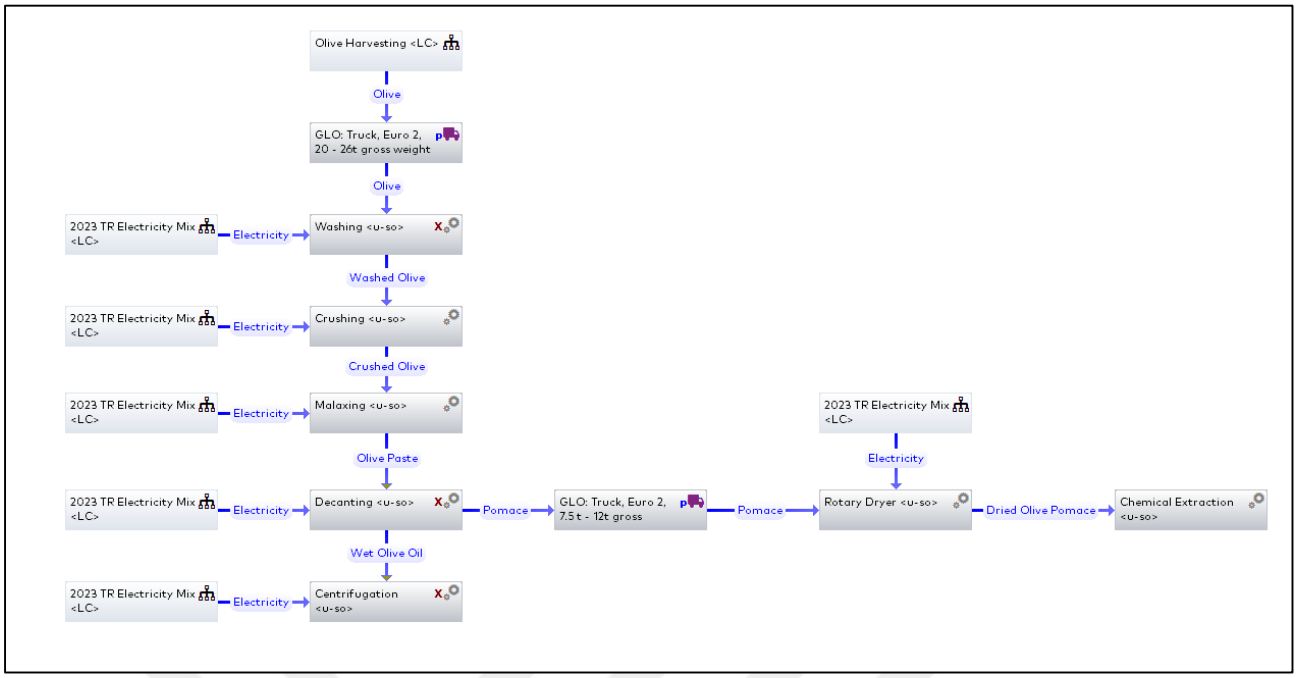

Figure 3.17. Scenario A Plan on GaBi.

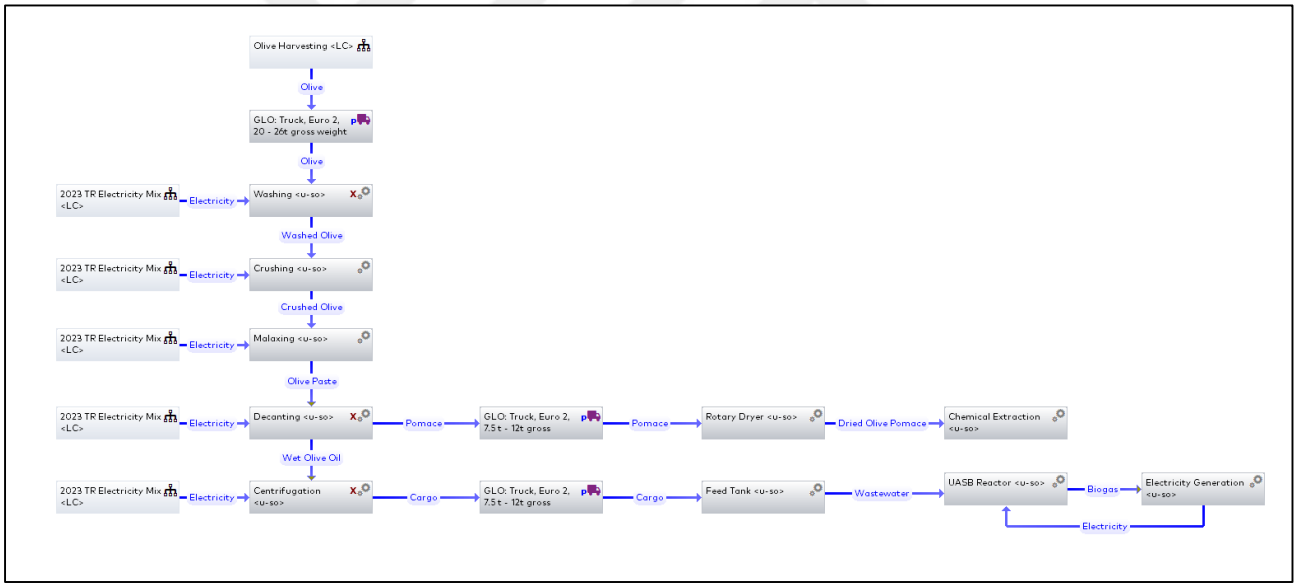

Figure 3.18. Scenario B Plan on GaBi.

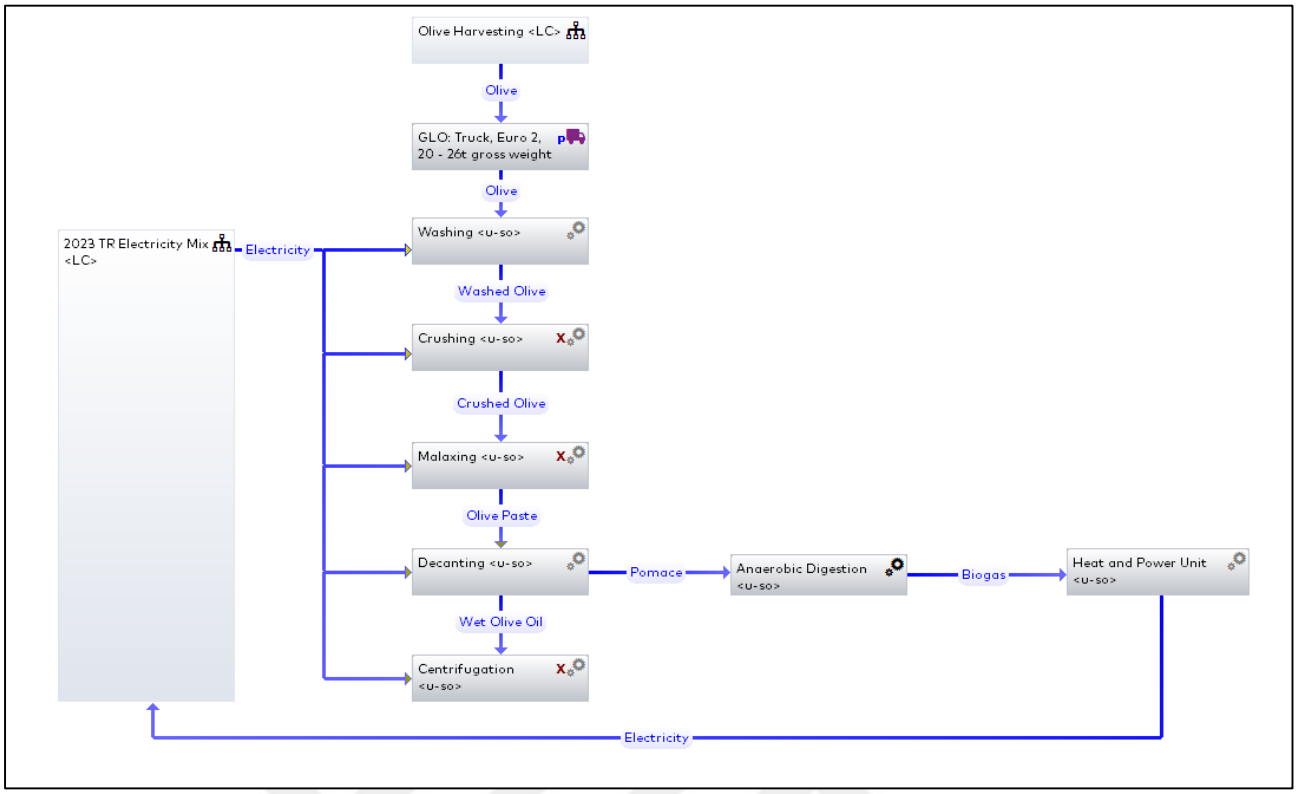

Figure 3.19. Scenario C Plan on GaBi.

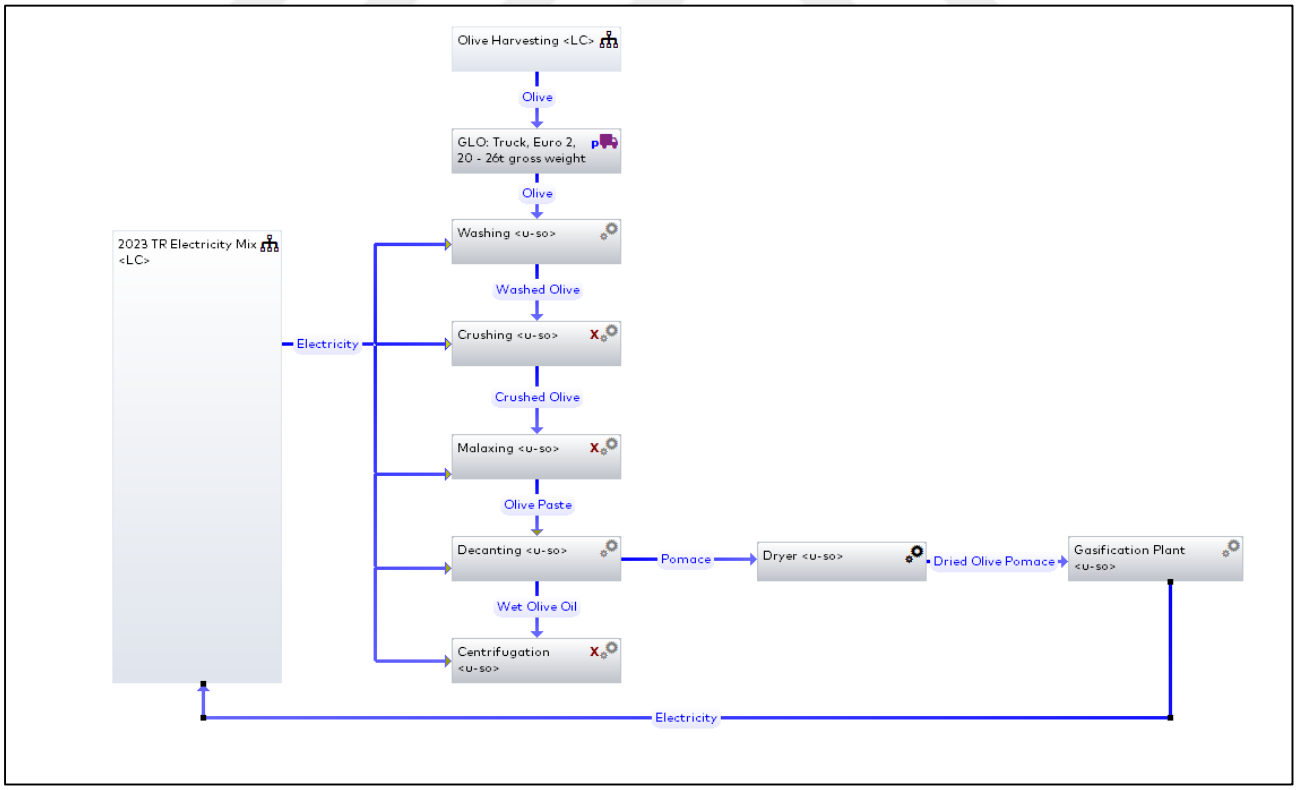

Figure 3.20. Scenario D Plan on GaBi.

