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Used-cooking-oil biodiesel: Life cycle assessment and comparison with first- and third-generation biofuel

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Abstract

The environmental sustainability of second-generation biodiesel (used-cooking-oil) was examined, at industrial-scale, in Greece. The total carbon and environmental footprint per tonne of biodiesel production was $\sim 0.55\text{t CO}_2\text{eq}$ (i.e. $\sim 14\text{g CO}_2\text{eq/MJ}$) and 58.37Pt, respectively. This is $\sim 40\%$ lower compared to first-generation biodiesel, an order of magnitude lower than the third-generation (microalgae), since the latter is not a fully-fledged technology yet. A threefold reduction in environmental impacts was observed compared to petrodiesel. Environmental hotspots include energy inputs to drive the process, followed by methanol (CH_3OH) and potassium methoxide (CH_3KO) consumption. Glycerol ($\text{C}_3\text{H}_8\text{O}_3$) and potassium sulfate (K_2SO_4), both process co-products, resulted to avoided environmental burdens. Furthermore, used-cooking-oil valorisation for biodiesel production can address water pollution concerns from its disposal to the sewage system. The total distance and means of transport were found to influence the system's environmental sustainability. Strong incentives for used-cooking-oil recycling, widespread collection systems, and biodiesel supply chain optimization are still pending in Greece, Europe, and further afield. Given its overall low environmental footprint and capability to be produced at commercial scales, the second-generation biodiesel, which currently represents 15% of the biodiesel market in Greece, could act as a stepping-stone in decarbonizing Europe's transport sector and improving supply and energy security.

Keywords: circular economy; life cycle inventory/assessment (LCI/LCA); used/waste cooking oil (UCO/WCO); SimaPro; waste management and valorisation; water pollution

34	Nomenclature
35	ALO: Agricultural Land Occupation
36	EU: European Union
37	CC: Climate Change
38	CO₂eq: Carbon Dioxide equivalent
39	FAME: Fatty Acid Methyl Esters
40	FE: Freshwater Eutrophication
41	FD: Fossil Depletion
42	FET: Freshwater EcoToxicity
43	FFA: Free Fatty Acids
44	GDP: Gross Domestic Product
45	GHG: Greenhouse Gas
46	H: Hierarchist
47	HT: Human Toxicity
48	IPCC: Intergovernmental Panel on Climate Change
49	J: Joule
50	kg: kilogram
51	L: Litre
52	LCA: Life Cycle Assessment
53	LCI: Life Cycle Inventory
54	LCIA: Life Cycle Impact Assessment
55	ME: Marine Eutrophication
56	MET: Marine EcoToxicity
57	NLT: Natural Land Transformation
58	PMF: Particulate Matter Formation

59 **Pt:** point
60 **TA:** Terrestrial Acidification
61 **TE:** Terrestrial Ecotoxicity
62 **t:** tonne
63 **UCO:** Used Cooking Oil
64 **ULO:** Urban Land Occupation
65 **WD:** Water Depletion
66

1. Introduction

The growing energy demand, along with fossil fuel depletion and the negative environmental impacts attributed to fossil fuel consumption in the transport sector, suggests that alternative, environmentally friendlier fuels should be introduced at large scale [1, 2]. Transport is a cornerstone of the European integration process, promoting jobs and economic growth, with the transportation sector employing ~10 M people and generating ~4.5 % of the EU's GDP [3]. Nonetheless, transport in the EU grossly depends on oil (~93 %) and therefore is responsible for almost a quarter of Europe's greenhouse gas (GHG) emissions, with road transport being by far the biggest emitter [4]. It has been claimed that more than two-thirds of transport-related GHG emissions are attributed to road vehicles [5]. Thus, there is a need to decrease petroleum fuel dependence and move towards low-emission mobility. To this end, the introduction of biofuels, such as biodiesel and bioethanol, could play a huge role in decarbonizing the transport sector in the EU and further afield. For example, biodiesel is an excellent substitute to petroleum diesel (i.e. petrodiesel) that is expected to play a major role in the decarbonization of the transport sector, as it currently accounts for nearly 80 % of the total biofuel production in EU [1, 6].

Biodiesel produced from used cooking oil (UCO) or waste cooking oil (WCO) is an advanced biofuel, i.e. second-generation since it is obtained from a non-crop feedstock. It is promising in terms of both quality and production cost [7], while UCO is currently considered as a cheap biodiesel feedstock [8]. In the EU, the total oilseed production in 2017 was nearly 35 Mt, with rapeseed representing around 63 % of this number [8]. Furthermore, the average vegetable oil consumption per capita in the Mediterranean is significantly higher than that of the rest of Europe, with Greece being among the greatest oil consumers (average of 26.6 kg per capita per year) [9]. As a result, in Greece, some estimate that the annual available UCO from both restaurants and homes could be as high as 220 kt, which, if totally recycled to biodiesel could potentially satisfy up to 9.5 % of the country's current diesel demand [10]. However, more than 60 % of household UCO is currently improperly disposed of, primarily to the sewage system, since, among others, widespread collection systems have not yet been introduced, as well as proper biodiesel distribution supply chain networks are limited [11]. Being this the situation, it has been estimated that the total amount of recoverable UCO in the EU was about 3.5 Mt in 2009 and that biodiesel produced from UCO could replace around 1.5 to 1.8 % of the EU-27 diesel consumption [12].

As mentioned above, currently the main route of UCO disposal is the sewage system. Every year vast quantities of UCO are poured into toilets and drains, contaminating water supplies and creating serious problems in wastewater treatment plants [13]. Specifically, UCO deposits in the sewage system cause blockages that could lead to sanitary sewer overflows, property flooding, and contamination of water bodies with sewage [6]. Furthermore, due to its bio-recalcitrant nature UCO disposal to the sewage system encumbers the wastewater treatment process, while due to its low solubility and low degradation rate in the biological processes it typically escapes intact from conventional wastewater treatment facilities, resulting to water and soil pollution [14, 15]. Its disposal to the sewage system also imposes additional costs on the wastewater treatment facilities [16], while only the electricity required for UCO degreasing is estimated at 28 kWh per m³ of UCO [17]. Hence, UCO recycling for biodiesel production has emerged as a promising strategy for its sustainable management [16].

Currently, there is a large trade deficit in fuels and mineral products in Europe, with more than 1,274 Mt imported but only 215 Mt exported [18]. It is a prerequisite to recycle UCO to biodiesel, especially under the circular economy concept [19], as a mean to improve Europe's energy supply and security. However, to encourage larger transformation schemes in Greece and Mediterranean, creditable analysis of the full chain environmental sustainability is required, to promote this sustainable alternative to petrodiesel.