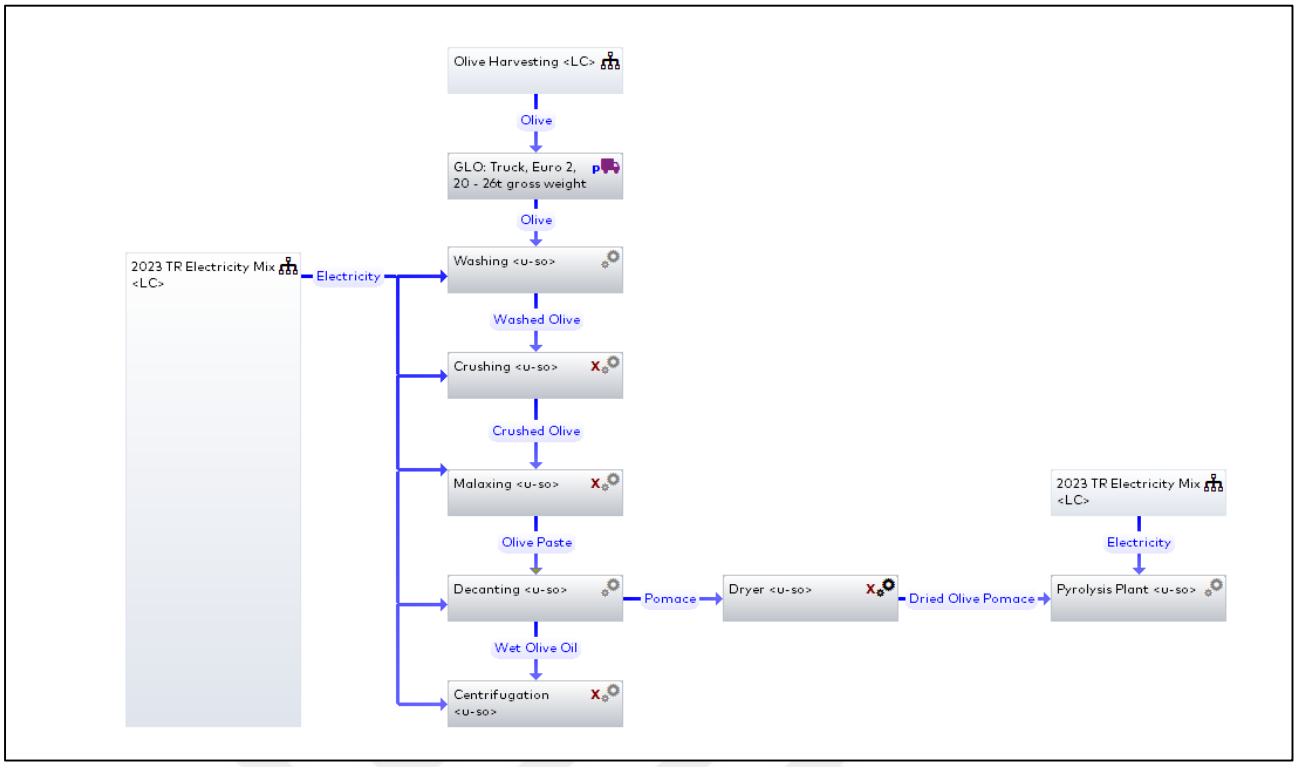

Figure 3.21. Scenario E Plan on GaBi.

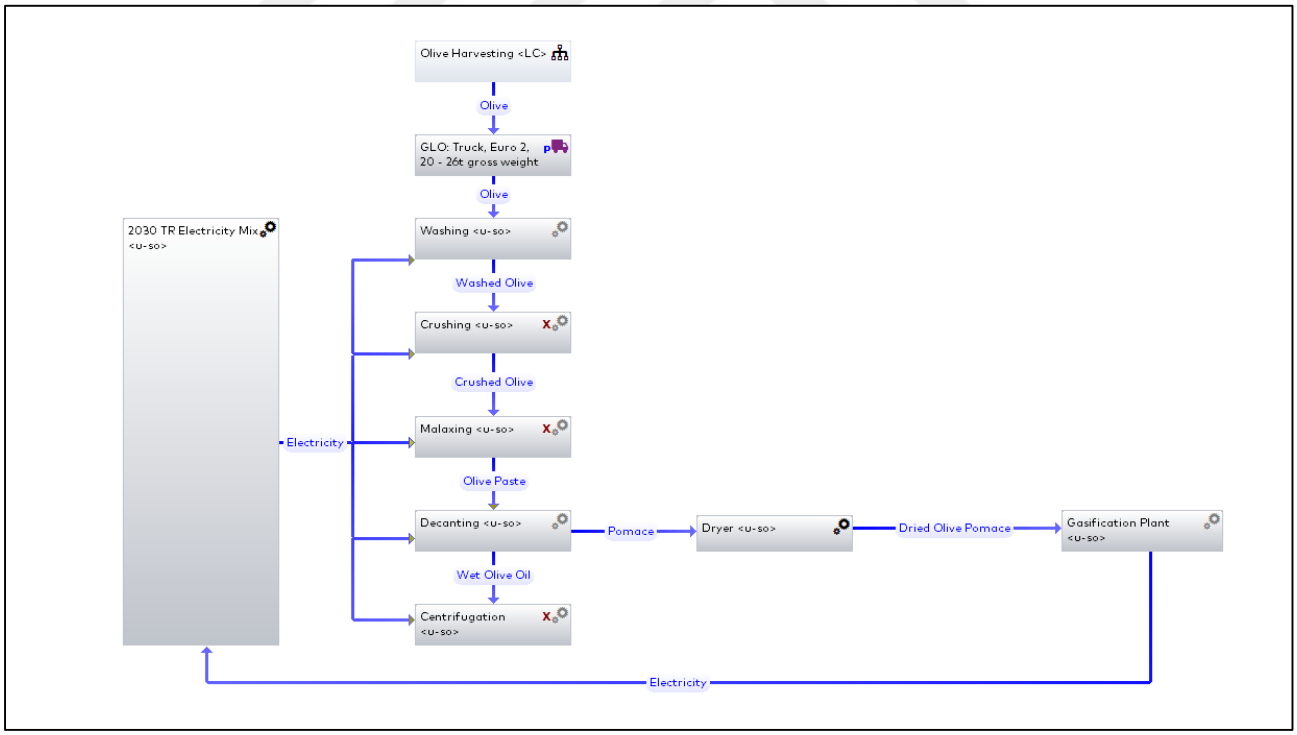

Figure 3.22. Scenario F Plan on GaBi.

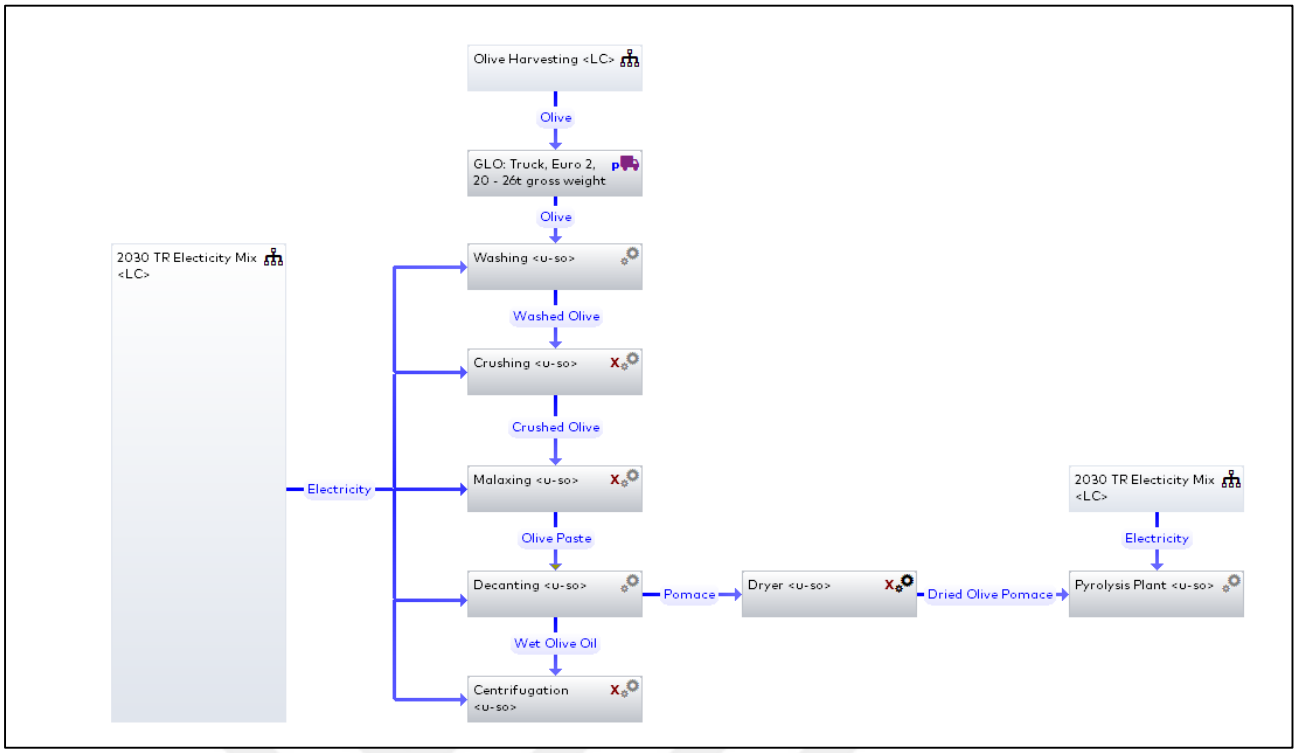

Figure 3.23. Scenario G Plan on GaBi.