Specifically, even though the technical and economic aspects of UCO recycling are well examined [7, 15, 16] and the optimal conditions for production are well, this is not the case for its environmental sustainability [17, 20]. Furthermore, the majority of household UCO is currently improperly disposed of [11], while the introduction of widespread collection systems is still pending [21]. In the EU, around 11.6 Mt/year of UCO-biodiesel are currently produced. In contrast, the capacity of the UCO refinery sector is over 21 Mt/year and this gap could be closed, at least partly, through domestic UCO recycling [19]. Consequently, there is a need to: i) supply the researchers and designers with an analysis of the UCO-to-biodiesel chain to support the further promotion of applied scientific and technical solutions, and ii) provide tools to decision- and policy-makers for introducing policies to further improve UCO collection and recycling schemes, in Greece, Europe, and the Mediterranean. In this work, the environmental performance of the second-generation (UCO) biodiesel is comprehensively examined using actual industrial life cycle inventory (LCI) data for the first time under the Greek setting. A comparative environmental analysis was carried out including comparison

with first- and third-generation biodiesel, as well as with petrodiesel. Finally, through sensitivity analysis, the effect of both total transportation distance and the means of transportation was further examined. The above analyses could provide context and insight on biodiesel environmental sustainability and also suggest promising routes towards decarbonising Greece's and Europe's transport sector.

2. System description

A UCO to biodiesel production system typically comprises of UCO collection from commercial or domestic sources and its transportation to the biodiesel production plant for processing. In this work, the environmental sustainability of a typical UCO to biodiesel production system was examined using actual LCI data, which were collected by consulting with a company that operates an industrial-scale biodiesel production plant in Greece (Elin Verd SA). Specifically, in the biodiesel production plant under study UCO processing entails first its pre-treatment and then a two-step acid-base catalyzed transesterification process, i.e. acid-catalyzed esterification and alkaline catalysts transesterification. Finally, the produced biodiesel is refined, i.e. washed, to improve its quality. All main steps of Elin Verd SA biodiesel production plant were considered herein (Figure 1), while a short description of each step is given below.

Figure 1: The main steps of the UCO to biodiesel production system under study.

2.1 UCO collection/transportation

In the context of this work UCO was assumed to be collected from i) commercial sources, such as fast-food restaurants and catering facilities and ii) drop-off collection tanks, typically used for domestically produced UCO. Both of these UCO sources are located in the prefecture of Rethymnon, the case study site of this work for UCO collection.

Specifically, the commercial sector in Rethymnon typically comprises UCO from restaurants, canteens, and the catering facility of the University of Crete campus in Rethymnon. In Greece, UCO is primarily produced through deep frying, followed by pan-frying, and to a much lesser degree by hot plate frying, with the deep frying of potatoes in

sunflower oil or palm oil and the pan-frying of fish in sunflower oil being common frying practices [22]. In general, commercial facilities in Greece typically gather the UCO in open-top drums and weekly collections are carried out, where the full drum is collected by small lorries, or in some cases by small vans, and replaced by an empty one. The full drum is then transported to the main collection point/hub, where it is uploaded in large tanks. The drums are then cleaned and prepared for delivery.

Regarding the domestically produced UCO in Greece, this is typically collected in drop-off collection containers/tanks (Figure 2). The collection tanks are placed in easily accessible points, such as in streets and supermarkets, where residents dispose of the UCO. In Rethymnon Prefecture, collection points have also been established in schools. Grease collection trucks are used for UCO collection and transportation to the main collection hub (Figure 2). Collection usually takes place at more extended periods, compared to the commercially produced UCO. This depends on many parameters, such as container volume and the awareness and involvement of local communities in the recycling of this important liquid waste. Similarly to the commercially produced UCO, the domestically produced UCO is also transferred to the collection hub, where it is uploaded in large tanks. From there UCO is then loaded into longer lorries (trucks thereafter) and transported first by ship to Athens and then by road to Elin Verd SA biodiesel production facility, which is situated in Volos, mainland Greece.

Figure 2: a) A UCO street drop-off container, in blue, yellow, and red colours, in Megali Akti port, Nea Peramos, Greece, b) and c) street drop-off containers and grease collection truck respectively, in Rethymnon, Crete, Greece.

2.2 Biodiesel production plant

In the context of this work, actual LCI data were collected from Elin Verd SA, which operates a 40 kt annual production capacity plant at Volos industrial area, Greece (Figure 3). The biodiesel production plant was commissioned in 2007 and initially, it was mainly based on the use of virgin vegetable oils for biodiesel production. However, in 2013 the plant was retrofitted to improve both i) the raw material flexibility, i.e. lower quality raw materials (UCO and animal fats) were included in its production process, and ii) the quality of the final product, i.e. achieving a high quality distilled biodiesel output.

Figure 3: The biodiesel production facility from where LCI data were sourced.

As such, currently, the biodiesel production plant can exclusively process waste oils and fats, such as UCO and animal fats, as raw materials for biodiesel production, while the produced biodiesel also meets the European standard EN 14214 and thus its overall quality is significantly better than conventionally produced biodiesel (Table 1). It should also be noted that the plant's production capacity can be increased from 40 kt to 80 kt/year; however, larger UCO volume would be required to sustain the larger production capacity, which is still missing. This also reflects the situation in Europe, where the UCO collected domestically cannot match the capacity of the UCO refinery sector (21 Mt/year) and UCO is regularly imported from third countries [19]. Obviously, stronger incentives for UCO recycling along with widespread collection systems and improved biodiesel supply chains [21] should be

introduced in Greece for the plant to operate at its maximum design. Below, a brief discussion on each of the plant's main production stages is given.

Table 1: The main physicochemical characteristics of the biodiesel produced at Elin Verd SA biodiesel production plant in Volos, Greece.

Parameter	Method	Unit	EN 14214		Typical Value
			min	max	
Density at 15 °C	EN ISO 3675	kg/m ³	860.0	900.0	879 - 883
Viscosity at 40 °C	EN ISO 3104	mm ² /s	3.50	5.00	4.00 - 4.50
Flash Point	EN ISO 3679	°C	101	-	165 - 175
Sulfur Content	EN ISO 20846	mg/kg	-	10.0	3.0 - 5.0
Cetane Number	EN ISO 5165	-	51	-	51 - 53
Sulfated Ash	ISO 3987	% m/m	-	0.02	<0.01
Water Content	EN ISO 12937	mg/kg	-	500	80 - 200
Total Contamination	EN 12662	mg/kg	-	24.0	<5
Copper Strip Corrosion	EN ISO 2160	rating	Class 1		Class 1
CFPP	EN 116	°C	-	13	(+1) - (+6)
Cloud Point	EN 23015	°C	-	16	(+2) - (+8)
Ester Content	EN 14103	% m/m	96.5	-	>99.0
Linolenic Acid Methylester	EN 14103	% m/m	-	12.00	0.70 - 1.00
Polyunsaturated Methyl Esters (≥ 4 double bonds)	EN 15779	% m/m	-	1.00	<0.6
Oxidation Stability at 110°C	EN 14112	Hours	8.00	-	>15.00
Acid Value	EN 14104	mg KOH/g	-	0.50	0.10 - 0.25
Iodine Value	EN 16300	g iodine/100 g	-	120.0	80.0 - 105.0
Monoglyceride Content	EN 14105	% m/m	-	0.70	<0.06
Diglyceride Content	EN 14105	% m/m	-	0.20	<0.01
Triglyceride Content	EN 14105	% m/m	-	0.20	<0.01

Free Glycerol	EN 14105	% m/m	-	0.020	<0.005
Total Glycerol	EN 14105	% m/m	-	0.25	<0.010
Phosphorous Content	EN 14107	mg/kg	-	4.0	<1.0
Metals I (Na / K)	EN 14108	mg/kg	-	5.0	<1.0
Metals II (Ca / Mg)	EN 14538	mg/kg	-	5.0	<0.5
Methanol Content	EN 14110	% m/m	-	0.20	<0.02

2.2.1 UCO pre-treatment

Firstly, UCO undergoes pre-treatment/purification, in order to enhance its quality so as to meet the specifications of the biodiesel production process. Specifically, cooking is a dehydration process and as such water, soluble compounds, and impurities are transferred from fried food to the hot oil [23]. Moreover, the high temperature of the oil in combination with the water that is transferred from the fried food accelerates the hydrolysis of triglycerides, which increases the content of free fatty acids (FFA) in the oil. This, along with the transferred water itself has considerable negative effects on the transesterification reaction and interferes with the separation of biodiesel and glycerol [15]. Therefore, in order to improve the UCO quality, Elin Verd SA employs gravity settling in combination with centrifugation to remove solid impurities, water, and water-soluble compounds from UCO. It should be noted that the materials and energy inputs required to drive this step are low compared to the remaining steps; however, Elin Verd SA did not provide a separate list of these inputs, but rather include them in the total inputs for biodiesel production. This does not affect the results.

2.2.2 Acid-catalyzed esterification

UCO contains a large amount (typically 2 – 7 %) of FFAs and as such its direct use for base-catalyzed transesterification can lead to soap formation (saponification), i.e. soap is a by-product of the reaction between FFAs and the base catalyst [24]. Specifically, FFA content higher than 0.5 wt% can lead to saponification [23], which leads to lowered yield, prevents the separation of biodiesel from glycerol [25] and increase the joint cost of separation and purification [24]. Therefore, UCO's FFAs have to be esterified, usually in

batch reactors under ambient pressure and mild temperature, before the transesterification of triglycerides can take place [23]. Esterification of oils with high FFAs content, such as UCO, is typically achieved through the acid-catalyzed process and thus this method is known as the two-step acid-base catalyzed transesterification [24]. Elin Verd SA makes use of the esterification process to remove excess FFA. This is achieved by using an acidic catalyst, i.e. sulfuric acid (H_2SO_4), in the presence of excess methanol (CH_3OH) in a continuous plug flow reactor, which is typically used in the UCO recycling industry [16]. After the esterification process, the esterified low-acidity oil undergoes the transesterification reaction described below.

2.2.3 Alkaline catalysts transesterification

Transesterification is the process that occurs when oil (vegetable or animal origin) and an alcohol (usually methanol (CH_3OH) or ethanol ($\text{C}_2\text{H}_5\text{OH}$)) are brought together in the presence of a homogeneous or heterogeneous catalyst. This is an alkaline-, acidic-, or enzymatic-catalyzed reaction that produces fatty acid methyl esters (FAME), while also glycerol ($\text{C}_3\text{H}_8\text{O}_3$) is also produced. The enzymatic-catalyzed reaction, i.e. lipase-catalyzed transesterification, is restricted by the rigorous reaction conditions and enzyme activity loss, and hence it is not used in large-scale commercial biodiesel production facilities. As a result, most biodiesel production plants use homogeneous alkali catalysts (sodium or potassium hydroxides, carbonates or alkoxides) since the application of these catalysts is comparatively cost-effective over the currently-available (eco-friendly) heterogeneous catalysts [16, 26].

Potassium hydroxide (KOH) is the most common catalyst used for the reaction of UCO with alcohol [15], with CH_3OH being the most commonly used alcohol, due to its low cost and physicochemical advantages (polar compound and short-chain alcohol) [23]. Moreover, potassium methoxide (CH_3KO) is also increasingly applied in recent years for biodiesel transesterification industrial applications, since the use of alcoholate instead of hydroxide allows for an increase in biodiesel output [27]. The transesterification process in the Greek biodiesel production plant takes place under the presence of excess CH_3OH and basic catalysts, mostly CH_3KO and to a lesser extent KOH, towards the production of FAME, i.e. biodiesel, in two continuous stirred tank reactors in series. Apart from FAME, the output of this unit contains numerous compounds, such as CH_3OH , potassium sulfate (K_2SO_4), and biodiesel distillation residue, which can be regarded as process co-products, while soap, catalyst, and wastewater that are regarded as waste.

2.2.4 Biodiesel refining

The produced biodiesel from the above-mentioned transesterification process is finally purified, in order to meet the European standard EN14214 for biodiesel used in diesel engines. Specifically, in Elin Verd SA plant the raw biodiesel undergoes three washing steps, one of which combines an acidulation step, and then it is vacuum dried so that the water level and CH_3OH and catalyst existence is minimized as to meet the EN14214 specifications. Since biodiesel produced from UCO might also contain heavy components (such as polymerized fatty acid methyl esters) or traces of sulfur, the washed and vacuum dried biodiesel is further processed using a vacuum distillation unit, in order for the final product to be ready for commercial applications.

Furthermore, a CH_3OH rectification unit is used in the biodiesel production plant in order to recover the CH_3OH that is contained in the process water. The recovered CH_3OH then undergoes distillation, as to improve its characteristics and be able to be re-used in the production process. It should be noted that in the context of the rectification of CH_3OH , the process water is initially evaporated in a multi-effect vacuum evaporator system, and then the light ends are separated in a distillation column. The clean distilled water is stored, as to re-use it in the process.

3. Environmental modeling and analysis

3.1. Goal and scope

The main goal of this work is to study the environmental performance and identify the main environmental hotspots of second-generation (UCO) biodiesel produced in the Greek setting. The environmental performance of UCO biodiesel was estimated employing the life cycle assessment (LCA) methodology, as set in ISO 14040:2006/DAmD 1 and ISO 14044:2006/DAmD 2. For the environmental modeling the software program SimaPro 8 was employed. The attributional LCA (ALCA) approach was chosen over the consequential (CLCA), since in the first the inventory of inputs and outputs, typically reflecting global or national averages and using normative allocation rules, is scaled linearly to the functional unit. On the other hand, the CLCA approach assesses the system-wide consequences of a change to the examined life cycle using marginal, or incremental, data and maintaining a cause-effect relationship [28]. Since, the main goal here is to evaluate the environmental performance of second-generation biodiesel, rather than assess the environmental

consequences of a change in its life cycle, the ALCA approach was used. It should be noted that the system under study is complex, generating different co-products; additional uncertainty can also be caused by choices regarding the UCO multi-functionality waste management processes. However, this analysis is outside of the goal of this work and all these could be addressed in future CLCA studies.