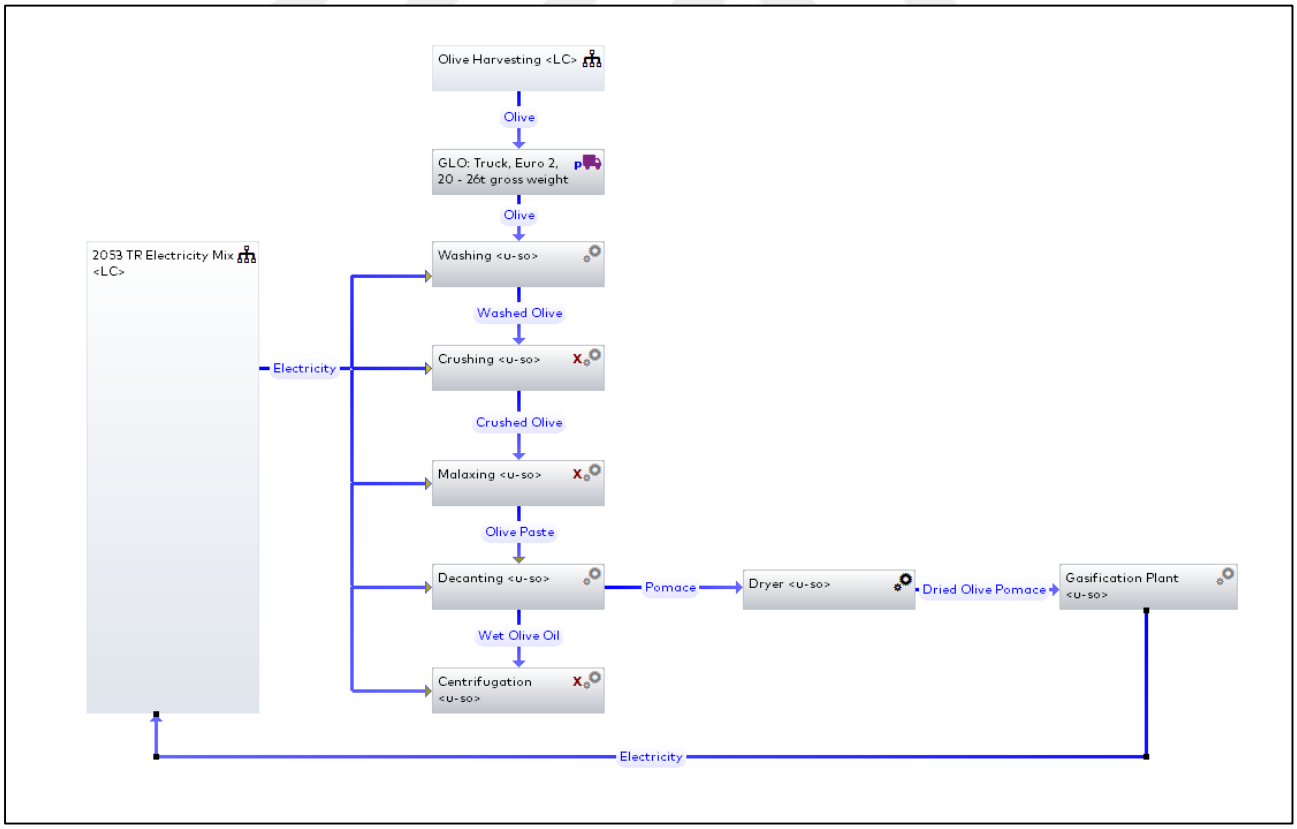

Figure 3.24. Scenario H Plan on GaBi.

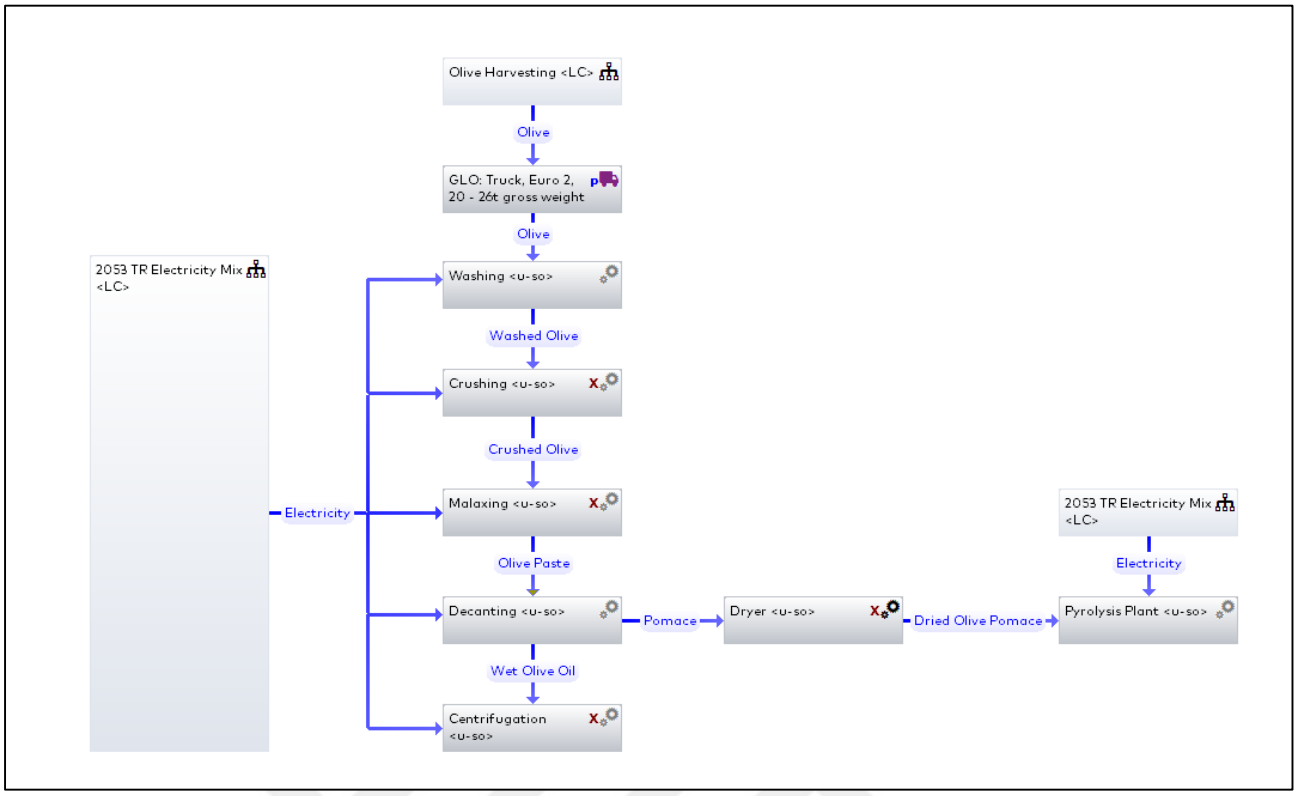

Figure 3.25. Scenario I Plan on GaBi.

4. RESULTS AND DISCUSSION

4.1. Life Cycle Impact Assessment

In the life cycle impact assessment phase of the LCA, potential environmental impacts of the flows is classified into different impact categories (ISO 14040, 2006). With the use of LCIA, inventoried flows are converted into environmental impact indicators. There are two primary methodologies in LCIA: midpoint and endpoint indicators. While endpoint approaches are used to convey the current level of damages, midpoint methods use characterization criteria to quantitatively estimate impacts (Espadas-Aldana et al., 2019).

CML, EPD, ReCiPe, IPCC, and ILCD are prominent and widely recognized evaluation methodologies in LCIA studies (Espadas-Aldana et al., 2019). CML is the most commonly used methodology to evaluate environmental impact assessment (Rapa & Ciano, 2022). In this LCA study, CML methodology is used and the classification, characterization, and normalization steps of LCIA were carried out.

Classification is a qualitative step based on scientific analyses of relevant environmental processes (Jensen et al., 1998). The input and output inventory data are assigned to different impact categories in the classification step. During the classification phase of this study, the life cycle inventory results are categorized into various impact categories. The highest impact categories, such as global warming potential (GWP), abiotic depletion (AD), eutrophication potential (EP), and marine aquatic ecotoxicity potential (MAETP), are prioritized in this study. Table 4.1 presents the selected impact categories and their units.

Table 4.1. Selected Impact Categories.

Impact Categories	**Defined Units for CML Methodology**
Global Warming Potential (GWP 100 years)	[kg CO_2-eq.]
Abiotic Depletion (ADP fossil)	[MJ]
Eutrophication Potential (EP)	[kg Phosphate-eq.]
Marine Aquatic Ecotoxicity Potential (MAETP inf.)	[kg DCB eq.]

The calculation methodology for the selected impact categories is defined based on a combination of environmental impact characterization factors, equivalence factors, and emission inventories. These factors enable the quantification of contributions from various substances to specific environmental impacts.

For GWP, the weighted contribution of each greenhouse gas is calculated relative to its global warming potential compared to CO_2 .

$$\text{Global Warming Potential} = \sum_i \text{GWMP}_{\text{a,i}} \times \text{m}_\text{i} \quad (4.1)$$

Where GWP measured in kilograms of the reference substance. Where $\text{GWMP}_{\text{a,i}}$ denotes the equivalence factor for substance i, m_i is refers to the quantified amount of substances i emitted (Guinée et al., 2002).

Similarly, for Eutrophication Potential (EP), the contribution of nutrients such as nitrogen and phosphorus to aquatic environments is assessed and measured in terms of phosphate equivalents (kg PO_4 -eq) (Guinée et al., 2002).

$$\text{Eutrofication Potential} = \sum_i \text{EP}_\text{i} \times \text{m}_\text{i} \quad (4.2)$$

In this equation EP_i represents the eutrofication potentialof substance , i emitted to air, soil or water while m_i denotes the quantity of substance the i emitted (Guinée et al., 2002).

In the case of Abiotic Depletion (AD), the extraction of non-renewable resources, such as fossil fuels and minerals, is quantified by considering energy demand and resource scarcity (Guinée et al., 2002).

$$\text{Abiotic Depletion} = \sum(\text{Factor}_i \times \text{m}_\text{i}) \quad (4.3)$$

Where Factor_i represents the equivalency factor for substance i, m_i is the amount of resource or substance iii extracted or used.

For Marine Aquatic Ecotoxicity Potential (MAETP), the calculation is based on the toxicity of substances harmful to marine ecosystems and is measured in terms of dichlorobenzene equivalents (kg DCB-eq), reflecting their potential to threaten marine life (Guinée et al., 2002).

$$\text{Marine Aquatic Ecotoxicity} = \sum_i \sum_{ecom} MAETP_{ecom,i} \times m_{ecom,i} \quad (4.4)$$

4.1.1. Characterization

Life cycle impact assessment includes the characterization of inventory data and aims to model impact categories in terms of indicator (Jensen et al., 1998). In this study, the four scenarios per impact categories are presented in Figure 4.1, using the characterization results obtained with the CML 2 baseline 2000 method.

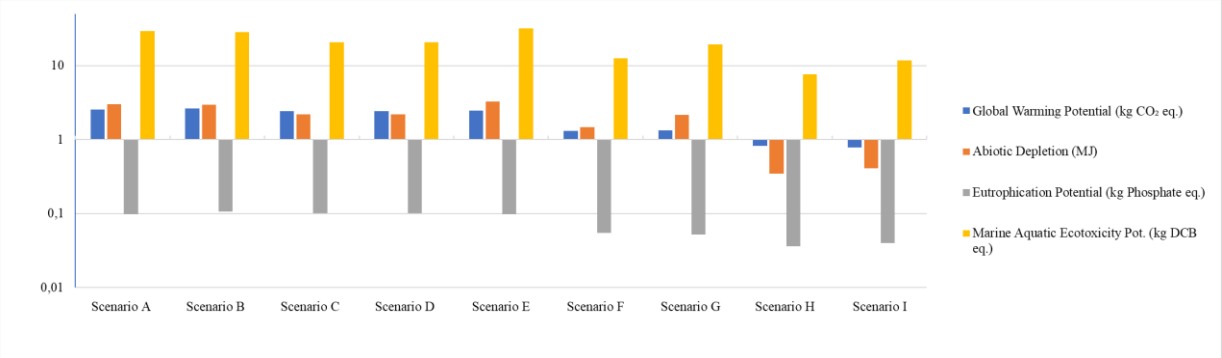

Figure 4.1. Scenario Based Impact Assessment.