The geographical coverage of this work is Greece, Europe, and beyond and the time-related coverage refers to the present, i.e. 2019, while for the background system, average technology has been taken into account. Furthermore, the transport sector in Europe, and further afield, is grossly dependent on petrodiesel and as a result, is associated with the large carbon footprints. Therefore, the results of this work would be of interest not only to researchers, but also to decision- and policy-makers, as well as the transportation industry. All the above constitute the intended audience of this study. Finally, as a case study area for UCO collection Rethymnon Prefecture, island of Crete, was used, as to include in the analysis, a large number of islands in Greece.

3.2 Functional unit

The functional unit (FU) of an LCA study is chosen according to its goal and scope and it provides a reference to which all inputs and outputs of the system under study are normalised and expressed. In this work, the production of 1 ton biodiesel from UCO was considered as the FU and therefore the collected LCI data were normalised and results were expressed per ton of biodiesel produced. This FU was chosen since: (i) it provides context with the existing literature; (ii) it enables the direct comparison of the results of this work with the existing body of knowledge on biodiesel and petrodiesel; and (iii) it can accommodate an easier understanding and better communicate the results to non-specialized audiences, including the policymakers.

3.3. System boundary

The system boundary defines the smallest elements, i.e. unit processes, that are included in the LCI analysis and therefore, the elements for which input and output data are quantified. In this work all main inputs and outputs of the UCO to biodiesel production chain

were identified by consulting with Elin Verd SA and are included in the analysis, i.e. they are inside the system boundary (Figure 4).

Specifically, the transportation of both the commercially and domestically produced UCO to the collection hub, as well as the UCO transportation from the collection hub to the biodiesel production plant are included in the analysis. Furthermore, the drums, street drop-off containers, as well as the tanks used for UCO storage, are inside the system boundaries. Since the relevant LCI data for the grease collection truck (or vacuum truck) were not identified in SimaPro's proprietary databases, only the truck as a material is included in the analysis, i.e. the pump, tank, and the associated energy input for pumping is external to the system boundary. Land use for both the UCO collection hub and the biodiesel production plant was considered, i.e. is included in the system boundaries. It should be mentioned that land-use change, attributed either to the UCO collection hub or the biodiesel factory, is assumed that does not take place.

Regarding the biodiesel production plant, all chemical reagents consumed during the process, i.e. CH_3OH , H_2SO_4 , CH_3KO , and KOH , are included in the analysis; the same for the process co-products, i.e. crude $\text{C}_3\text{H}_8\text{O}_3$ and K_2SO_4 , and biodiesel distillation residue, which are also inside the system boundary (Figure 4). However, the refining of the crude $\text{C}_3\text{H}_8\text{O}_3$ and K_2SO_4 to produce marketable products is external. The tanks that are used for UCO and for biodiesel storage are included in the analysis; the same for the electrical substation (transformer and generator), which is used to ensure the plant's uninterrupted and safe operation, as well as for biodiesel washing water, i.e. inside the system boundary. The wastewater, originating from biodiesel washing, is also included in the analysis.

Furthermore, all energy inputs required in the biodiesel factory, along with the corresponding emissions to the atmosphere, are inside the system boundaries. These include i) the heavy fuel oil (mazut) burning, along with the corresponding airborne emissions and ii) the biodiesel distillation residue (e.g. polymerized fatty acid methyl esters), which is process by-product that is reused in the process (Figure 4). For the biodiesel distillation residue, the corresponding airborne emissions were taken into account, which were assumed to be similar to those of heavy fuel oil burning of the same mass.

Figure 4: The system boundary of the second generation biodiesel production system.

3.4 Life Cycle Inventory (LCI)

As mentioned above, actual LCI data were collected from an industrial (40 kt annual production capacity) biodiesel production plant and were used to model the environmental performance of the second-generation biodiesel. The plant's lifespan is 20 years. The collected LCI data were then used to express the mass and energy flows entering and leaving the UCO biodiesel production system per FU. For the environmental modelling, the mass and energy flows were taken from the SimaPro's proprietary databases, where possible. In their absence, proxy LCI data from the literature were used (Table 2).

Specifically, for commercially produced UCO in Rethymnon Prefecture a mean transportation distance of 60 km per ton of UCO, employing a Euro 4 emission standards small lorry (3.5 - 7.5 metric tons), was ascribed. Domestically produced UCO in Rethymno Prefecture is delivered by foot to the collection tanks and therefore a mean transportation distance of 20 km per ton of UCO, utilizing a grease collection truck (Euro 4 emission standards 3.5 - 7.5 metric tons lorry), was considered. For UCO transportation to the biodiesel facility, 330 km were ascribed to truck transport (16 - 32 metric tons, Euro 4 emission standard) and 300 km to ship transport. For UCO transportation, relevant data were identified and taken directly from SimaPro's proprietary databases (Table 2). High-density polyethylene (HDPE) drums (60 L volume) are used for the collection of commercially produced UCO. A 5-year lifespan was assumed, since their transportation stresses their

mechanical properties, leading to failures and breaks. For the drop-off collection tanks HDPE was considered as their main material, but in this case, having a 1,000 L mean volume and an estimated 10 years life span. Larger volume collection tanks, i.e. 5,000 L, made from mild steel are assumed to be used in UCO collection hub. Since data for the HDPE drums/tanks and the mild steel tanks were not identified in SimaPro's databases, LCI data were collected from the literature [29] and used as proxies. Here 70 % of the collected UCO was assumed to originate from commercial and 30 % from domestic activities, to account for the fact that the amount of the collected commercially produced UCO is currently larger than that of domestically collected UCO.

For the biodiesel production plant, most LCI data (Table 2) were taken directly from SimaPro's databases, except for CH_3KO [27] and for the stainless steel tanks [29] where proxy LCI data from the literature were used. It must be noted that $\text{C}_3\text{H}_8\text{O}_3$ and K_2SO_4 are both marketable co-products of the transesterification process. In this sense, energy and raw material consumption and emissions related to the production of their equivalent products are avoided. Specifically, the equivalent product to biodiesel-glycerol is synthetic glycerol from the petrochemical industry, while K_2SO_4 is sold as fertilizer to local farmers and thus its equivalent product is K-fertilizer [30]. To avoid the allocation process, the substitution process, i.e. system boundary expansion, was used. Thus, UCO biodiesel production was credited with avoided materials, energy consumption, and the associated emissions of synthetic glycerol and K-fertilizer production [30]. Furthermore, in total 13 stainless steel storage tanks, with capacities ranging from 56 - 1,184 m^3 (total capacity of 5,429 m^3) are used during the biodiesel production procedure. The produced biodiesel is then stored in 6 additional stainless steel storage tanks, each having a capacity of 125 m^3 . Similarly to the tanks used in the UCO collection hub, LCI data from the literature [29] were used as a proxy for these tanks. An electrical substation is also in place, to ensure the uninterrupted operation of the machinery and its safe emergency shut-down, comprising of a 1,250 kVA transformer and a 500 kVA generator. For the 1,250 kVA transformer and the generator Ecoivent's process for a high voltage transformer and a 200 kW generator, respectively, were used. In the latter case, two transformers were considered to account for the fact a 500 kVA is used in the biodiesel production plant. Regarding the biodiesel washing, the water input consumed in this stage is 11 wt% of biodiesel produced, with 6 % originated from the recovered distilled water and 5 % being freshwater. As such, here, 50 L of tap water was considered as input and 50 L of wastewater as output, both taken from Ecoivent database (Table 2).

Finally, all energy inputs in the biodiesel production plant are covered by mazut and biodiesel distillation residue burning, with the latter being a process by-product that is recycled within the process (Table 2).

Table 2: Life cycle inventory data for the production of one tonne of biodiesel from UCO.

Process	Input	LCI data reference
UCO collection and transportation		
Commercially produced:		
UCO to the hub	60 km	Ecoinvent 3 - Euro 4 lorry
Collection drum	LLPE (60 L)	[29]
Domestically produced:		
UCO to the hub	20 km	Ecoinvent 3 - Euro 4 lorry
Collection tank	LLPE (1,000 L)	[29]
Collection tank	Stainless steel (5,000 L)	[29]
Ship transport to plant	300 km	Ecoinvent 3
Land use	400 m ²	CORINE 121a
UCO transport to biodiesel facility	330 km	Ecoinvent 3 - Euro 4 lorry
Biodiesel facility (per ton of biodiesel)		
Input		
Used cooking oil	1,077 kg	Input from nature
Land use	1,000 m ²	CORINE 121a
Oil boiler	18,000 kg/hour	Ecoinvent 3 – Industrial furnace
		Ecoinvent 3 – transformer high voltage
Transformer	1,250 kVA	
Generator	500 kVA	Ecoinvent 3 – 200 kW generator
Storage tanks	Stainless steel (5,429 m ³)	[29]
Biodiesel tanks	Stainless steel (750 m ³)	[29]
CH ₃ OH	111 kg	Ecoinvent 3
H ₂ SO ₄	15 kg	Ecoinvent 3
CH ₃ KO	44 kg	[27]
KOH	4 kg	Ecoinvent 3
Mazut (heavy fuel oil)	64 kg	Ecoinvent 3
Washing water	50 L	Ecoinvent 3 – tap water
Output		
Biodiesel distillation residue	53 kg	Recycled in the process to provide energy – emissions were taken from Ecoinvent 3
Biodiesel	1,000 kg	Final product
C ₃ H ₈ O ₃	126 kg	U.S. LCI database - coproduct
K ₂ SO ₄	19 kg	Ecoinvent 3 - coproduct
Wastewater	50 L	Ecoinvent 3 - wastewater from vegetable oil refinery

3.5 Life cycle impact assessment (LCIA) stage

In order to examine the environmental sustainability of the second-generation biodiesel production, ReCiPe LCIA method was used. ReCiPe is a state of the art multi-issue method, harmonized both in terms of modelling principles and choices. It comprises both midpoint and endpoint approaches, which examine different stages in the cause-effect chain to calculate impacts/damages [31]. At midpoint level, a problem-oriented approach is accomplished, where impacts are translated into eighteen environmental themes (impact categories). The endpoint or damage-oriented approach translate environmental impacts into issues of concern (damage categories), i.e. human health, ecosystems, and resource availability. Due to data gaps and assumptions stacking up along the cause-effect chain, endpoint results are associated with higher levels of statistical uncertainty, compared to the midpoint, but are easier to comprehend by decision- and policy-makers and to be communicated to lay citizens and the general public [32]. In this work, the hierarchist (H) perspective was used, which is ReCiPe's default model and is based on the most common policy principles and on mean scientific consensus, while it assumes that with proper management environmental impacts can be avoided [32].

At midpoint level ReCiPe comprises the following impact categories: climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), ionising radiation (IR), agricultural land occupation (ALO), urban land occupation (ULO), natural land transformation (NLT), water depletion (WD), mineral resource (metal) depletion (MRD), fossil fuel depletion (FD). The units of the midpoint impact categories vary, as shown in Table 3, and thus cannot be aggregated. For this reason, in order to reach endpoint, ReCiPe converts and aggregates midpoint impact categories into three damage categories, i.e. i) damage to human health, ii) damage to ecosystem diversity, and iii) damage to resource availability, which can be further aggregated into a single score and allow a more effective communication of the results, even to non-specialised audiences [33]. The unit of measurement for ReCiPe single score results is the Eco-indicator Point (Pt), where 1000 Pt is the annual environmental load of an average European citizen [31].

446

447 4. Results and discussion

448 As mentioned above ReCiPe LCIA method was used, bot at midpoint and endpoint level, to
 449 model the environmental performance of the second-generation biodiesel, produced in the
 450 Greek setting. Results for the midpoint level are presented first and thence the results at
 451 endpoint level, along with a comparison with the first- and the third-generation biodiesel and
 452 with petrodiesel, are given.

453 4.1 ReCiPe results at midpoint level

454 To gain insight on UCO biodiesel environmental sustainability, ReCiPe LCIA method
 455 was first applied at midpoint level and by using the European reference inventories. The
 456 system was divided into two main sub-systems, i.e. i) the UCO collection and transportation
 457 stage and ii) the biodiesel production stage (biodiesel production plant). Results are shown in
 458 Figure 5, using ReCiPe's 18 midpoint impact categories (characterization). As was expected,
 459 the biodiesel factory has the higher contribution across midpoint impact categories, except for
 460 ULO, where transportation largely dominates this category, primary due to land occupied by
 461 roads (Figure 5).

462

463 Figure 5: The contribution of i) UCO collection and transportation and ii) the biodiesel
 464 production plant on ReCiPe's midpoint impact categories and per FU(1 t of biodiesel).

Table 3 shows the score of each midpoint impact category, along with the corresponding unit. Specifically, the results for UCO transportation, for biodiesel factory, and the total score, i.e. the score of UCO transportation plus the score of the biodiesel factory, in each of ReCiPe's midpoint impact category are shown. As mentioned above, the high score of UCO transportation to ULO category is mainly attributed to road infrastructure required for UCO transportation. On the other hand, the large contribution of the biodiesel production plant to the remaining impact categories is mainly attributed to mazut and biodiesel distillation residue burning, followed by the chemical reagents consumed in the transesterification process. Furthermore, the impact categories ME, TE, ALO, and WD yielded a negative score (Figure 5 and Table 3). This is attributed to the avoided environmental impacts originating from the co-products of the transesterification process, mainly to $C_3H_8O_3$ and to a lesser extent to K_2SO_4 .