The results of this study have been analyzed based on scenarios and it has been observed that that the highest environmental impacts are primarily observed in the marine aquatic ecotoxicity potential. While, the abiotic depletion shows a positive trend in most scenarios, the eutrophication potential remains relatively modest and lower compared to other impact categories. Additionally, the global warming potential typically ranges between 1 and 3 kgCO2 eg for FU.

When evaluating environmental impacts across different scenarios, notably higher values were observed in Scenario A, Scenario B, Scenario C, Scenario D, and Scenario E. This is primarily due to selecting 2023 as the projection year for these scenarios, a period when the electricity grid heavily relies on fossil fuel-based energy sources, unlike the other scenarios. Furthermore, the use of pesticides and fertilizers in these scenarios is considerably greater, particularly in relation to the Farm to Fork Strategy.

4.1.1.1. Global Warming Potential. In the scope of the study, the first analyzed category is global warming potential (GWP). GWP refers to the potential of the system to trap greenhouse gases in the atmosphere, which leads to global warming. Carbon dioxide, methane, and nitrogen dioxide are such gases that contribute to global warming. GWP is measured in kilograms of carbon dioxide equivalent (kg CO2-eq) (Murphy et al., 2013).



Figure 4.2. Quantified GWP for each stage across all scenarios.

In Figure 4.2, the contribution of the GWP impact from all scenarios for each stages is presented. For each scenario, the raw material extraction stage has a higher contribution to GWP compared to the other stages. Fernández-Lobato et al., (2024) states that, the higher values in the agricultural stage are responsible for the high use of fertilizers, harvesting and irrigation activities.

Additionally, the highest GWP is attributed to the fertilization which is a step of raw material extraction stage. In Scenario A and Scenario B, 52.7% of the total GWP is associated with fertilization, while approximately 34% is related to pest and weed control. In contrast to these scenarios, the contribution of fertilization to GWP decreases by almost 4%, reaching approximately 48% in Scenario H and Scenario I. This reduction is mainly due to the 70% decrease in pesticide use, which aligns with the EU Green Deal's Farm to Fork Strategy. As indicated by Sales et al. (2022) fertilization is the agricultural practice with the highest contributions in terms of environmental impacts in most of the categories.

Furthermore, in the raw material extraction phase, Scenario A and Scenario B ,which exhibits the highest GWP among all scenarios, while Scenario H and Scenario I have the lowest GWP. One of the main reasons for this is that the electricity power generation mix used in these scenarios, as of 2023, has the lowest proportion of renewable energy in electricity generation. In 2023, renewable energy sources accounted for approximately 40% of electricity generation, and this share is expected to increase significantly by 2053.

Additionally, a significant difference is observed, particularly between Scenario A and Scenario B, which use two-phase extraction technology, and three-phase extraction technologies, respectively. Scenario B has a 4% higher GWP value compared to Scenario A. The main reason for this difference is the lower efficiency of three-phase technology that, is caused by higher electricity usage observed in each functional unit, resulting in a greater environmental impact. This situation demonstrates that the extraction technology plays a significant role in ecological footprint.

When comparing the end-of-life phases of Scenario A and Scenario B, the VOO obtained through the three-phase extraction method produces 2.55 kg of pomace and 5.67 m^3 of wastewater, while the VOO produced with the two-phase extraction method generates 3.62 kg of pomace with a higher moisture content which contains both wastewater and pomace. It has been noted that the three-phase extraction technology produces more waste, leading to an increase in the amount of waste that needs to be managed. Consequently, Scenario B's GWP value is 7% higher due to the environmental impacts of the three-phase extraction. This highlights the decisive role of waste management in environmental impacts and the effects of different extraction methods on sustainability. Furthermore, in Scenario B, the biogas produced is combusted to generate electricity, which is subsequently used in the anaerobic digestion plant and the excess electricity generated is fed into the grid, resulting in a 4% improvement in the GWP.

Examining the end-of-life phase reveals significant differences between the scenarios. In both Scenario A and B, the chosen chemical extraction method requires transporting pomace to the treatment facility. This transporting process possess additional environmental impacts. In respect to this, in other scenarios aims to minimize these environmental impacts by applying gasification and pyrolysis methods directly in the facility. Reduced transportation process' impacts on environment resulted in 3% decrease in GWP value. This situation shows that on-site operations significantly reduce the environmental burden during the transportation phase, making it an effective strategy for reducing environmental impacts.

When comparing Scenario B and Scenario C, the anaerobic digestion method is evaluated in terms of waste management. In Scenario B, anaerobic digestion is used solely for treating olive mill wastewater. This process converts pomace into biogas, which is then utilized for energy production. However, due to the lack of an on-site system, the electricity generated for waste management is directed towards self-consumption, leading to dependence on external energy sources olive production facility. On the other hand, in Scenario C, anaerobic digestion is applied to the extraction

of pomace. This process reduces the volume of pomace and converts it into biogas, which can then be used to generate electricity. Furthermore, this electricity is sufficient to meet the entire energy demand of the olive oil production process. The biogas produced from wastewater also plays a significant role in energy generation, thereby enhancing the sustainability of the system and reducing environmental impacts. Scenario C offers a more efficient waste management solution by generating on-site energy while ensuring that waste is valorized without causing harm to the environment.

Comparing scenarios involving gasification and pyrolysis, a higher GWP is observed in the gasification unit than the pyrolysis unit, while the gasification unit consumes 17% more energy than the pyrolysis unit. Furthermore, a Combined Heat and Power (CHP) unit is integrated in addition to the gasification unit in Scenario F. The CHP unit, while aiming to increase energy production efficiency, also leads to increased emissions due to the combustion process. However, thanks to the electricity production in the gasification plant, energy recovery becomes feasible. In this way, the total energy demand of the olive mill area can be met with the energy produced by the gasification plant. In addition, the surplus electricity is supplied to the grid. The results indicate that 0.88 kWh of energy is produced through gasification during the production of 1 kg of unpacked virgin olive oil. Thus, the self-consumption of the produced energy results in a 6% reduction in the GWP. Rather than gasification scenarios, due to the lack of sufficient data, energy production within the pyrolysis system has not been included within the system boundaries. As a result, the potential improvement in the GWP value related to the self-consumption of energy has not been evaluated.

4.1.1.2. Abiotic Depletion. Abiotic depletion (AD) is defined as the reduction of abiotic resources, such as fossil fuel, clay, minerals, and peat. For fossil fuels, AD is measured in megajoules (MJ) (Murphy et al., 2013). Fossil fuels, including petrol, natural gas, and coal, are classified in the abiotic depletion effect category that are assessed as energy carriers. Therefore, AD consists of the total amount of fossil fuels expressed in megajoules (van Oers & Guinée, 2016).

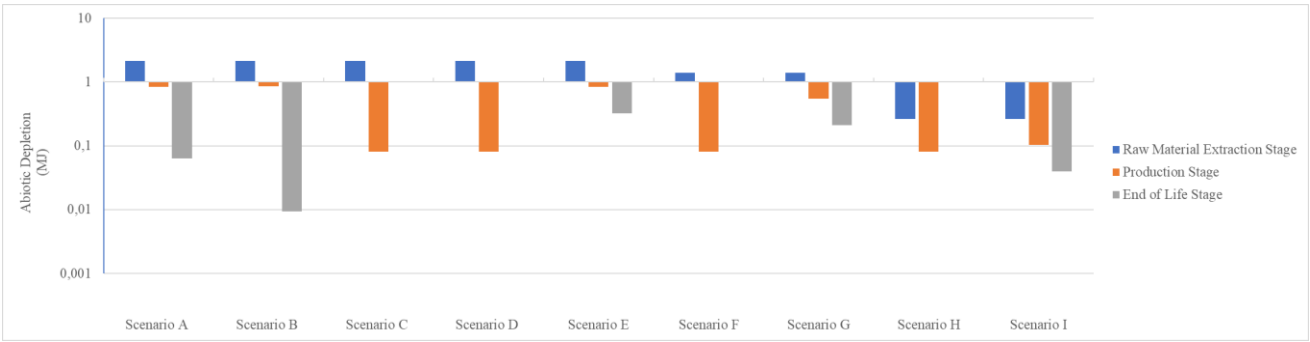

Figure 4.3. Quantified Abiotic Depletion for each stage across all scenarios.

When examining the virgin olive oil production stages, it is observed that the highest energy demand occurs at the raw material extraction stage. This situation also leads to the AD value reaching its highest level at the raw material extraction stage. For Scenario A, the raw material extraction stage consumes 55% of the total energy, while the production stage uses 21% and the end-of-life stage uses 24%. This finding indicates that raw material extraction is the most energy-intensive stage of the production process and therefore has a significant impact on AD.

Additionally, the highest AD is observed in Scenario A and B which the projection year is set to 2023, while the lowest AD is recorded in Scenario H and H in the raw material extraction stage. One of the main reasons for this difference is related to the net zero emissions and climate strategies that foresee a 90% increase in renewable energy use by 2053. The AD in the raw material extraction stage is particularly associated with the energy consumption of the irrigation unit, making this process significant in terms of abiotic depletion impact.

Furthermore, due to the higher energy demand of the gasification unit, a roughly 3% higher AD is observed compared to the pyrolysis scenarios. However, an increase in renewable energy sources within the electricity generation power mixture results in a reduction in the AD. In the pyrolysis-based scenarios, a decrease of approximately 10% in AD is observed by 2053 in Scenarios D and F, while in the gasification-based scenarios, this reduction is about 8% in Scenarios C and E. This trend is mainly attributed to the net-zero emissions and climate strategies, which forecast a significant increase in renewable energy use, contributing to a lower AD in the long term.

In the pyrolysis scenarios, the reuse of air from the air heat exchanger is sufficient to meet the energy demands of the dryer which is used for drying the pomace. Therefore, the dryer does not have an impact on the AD.

When all scenarios are evaluated, the scenario with the lowest environmental impact in terms of abiotic depletion is identified as Scenario I, with 0.4 MJ AD for the production of 1 kg of unpackaged virgin olive oil. In contrast, the scenario with the highest abiotic depletion value is Scenario A, with 3.02 MJ AD. This result highlights the reduction in the amount of fossil fuels in the energy sources defined in the scenarios and emphasizes the growing importance of electricity self-consumption

4.1.1.3. Eutrophication Potential. Eutrophication potential (EP) is defined as the potential of nutrients to cause over-fertilization of water and soil, which can lead to excessive growth of undesirable biomass. This biomass has negative impacts on other life forms in the ecosystem. Contributing substances include phosphates, nitrates, ammonia, nitrous oxides, among others. Additionally, EP is measured in kilograms of phosphate equivalents (kg PO4-eq) based on CML 2001 methodology (Murphy et al., 2013).