Table 3: ReCiPe midpoint results (Characterisation) for the production of 1 tonne of biodiesel from UCO.

Impact category	Unit	Total	Transportation	Biodiesel plant
Climate change	kg CO ₂ eq	5.53E+02	8.20E+01	4.71E+02
Ozone depletion	kg CFC-11 eq	9.56E-05	1.45E-05	8.10E-05
Terrestrial acidification	kg SO ₂ eq	5.52E+00	3.32E-01	5.18E+00
Freshwater eutrophication	kg P eq	4.77E-02	6.97E-03	4.07E-02
Marine eutrophication	kg N eq	-1.31E-01	1.67E-02	-1.47E-01
Human toxicity	kg 1,4-DB eq	1.01E+02	2.11E+01	8.04E+01
Photochemical oxidant formation	kg NMVOC	1.66E+00	4.47E-01	1.21E+00
Particulate matter formation	kg PM10 eq	1.54E+00	1.67E-01	1.38E+00
Terrestrial ecotoxicity	kg 1,4-DB eq	-4.62E-01	3.15E-02	-4.94E-01
Freshwater ecotoxicity	kg 1,4-DB eq	2.20E+00	2.89E-01	1.91E+00
Marine ecotoxicity	kg 1,4-DB eq	2.30E+00	4.64E-01	1.84E+00
Ionising radiation	kBq U ²³⁵ eq	3.28E+01	6.10E+00	2.67E+01
Agricultural land occupation	m ² a	-1.88E+01	1.04E+00	-1.98E+01
Urban land occupation	m ² a	4.52E+00	3.80E+00	7.20E-01
Natural land transformation	m ²	1.86E-01	3.08E-02	1.55E-01
Water depletion	m ³	-3.32E+00	4.62E-01	-3.78E+00
Metal depletion	kg Fe eq	1.25E+01	3.52E+00	9.02E+00
Fossil depletion	kg oil eq	2.19E+02	2.94E+01	1.90E+02

It appears that in terms of carbon emissions, i.e. the CC midpoint impact category, the production of one tonne of biodiesel from UCO is responsible for about 553 kg CO₂eq, or, in other words, that UCO biodiesel production emits around 14 g CO₂eq per MJ of biodiesel fuel. This number is also in good agreement with existing literature [28]. However, LCIA

methods based solely on the carbon footprint tend to tell only half the story, since the remaining midpoint impact categories can largely affect the environmental performance of the process and thus should also be examined.

When results are normalized, using Europe's reference inventories, it is shown that environmental impacts are attributed, by and large, to the biodiesel production plant, while UCO transportation has a very low contribution across midpoint impact categories (Figure 6). Moreover, the impact category that is the most affected is NLT, when using the European reference inventories for normalisation. This is attributed to, from higher to lower score, mazut extraction/processing, CH_3OH production and use, natural gas required for CH_3KO production and sulfuric acid. All the above are fossil-fuels and fossil-fuel derived products and hence for their production large areas of natural land are transformed. For example, natural land is occupied and transformed during crude oil extraction and refining, e.g. infrastructure and access roads for crude oil extraction and transportation to the refinery [31].

Furthermore, the impact categories MET, FET, TA, HT, FD, FE, PMF, and CC are also affected, but to a lesser extent compared to NLT. The main contributors to those impact categories are: emissions from mazut extraction and burning, along with emissions from biodiesel distillation residue burning, as well as CH_3OH , CH_3KO and H_2SO_4 production. Specifically, MET is affected, from higher to lower score, by CH_3OH , mazut, KOH, and emissions from biodiesel distillation residue burning. FET is affected by CH_3OH production, KOH, and mazut. TA is mainly affected by mazut, emissions from biodiesel distillation residue burning, and CH_3OH . On the other hand, HT is mainly affected by CH_3OH , followed by mazut, emissions from biodiesel distillation residue burning, and CH_3KO . FD is affected by CH_3OH , followed by mazut, CH_3KO , H_2SO_4 , and to a lesser extent KOH. The score of FET is mainly attributed to CH_3OH , KOH, mazut and CH_3KO . Finally, PMT and CC are affected by mazut, followed by biodiesel distillation residue burning, CH_3OH , and CH_3KO .

Figure 6: The normalised scores of ReCiPe's midpoint impact categories attributed to the production of one tonne of biodiesel from UCO using Europe's reference inventories.

4.2 ReCiPe results at endpoint level and comparison with petrodiesel and first- and third-generation biodiesel

When results are expressed at endpoint level, the aggregated total environmental footprint per tonne (t) of the biodiesel is was found to be 58.37 Pt. From it, 8.52 Pt, i.e. 14.57 % of the total environmental footprint, is attributed to the transportation phase (2.12 Pt are attributed to domestically and 6.4 Pt to commercially collected UCO). The biodiesel production facility contributes the remaining 49.9 Pt, i.e. 85.4 % of the total environmental footprint. From this score, mazut is responsible for 40.3 % (23.6 Pt/t), CH₃OH for 27.8 % (16.2 Pt/t), CH₃KO for 20.5 % (12 Pt/t), biodiesel distillation residue burning for 17.8 % (10.4 Pt/ton), while glycerol and K₂SO₄, both marketable process co-products, resulted to avoided the environmental burdens of -7.45 Pt/t and -2.08 Pt/t respectively, i.e. a 16.37 % reduction on the biodiesel's production plant environmental footprint is attributed to these two co-products.

As shown in Figure 7, the damage category that is affected the most by second-generation biodiesel is human health (24.71 Pt/t), closely followed by resources (24.06 Pt/t), while ecosystems yielded a lower score (9.60 Pt/t). Specifically, the damage category human health is mainly affected by emissions originating from mazut and biodiesel distillation residue burning, and to a smaller degree by emissions originating from CH₃OH, CH₃KO and

KOH production. The resource availability damage category is affected by CH_3OH and mazut use, as well as to natural gas consumed during CH_3KO production. Also, the production of KOH and sulfuric acid contributed to this damage category, but to a lesser extent. The score on ecosystem diversity is attributed to mazut extraction and burning, followed by the emissions from biodiesel distillation residue burning, CH_3OH and CH_3KO use, and to a lesser extent to KOH.

In a nutshell, the UCO transesterification process is responsible for the majority of the environmental impacts. The underlying reason is twofold: firstly to the energy input, i.e. mazut and biodiesel distillation residue, required to drive the process, and secondly to the chemicals, mainly to CH_3OH and CH_3KO , consumed during the two-step acid-base catalyzed transesterification process. In detail, crude oil extraction and refining to produce mazut, as well as mazut and biodiesel distillation residue burning release toxic materials, such as heavy metals, sulfurous compounds and polycyclic aromatic hydrocarbons (PAHs) to the environment [31]. Moreover, worldwide the most widely used technique for CH_3OH production is by natural gas synthesis, which entails a combination of steam reforming and partial oxidation, with up to about 70 % energy efficiency [34]. Furthermore, CH_3KO synthesis is conducted in a continuous process in a closed circuit, with the initial raw materials being solid potassium and CH_3OH (the latter is recirculated in the process) [27]. As such, CH_3OH and CH_3KO contributions on the process total environmental footprint can be traced back to CH_3OH , and by extension to natural gas consumption, required their production [34]. It should be noted that since limited amounts of KOH are used, its contribution to the total environmental footprint is also minimal.

To provide context and insight, the identified environmental footprint of the second-generation biodiesel was compared to that of the first- and of the third generation biodiesel, produced in the Greek setting, and with petrodiesel. Specifically, the environmental footprint of the second-generation biodiesel was compared to petrodiesel having the same calorific value, i.e. one unit of biodiesel was comparable to 0.873 units of petrodiesel [35]. Petrodiesel's environmental footprint was identified using the same LCIA method as the second-generation biodiesel, i.e. ReCiPe (endpoint H/A). As shown in Figure 7, the second-generation biodiesel has a significantly lower total environmental footprint, about 3 times, compared to that of petrodiesel. Regarding the total environmental footprint of the first- and third-generation biodiesel, both had been identified in previous works of our group in the Greek setting [33, 35]. However, even though the latter had been identified using ReCiPe

(endpoint H/A), the total environmental footprint of the first-generation biodiesel had been estimated using Eco-Indicator 99 LCIA method. Eco-Indicator 99 is an endpoint LCIA method and is ReCiPe's predecessor at the endpoint level. To overcome this limitation petrodiesel's environmental footprint, which was identified by both the Eco-Indicator 99 and ReCiPe, was used as a mean to extrapolate the first-generation biodiesel total environmental footprint from Eco-Indicator 99 to ReCiPe, thus allowing the comparison in the context of this work.

In particular, when comparing the results with those of the first-generation biodiesel [35], it was found that the environmental footprint of the second-generation biodiesel is around 40 % lower than that of the best scenario (sunflower oil) for the first-generation biodiesel. Furthermore, when results are compared with those of the third-generation (microalgae) biodiesel, the environmental footprint of the second-generation biodiesel is substantially better (more than an order of magnitude lower). Specifically, Foteinis et al. [33] estimated that the total environmental footprint of biodiesel produced from *Nannochloropsis* sp. in an open and closed cultivation system, and under Greek climate conditions, would amount to 1.94 MPt/t and 11.22 MPt/t, respectively [33]. These are substantially higher than the 58.36 Pt/t of the second-generation biodiesel. However, these large differences were expected, since the third-generation biodiesel is not a fully-fledge technology yet, and therefore it is still associated with high environmental footprints [33].

Overall, results indicate the better environmental performance of the second-generation biodiesel, compared to its first- and third-generation counterparts as well as compared to petrodiesel. Nonetheless, according to estimates provided by Elin Verd SA, the share of UCO-biodiesel in the 187.000 metric tones per year Greek biodiesel market is only around 15%. Therefore, since currently the majority of household UCO is improperly disposed of [11], decision- and policy-makers should step in to promote strong incentives for UCO recycling, and to establish widespread UCO collection systems and biodiesel distribution networks [21]. Furthermore, given its overall low environmental footprint and its capability to be produced at commercial scales, UCO biodiesel could play a key role in decarbonizing Europe's transport sector. It could also improve fossil fuel supply and energy security in Greece, Europe, and further afield. Finally, results are suggestive of the large strides that have been made during the past years in producing environmentally sustainable liquid biofuels at commercial scales.

Figure 7: The total environmental impacts of the second-generation biodiesel and its comparison with petrodiesel and first- and third-generation biodiesel. *Results taken from Tsoutsos et al. [35] have been generated by Eco-indicator 99 LCIA method and in the context of this work were extrapolated to approximate ReCiPe results.

5.3 Scenario/sensitivity analyses

5.3.1 Effect of avoiding UCO degreasing in wastewater treatment plants (WWTPs)

The environmental impact of UCO improper disposal depends on many specific and local parameters, such as the pathway to the environment and the ecosystem of the receiving water bodies or soil. Since WWTPs are the main recipients of improperly disposed UCO, a scenario dealing with the effect of avoiding the degreasing process of UCO in WWTPs was examined. Following Caldeira et al. [17], 0.028 kWh are required for the degreasing process per L of UCO in a typical WWTP. Therefore, the substitution process was applied and the avoidance of 28 kWh, from the fossil-fuel dependent Greek energy mix, was ascribed per m³ of collected UCO. It was found that only the avoided environmental impacts from UCO degreasing process in WWTPs would decrease the environmental footprint of the second-generation biodiesel by around 6 % or it would reduce it by 3.33 Pt/t making it 55.04 Pt/t instead of 58.37 Pt/t. These environmental savings refer only to electricity consumption from the Greek energy mix and only for the wastewater treatment degreasing process, and not to the overall energy/material savings and the avoided environmental impacts from UCO disposal to the sewage system. However, the environmental gains attributed to avoiding UCO degreasing process in WWTPs can inform decision and policymakers about the many possible environmental benefits of UCO recycling for biodiesel production, instead of its disposal to the sewage system.

620

621 **5.3.2 Effect of distance, mode, and means of transport**

622 The effect of the: i) transportation distance, ii) the mode (road transport and ship
623 transport), and iii) means (vehicle type) of transport on the system's environmental
624 sustainability was examined. This was achieved by taking into account both different
625 transportation distances and different modes and means of transportation. Specifically, apart
626 from the base scenario, i.e. UCO is collected in Rethymnon, transported by ship to mainland
627 Greece and then by truck to the biodiesel production plant in Volos, the following scenarios
628 were examined: 1) the biodiesel plant is located in Rethymnon and thus ship and truck
629 transport are not required (i.e. the UCO collection hub is inside the biodiesel plant); 2) the
630 biodiesel production plant is located in the city of Heraklion, (the biggest city of Crete and
631 ~80 km away from Rethymnon), and the UCO collection hub is located in Rethymnon, thus
632 only truck transport is required; 3) the biodiesel production plant and the UCO collection hub
633 are both located in the city of Heraklion and only transport by small lorries is required; 4) the
634 UCO collection hub is located in Rethymnon but the UCO is transported to the Heraklion,
635 where frequent ship connection to the mainland Greece is available year-round, and thus
636 additional truck transport is required; 5) the UCO collection hub is located in Heraklion and
637 biodiesel production plant in Volos, thus additional lorry transport is ascribed both to
638 domestically and commercially collected UCO.