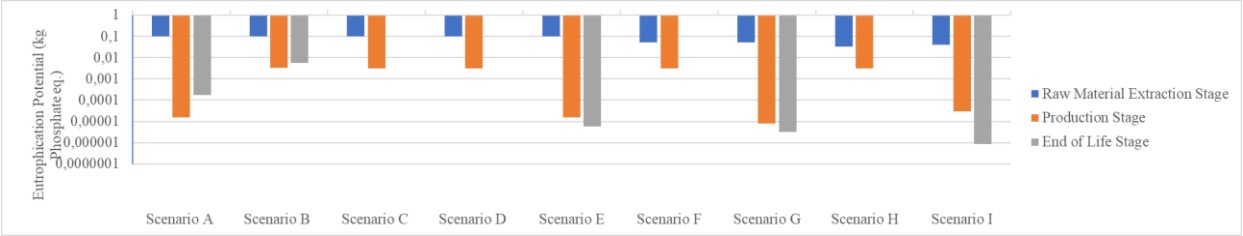

Figure 4.4. Quantified Eutrophication Potential for each stage across all scenarios.

In Figure 4.4, EP values are presented for each scenario. The highest EP is observed in the raw material extraction stage across all of them. Main contributor of raw material extraction stage is fertilization step. According to Cossu et al. (2013), the main contributor for eutrophication potential is fertilizers leaching specifically nitrates and phosphate leaching. For this study, EP is dramatically decreased in Scenario G and Senaryo H. The main reason for this decrease is that, within the Farm to Fork Strategy framework,one of the EU's Green Deal strategies, fertilizer use is targeted to be reduced by 50% by 2030. On the other hand, in this study, it is assumed that this reduction will reach 70% by 2053. In this context, an environmental impact value of 0.034 kg Phosphate eq is observed per 1 kg of unpackaged virgin olive oil when scenarios G and H are examined. In contrast, Scenarios A, B, C, and D representing the electricity power generation mix for 2023, exhibit the highest environmental impact with a value of 0.097 kg Phosphate eq. These findings highlight the significant positive impact of reducing fertilizer use on environmental effects and emphasize the importance of sustainable production processes.

Secondly, when the production stage is examined, it has been observed that the impact of the malaxing units has significantly increased compared to other units. Thus, the malaxing unit is the highest contributor for the production stage for scenarios. Cossu et al. (2013) explained that when eutrophication potential is considered, the impact of the disposal options “power production” and “domestic heating” is significant. In this LCA study, the malaxing unit is the only unit that uses heat. Thus, the malaxing unit is the highest contributor for the production stage.

When evaluated based on scenarios, the highest eutrophication potential is identified in Scenario B. The primary reason for this is that the raw material extraction stage is the main factor, and the three-phase production process generates significantly more wastewater compared to the two-phase production process. In the three-phase system, 5.67 m³ of wastewater is generated per 1 kg of virgin olive oil production, and the management of this wastewater increases the eutrophication potential. When comparing Scenario A and Scenario B, it has been observed that Scenario B leads to 7% higher eutrophication potential.

In Scenarios A and B, it has been determined that the transportation of pomace to disposal facilities during the chemical extraction method applied at the end-of-life stage has only a 0.12% effect on abiotic depletion (AD). Furthermore, it has been observed that the impact of transportation on eutrophication potential (EP) is negligible.

4.1.1.4. Marine Aquatic Ecotoxicity Potential. Marine aquatic ecotoxicity potential (MAETP) refers to the impacts of toxic substances on marine ecosystems. The impact category encompasses exposure, fate, effect, and severity factors, MAETP is quantified in kilogram 1,4-dichlorobenzene equivalent emission (kg 1,4-dichlorobenzene eq.) (Marzeddu et al., 2021).

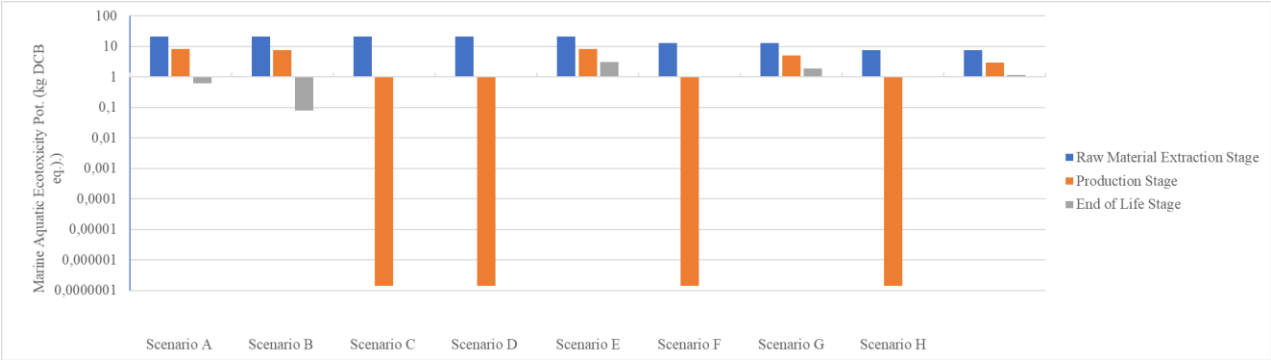

Figure 4.5. Quantified Marine Aquatic Ecotoxicity Potential for each stage across all scenarios.

In this study, it was observed that the environmental impact of the raw material extraction stage is the major contributor. Salomone et al., (2015) states significant portion of the system's environmental impacts are caused by the agricultural activity. This result is consistent with the conclusions drawn by other researchers, who found that the raw material extraction stage significantly contributes to the total environmental efficiency of the virgin olive oil production process. In this study, as a result of examinations carried out on a scenario basis, it has been determined that 55% to 70% of marine aquatic ecotoxicity potential originates from the raw material extraction stage. This finding reveals that the raw material supply process is the most critical stage in terms of toxic effects

on marine ecosystems. Particularly, the irrigation phase in the raw material supply process emerges as the main unit contributing to this.

Scenario A, which utilizes the two-phase production method, the wastewater generated during the process is combined with pomace in the decanter unit and disposed of as pomace with high moisture content. This integration of wastewater with the solid byproduct eliminates the need for a separate wastewater treatment process in Scenario A. As a result the energy requirement and water consumption is highly related with agricultural activities. Nearly 70% of this environmental impact originates from the agriculture phase, 27% from the production phase, and 3% from the end-of-life phase.

In Scenario B, due to having wastewater treatment activities and related to high amount of energy and water consumption that it is expected that scenario B has significantly higher marine aquatic potential related to the energy consumption due to treatment of wastewater. However, thanks to the UASB reactor, biogas is generated, which is then converted into electrical and thermal energy. The produced energy is used in end of life phase and so, marine aquatic ecotoxicity potential decreases by 24% in Scenario B.

When comparing Scenarios C, E, and F, the use of electricity obtained from the gasification unit within the olive mill significantly improves marine aquatic ecotoxicity, providing a 12% improvement when scenarios are compared.

The increase in the share of renewable energy in the energy mix has been observed to have a positive environmental impact on marine aquatic ecotoxicity, particularly evident at the raw material extraction stage. This study, the scenarios conducted within the framework of the EU Farm to Fork strategy forecasts a 70% reduction in fertilizer use in the energy mix by 2053, while the reduction is aimed to be 50% in 2030. Additionally, the increase in the share of renewable energy in the energy grid mix also contributes to environmental improvement. In this context, comparing Scenarios D, F, and G, a 39% reduction in environmental load is achieved from 2023 to 2030, and approximately a 40% environmental improvement is observed from 2030 to 2053. This finding underscores the significant role of increased renewable energy use and decreased fertilizer consumption in reducing toxic effects on marine ecosystems.

4.1.2. Normalization

Normalization and weighting are integral components of analyzing environmental impacts within the life cycle assessment (LCA) framework, each serving a distinct purpose. Normalization helps evaluate the relative importance of impact category results by comparing the magnitude of each category indicator to a predefined reference value. Based on ISO 14044, normalization is the calculation of the magnitude of indicator results relative to the reference unit. (ISO 14044, 2006) The aim of normalization is to better understand the relative magnitude of each indicator result for the studied product system. Furthermore, normalization results have no unit, which allows for comparison between impact categories (Abdallah et al., 2021). However, it is not a compulsory step for LCA (Türk Standartları Enstitüsü, 2018). Conversely, weighting involves applying numerical factors, which reflect stakeholder or decision-maker value preferences, to the normalized results. It may also include aggregating impacts across categories when necessary(Seppälä et al., 2006). This process is inherently subjective, as it prioritizes impact categories based on perceived importance. In essence, normalization provides a contextual framework for data, while weighting highlights their significance through value-based prioritization (Seppälä et al., 2006).

In this study, results are normalized and presented in Figure 4.6. As a result of the normalization, Scenario A exhibits the highest GWP value, showing 5% greater impact compared to the other scenarios. The GWP of the other scenarios is between 1% and 25% lower than Scenario A, which indicates the impact of Scenario A on global warming is more noticeable compared to the others. Results show that generation of electricity for self-consumption has a highly effective impact on reduction of GWP. Additionally, the renewable electricity portion in the electricity generation mixture has also positively affected and reduced the environmental impact.

Evaluating abiotic depletion, Scenario H has an 85% lower impact, whereas scenario B shows a 15% higher impact in terms of scenario A. The increase in Scenario B indicates a higher rate of depletion of abiotic resources, highlighting the significant effect of waste treatment and three-phase extraction technology.

In the eutrophication potential impact category, Scenario A exhibits the highest impact, while most of the other scenarios show 10% to 25% lower impacts compared to Scenario A. Scenario A displays a higher eutrophication potential due to factors related to fertilization and other agricultural practices. Additionally, there are no environmental and sustainability targets for the raw material

extraction stage in the 2023 projection year. Therefore, Scenario A has the highest environmental impact in terms of eutrophication potential.

Scenario B presents the highest value for aquatic ecotoxicity potential, while Scenario H shows a 70% lower impact. This indicates that Scenario B generates a larger toxic impact on aquatic ecosystems, whereas Scenario H significantly minimizes this impact.

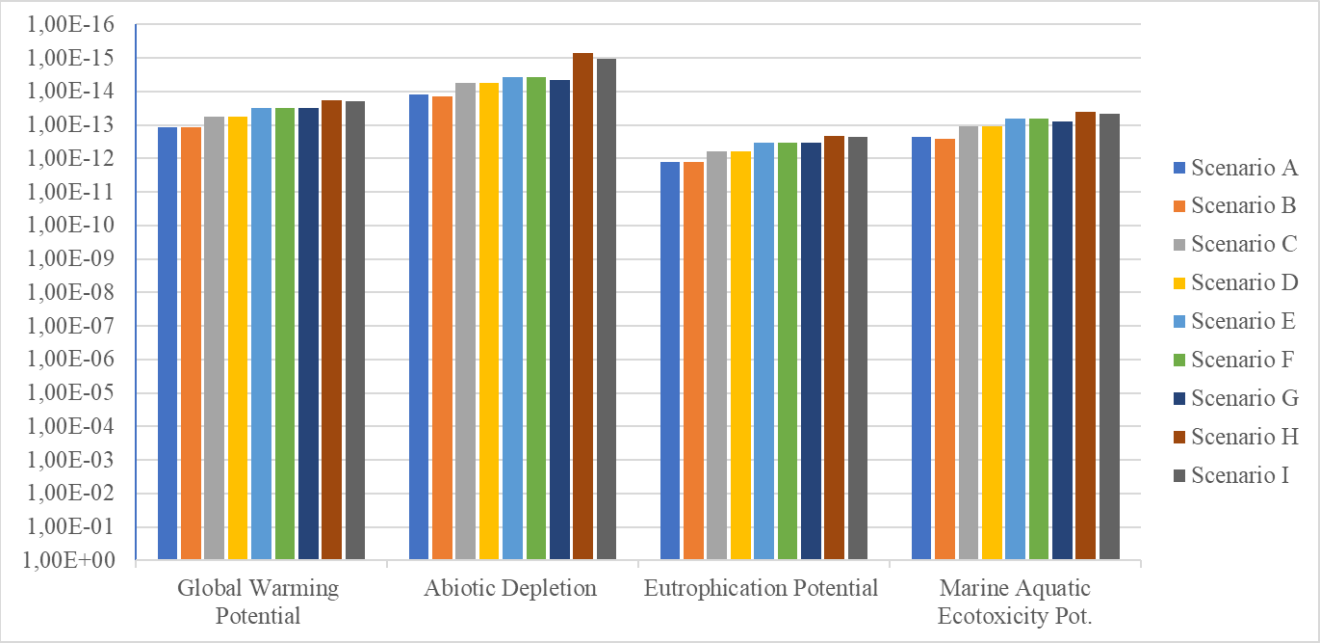

Figure 4.6. Normalization.

5. CONCLUSION AND RECOMMENDATION

This study comprehensively evaluates and examines the raw material extraction, production and end of life stages of virgin olive oil production using a life cycle assessment methodology. The goal and scope of the study focus on identifying 'hot spots' on the production chain of 1 kg unpacked virgin olive oil with eight different alternative systems compared and the highest impact categories, global warming potential (GWP), abiotic depletion (AD), eutrophication potential (EP), and marine aquatic ecotoxicity potential (MAETP), are prioritized.

Firstly, it has been analyzed that the environmental impacts of the raw material extraction stage exhibit the highest impact values across all scenarios. According to Salomone et al., (2015), a significant portion of the system's environmental impacts are caused by the agricultural phase. This result aligns with the conclusions drawn by other researchers, who found that the agricultural stage significantly contributes to the total environmental efficiency of the olive oil production process. In this study, in line with the EU Green Deal Farm to Fork Strategy integrated into the scenarios, the use of pesticides and fertilizers will be reduced by 50% in 2023. For this particular study, it is assumed that by 2053, the usage will decrease by 70%. Over time, this reduction leads to a minimization of the environmental impacts originating from the raw material extraction stage. Compared to 2023, eutrophication potential will decrease by approximately 60% and marine aquatic ecotoxicity by 63%. Similarly, due to the increased share of renewable energy in the electricity power generation mix, it has been analyzed that GWP will decrease by 70% and AD by 80% from the 2023 projection year to the 2053 projection year.

Secondly, the results indicate that production of 1 kg of unpacked VOO using the two-phase extraction technolog results in 2.55 kg of CO_2 equivalent in the global warming potential impact category . Specifically, the GWP of the raw material extraction phase accounts for for 93% of the total impact. The two phase extraction technology is more environmental friendly than three phase extraction technology due to reduce waste generation and lower water consumption. However, in this study anaerobic digestion units producing energy from biogas to self consumption integrated into the Scenario B and Scenario C to minimize the environmental impact. Thanks to the generation electricity from biogas, energy requirement of anaerobic digestion reactor was met and 24% reduction observed in marine aquatic ecotoxicity and 3% GWP.

Another valuable aspect of this study is end of life stage waste management options. As a result of the analysis of the scenarios, it has been determined that the gasification scenarios are designed for the production of heat and energy from olive pomace. The aim is to use the energy produced in these facilities for self-consumption and the location of gasification plant in the same area as the virgin olive oil production facility, thereby eliminating the environmental impact associated with transportation of waste. Consequentlyi it revealed that 0.88 kWh of energy is produced per kilogram of unpacked virgin olive oil and this energ is utilized in virgin olive oil facility, leading 6% improvement in the GWP value.

Due to data limitations in the pyrolysis scenarios, energy production and self-consumption of energy were not realized. The tar, gas, and bio-oil byproducts resulting from pyrolysis were not integrated into the system boundaries. However, energy requirements is supplied by the air heat exchanger to dryer unit, thereby eliminating the need for natural gas in drying unit. Consequently, improvements in the abiotic depletion values were observed.

This study suggests that enhancing the environmental performance of the virgin olive oil production chain can be achieved by implementing appropriate strategies. Fertilizer use was considered as the agricultural practice with the highest contributions to most categories evaluated. Therefore, it is recommended to implement integrated management practises to improve the environmental performance of olive production. Innovative systems should be optimally designed to mitigate the impacts of their mechanization (Espadas-Aldana et al., 2019).

Within this study perspective, due to the distance between the orchards and the virgin olive oil production facilities and waste valorization facilities, the amount of energy used in the raw material extraction stage could not be fully met by the energy produced in the scenarios. However, a certain reduction in environmental impacts associated with electricity consumption was noted. This finding underscores the importance of integrating renewable energy systems into orchards. To more efficiently meet the energy demands of agricultural activities, it becomes essential to apply renewable energy sources more extensively. Moreover, there is a critical need to prioritize the adoption of renewable energy sources and to optimize the agricultural activities (Fernández-Lobato et al., 2021).

On the other hand, energy for self consumption is anticipated to make significant contributions to sustainability efforts in the virgin olive oil production. Studies in the literature support the

utilization of energy derived from residues generated during virgin olive oil production (Fokaides, 2018).

As a result, this study enables the expansion and development of sustainability in the field of olive oil production on scientific foundations. Furthermore, it presents significant findings on how Türkiye's and the European Union's emission reduction targets and desire for increasing use of clean energy sources contribute to combating climate change. This research also explains how it participates to the achievement of the targets set within the framework of the EU Green Deal especially Farm to Fork Strategy. All these elements collectively serve as a crucial source of information for authorities developing new regulations aimed at supporting olive oil production chain while focusing on environmental objectives. Additionally, this study highlights the potential for reducing environmental impacts through innovative technologies such as gasification, pyrolysis and anaerobic digestion, which convert by products into energy and reduce reliance on extrenal sources. Moreover, it emphasizes the importance of circular economy principles in the olive oil sector, encouraging the recycling and reusing of by-products.

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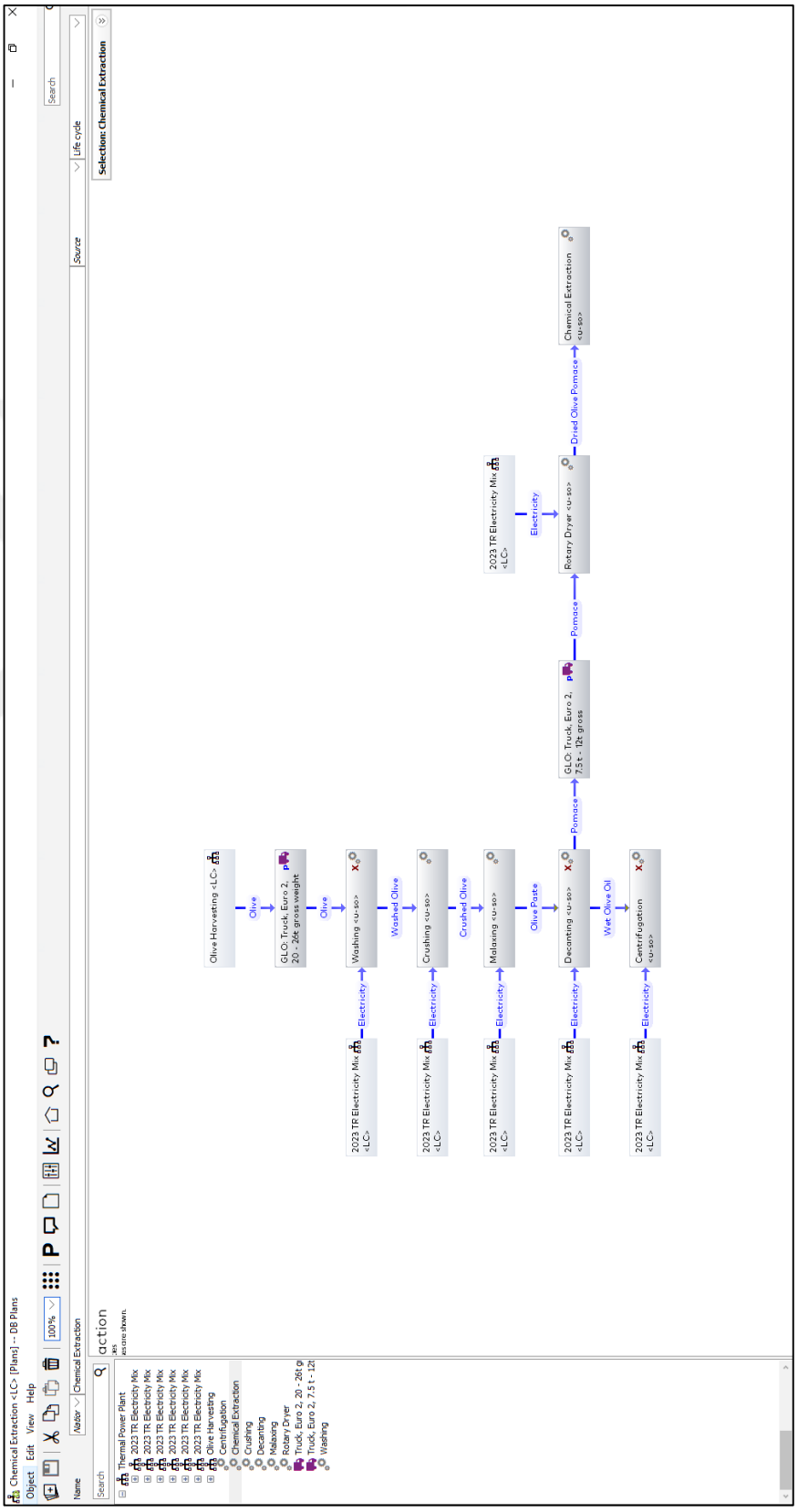
APPENDIX A: SCENARIO A PLAN ON GABI