639 Furthermore, the effect of the means of road transport was examined. First, the effect
640 of using a different emissions standard vehicles was examined by taking into account
641 scenario 6, where the use of the best available technology for road transportation (EURO 6)
642 was considered, and scenario 7 where worse emissions standards (EURO 3) vehicles,
643 compared to the base scenario, were considered. Furthermore, in scenario 8 the effect of
644 using a light commercial vehicle, instead of a small lorry, for commercially produced UCO
645 transportation was examined. Finally, a best-case scenario (scenario 9), where the best
646 available technology for road transportation (EURO 6) is combined with the minimum
647 transportation distance (as in scenario 1), and a worst-case scenario (scenario 10), where the
648 use of a light commercial vehicle is combined with the maximum transportation distance (as
649 in scenario 5) and by using a lower emission standards vehicles (EURO 3) for truck transport,
650 were considered. The abovementioned transportation scenarios are shown in Table 4.

Table 4: Sensitivity analysis regarding the total distance and the means of UCO transportation.

Means of transport	Scenario name										
	Base	1	2	3	4	5	6*	7**	8	9	10
Commercially produced UCO											
Small lorry (3.5-7.5 metric tons)	60	6 0	6 0	140	60	140	60	60	-	6 0	-
Light commercial vehicle	-	-	-	-	-	-	-	-	60	-	140
Domestically produced UCO											
Small lorry (3.5-7.5 metric tons)	20	2 0	2 0	100	20	100	20	20	20	2 0	100
Transportation from UCO collection point/hub to the biodiesel production facility											
Truck (16-32 metric tons)	10	-	9 0	-	90	10	10	10	10	-	10
Ship	300	-	-	-	300	300	300	300	300	-	300
Truck (16-32 metric tons)	320	-	-	-	320	320	320	320	320	-	320

* EURO 6 emission standard

** EURO 3 emission standard

The results of the sensitivity analysis, regarding both the total transportation distance and the mode and means of transport, are shown in Figure 8 and are listed in Table 5. It should be noted that ship transport only slightly affects the results, while the total distance and particularly the type of vehicle used in road transport grossly affects the results. Specifically, compared to the base scenario, scenarios 1, 2, and 3 have a lower total environmental footprint (Table 5), since in these scenarios the mode of transport, as well as the distance, is reduced. More specifically, in these scenarios ship transport is not required, while in scenario 1 truck transport is also not required, which lead to a large reduction (10.24 %) on the system's total environmental footprint. Furthermore, in scenario 2 and 3 the total environmental footprint of the process is reduced by 7.88 %, and 3.10 % respectively. The main difference between these two scenarios is that in scenario 3, truck (16-32 metric tons)

transportation is replaced by lorry (3.5-7.5 metric tons) transportation, which leads to a higher total environmental footprint compared to scenario 2. This suggests that the smaller the vehicle the higher the environmental footprint, which was expected. This is further corroborated by scenario 8, where the lorry (3.5-7.5 metric tons) transportation employed in the base scenario is replaced by light commercial vehicle transportation and the system's total environmental footprint largely increases (10.90 %). Furthermore, the use of vehicles with newer (EURO 6) or older (EURO 3) transportation technology, compared to the base scenario (EURO 4) only slightly improves (0.56 % reduction) or decreases (0.58 % increase) the system's total environmental footprint.

Table 5: ReCiPe results (single score H/A) of the sensitivity analysis regarding total distance and the means of UCO transportation.

Scenario	Base	1	2	3	4	5	6	7	8	9	10
Score (Pt)	58.37	52.39	53.77	56.56	59.76	62.55	58.04	58.71	64.74	52.32	65.90
Variation	-	-10.24%	-7.88%	-3.10%	2.38%	7.16%	-0.56%	0.58	10.91%	-10.36%	12.90%

Finally, large differences in the system's environmental sustainability were observed in the best- and worst-case scenarios (Table 5 and Figure 8). Specifically, compared to the base scenario in the best case scenario (scenario 9), the total environmental footprint of the systems is reduced by 10.36 % while in the worst-case scenario it largely increases by 12.90 % (Table 3). In these scenarios, the contribution of UCO transportation is minimized (4.72 %) or maximized (24.3 %), respectively. All the above suggest the strong dependence of the distance and means of transport on UCO's-biodiesel environmental sustainability.

Method: ReCiPe Endpoint (H) V1.13 / Europe ReCiPe H/A / Single score

Figure 8: The results of the 10 different scenarios dealing with the sensitivity analysis of different means of transportation and different transportation distances.

6. Conclusions

The environmental performance of biodiesel fuel production from used cooking oil (UCO), a promising raw material for advanced biofuel production, was examined. The life cycle assessment (LCA) methodology was applied using actual life cycle inventory (LCI) data, collected from a commercial-scale biodiesel production plant in Greece. ReCiPe, a multi-issue life cycle impact assessment method (LCIA), was applied, both at the midpoint and endpoint level, to estimate the system's environmental impacts/damages. The results were also compared with petrodiesel and with its first- and third-generation biodiesel counterparts. It was found that UCO-biodiesel environmental footprint was 58.37 Pt/t and it is mainly attributed to the transesterification process and especially to emissions from mazut and biodiesel distillation residue burning, followed by alcohol (i.e. CH_3OH) and potassium methoxide (CH_3KO) used in the base-catalyzed transesterification process. Glycerol ($\text{C}_3\text{H}_8\text{O}_3$) and potassium sulfate (K_2SO_4), both process co-products, reduced the total environmental footprint by -13.7 % and -3.84 %, respectively.

UCO transportation contributed 14.57 % to the total environmental footprint. However, when possible scenarios that entail both shorter and longer transportation distances and different means of transportation were examined its contribution largely varied, from as little as 4.72 % (scenario 9 of the sensitivity analysis section) to as high as 24.3 % (scenario 10). This suggests the strong dependence of the system's environmental sustainability on the means and transportation distance. Moreover, when taking into account the avoided energy consumption of the degreasing process in wastewater treatment plants, it was identified that UCO's-biodiesel environmental footprint is decreased by about 6 %. This environmental saving refers only to the avoided electricity for the UCO degreasing process in a typical wastewater plant, and not the environmental benefits of avoiding UCO soil and water pollution. Nonetheless, it highlights the possible environmental benefits of using UCO for biodiesel production and also can inform decision- and policy-makers about the need for recycling this important waste.

Finally, the total environmental footprint of UCO biodiesel was found to be about 3 times lower compared to petrodiesel's total environmental footprint of the same calorific value. It was also around 40 % lower than the first-generation and at least one order of magnitude lower than the third-generation biodiesel. Given low environmental footprint of UCO biodiesel, it is suggested that this alternative fuel could play a key role in decarbonizing Europe's transport sector and improving fossil fuel supply and energy security in Greece, Europe, and beyond.

7. Declaration of interest

None

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