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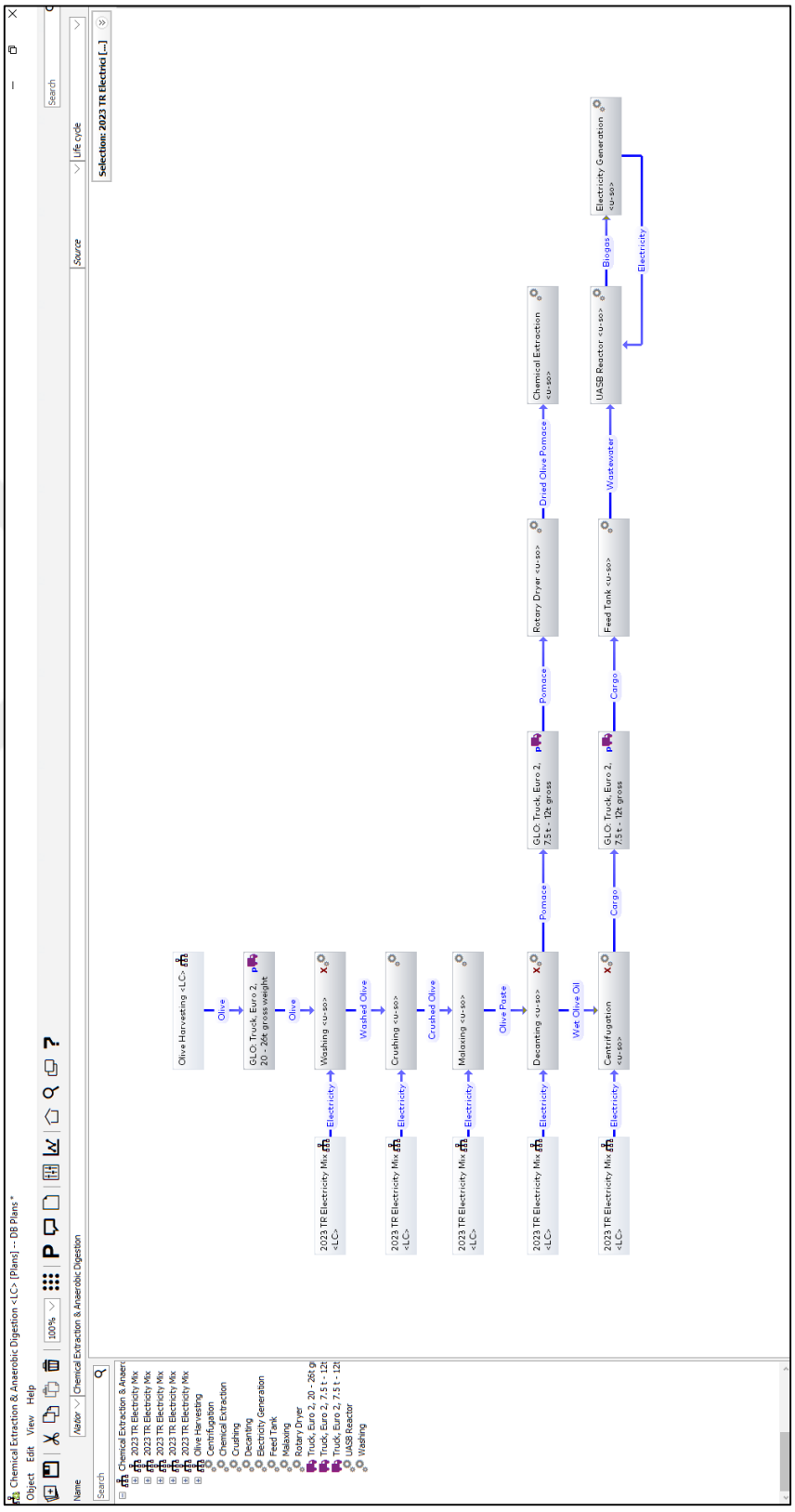

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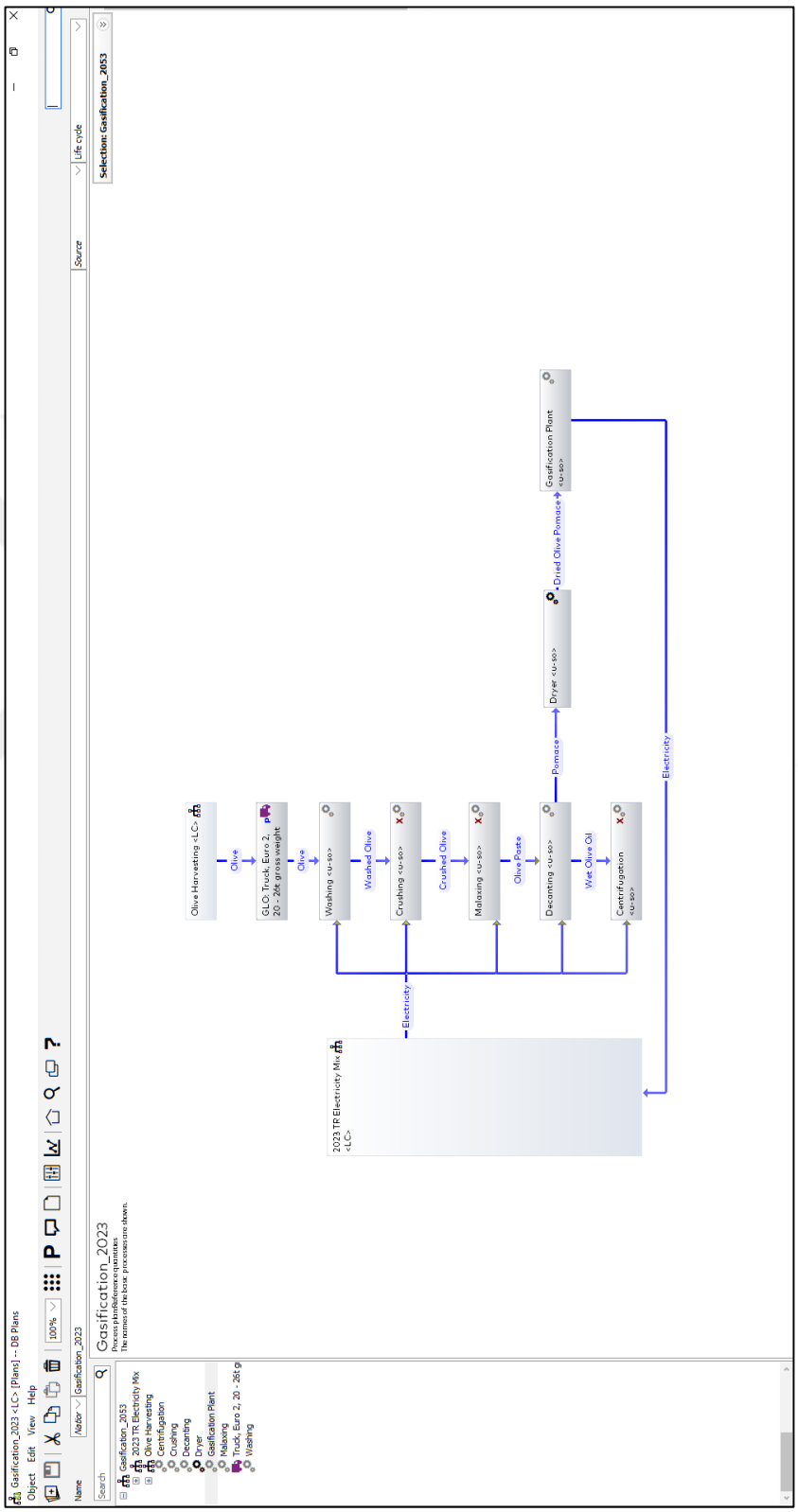

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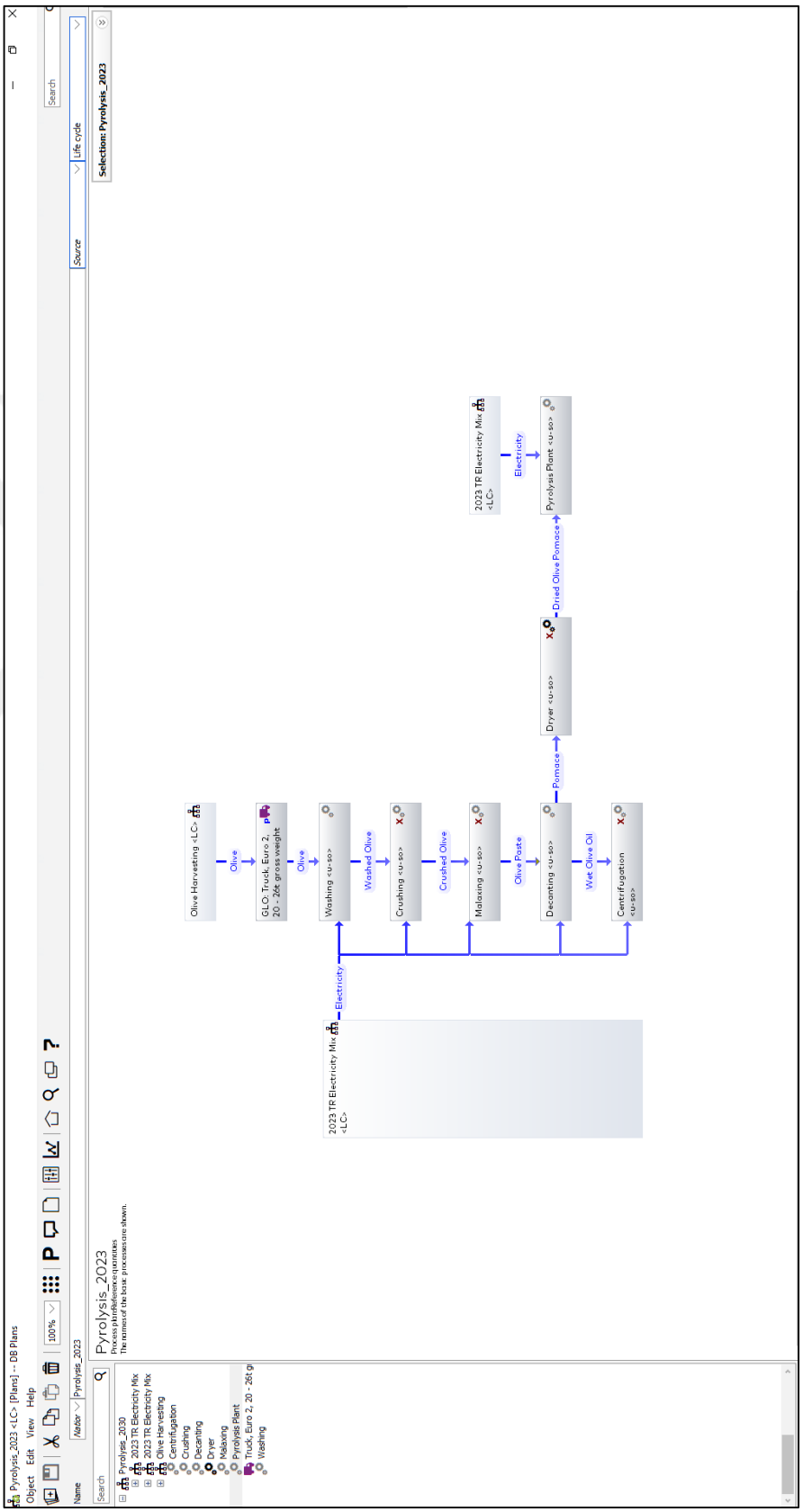

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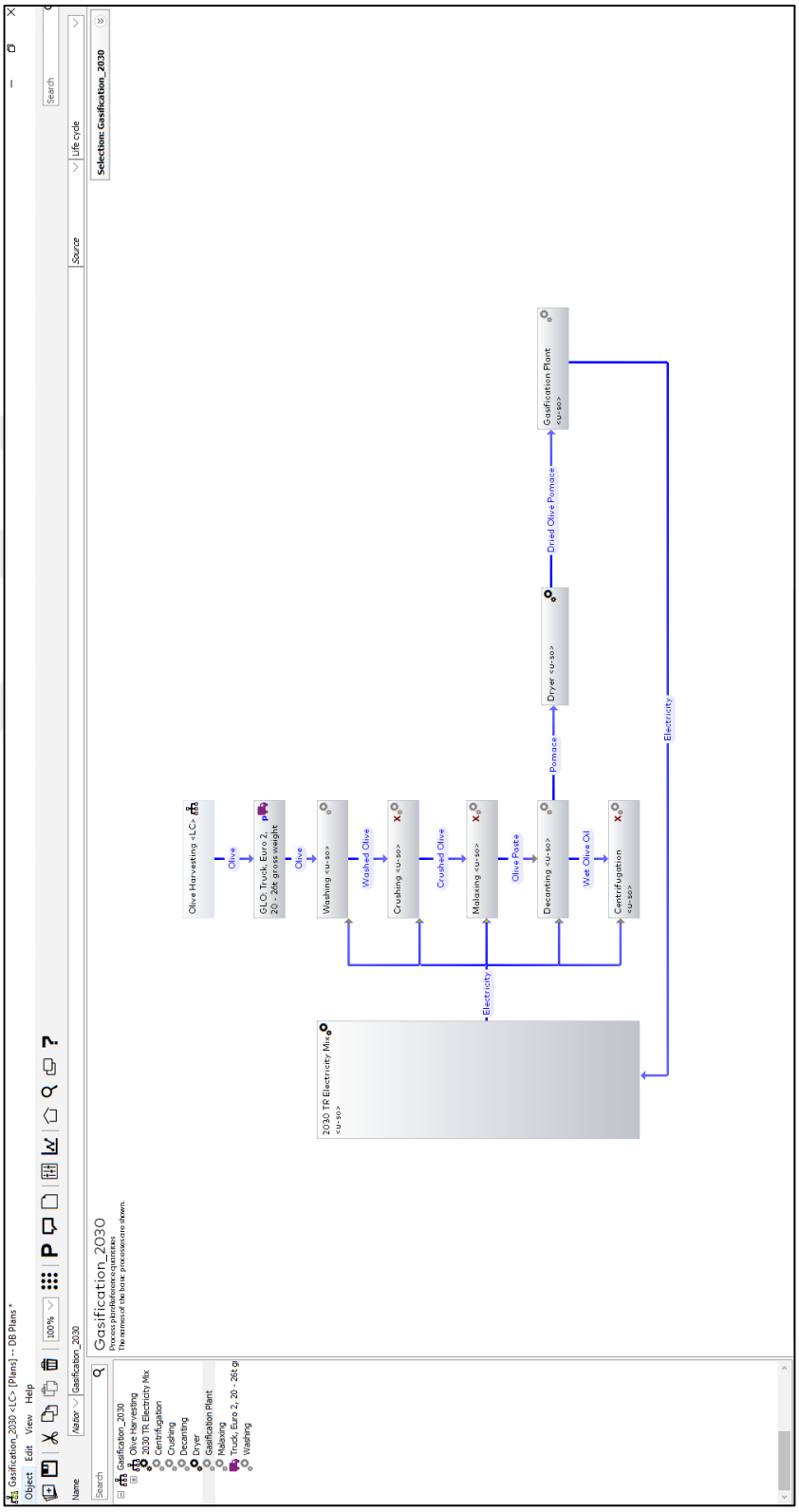

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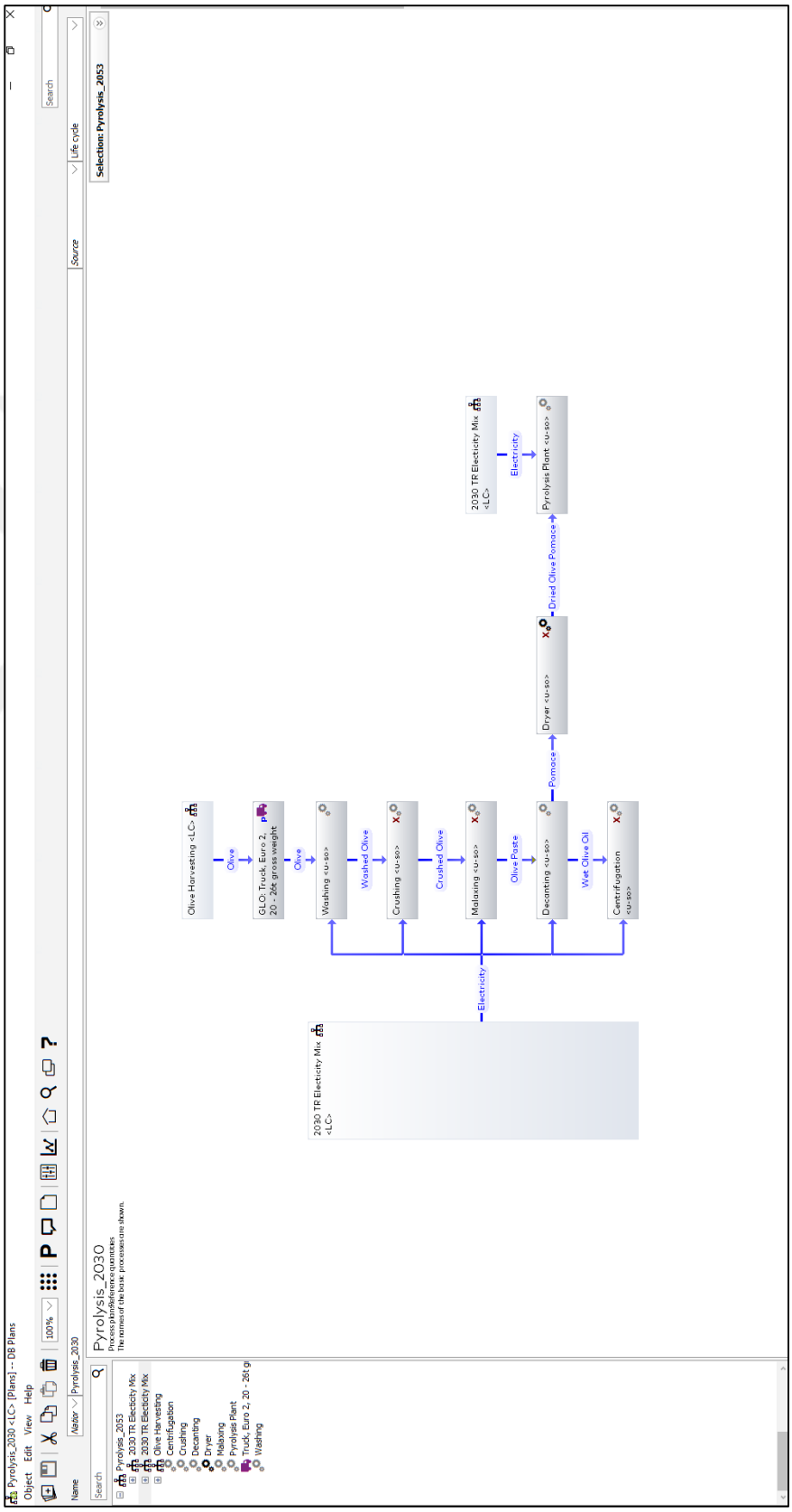

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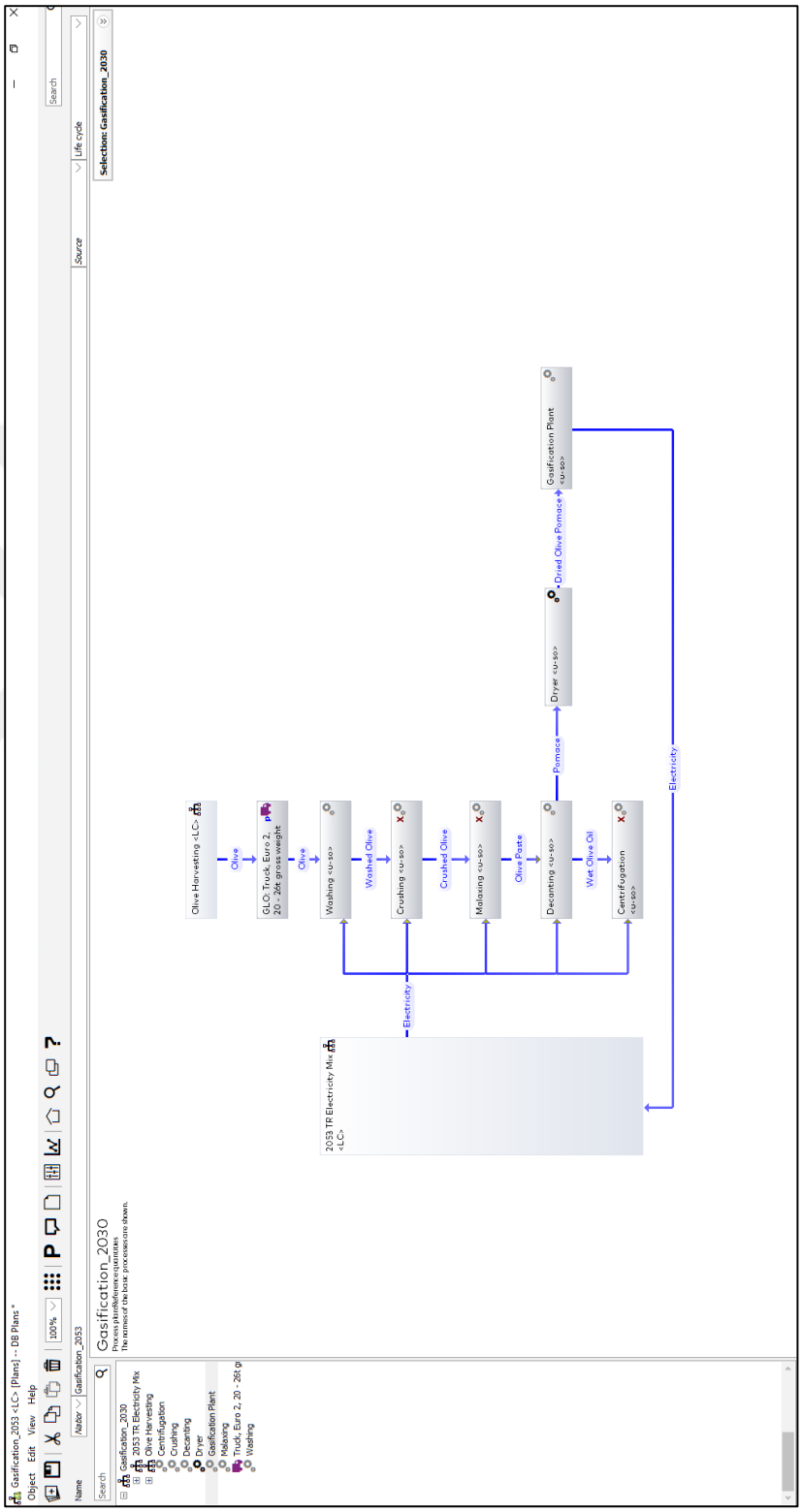

APPENDIX H: SCENARIO I PLAN ON GABI

