Waste and Biomass Valorization
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Used Cooked Oils in Sewage and Wastewater System: Qualitative Characterisation and Environmental Impacts Assessment in Different Discharge and Recovery Pathways

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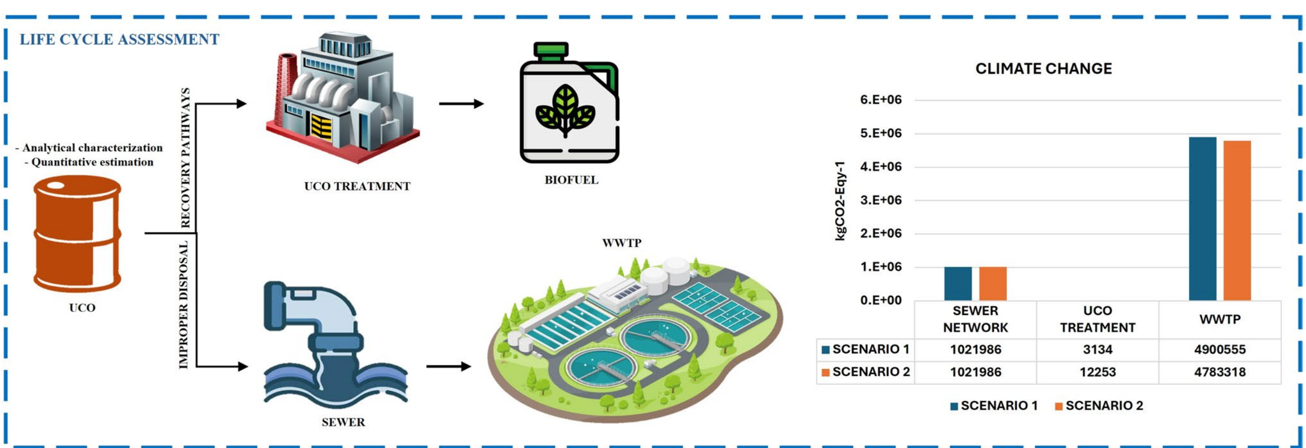
Abstract

Nowdays only 30% of domestic used vegetable oil is currently recovered, with significant quantities discharged into sewer systems, strongly contributing to environmental degradation. Converting used cooked oil (UCO) into biodiesel is the most suitable approach to minimize environmental impacts and exploit the potentiality of a valuable resource. Although biodiesel is widely recognized as a promising technology for clean electricity production, the environmental impacts and its advantages in terms of carbon footprint remain partially unclear in the territorial framework. This study investigates and quantifies the technical and environmental impacts associated with the production, consumption and recovery of used cooking oil in Italy and Europe through life cycle assessments (LCA) approach. Different Scenarios, considering partial oil recovery, partial discharge in the sewage system and total oil recovery for biodiesel production, were investigated. Real data were collected by a territorial company in central Italy. LCA results reveals the transition from the Scenarios, resulting in a significant improvements in terms of environmental indicators especially, in order of prorioty, as climate change, freshwater eutrophication and terrestrial acidification. Overall, considering the total oil recovered and biodiesel production, the carbon footprint mitigation shows 14–27% reduction in CO_2 (carbon dioxide) emissions in respect to the Scenario where the oil is partially recovered, equivalent to an environmental impact of 48–199 Pey^{-1} (people equivalent per year).

Graphical Abstract



Keywords Biodiesel · Circular economy · Life cycle assessment · Used cooked oil · Sewage and wastewater systems

Abbreviations

UCO	Used cooked oil
RUCO	Resued cooked oil

Extended author information available on the last page of the article

LCA	Life cycle assessment
CO_2	Carbon dioxide
PE	Person equivalent
LHV	Lower heating value
FAME	Fatty acid methyl esters
HVO	Hydrotreated vegetable oil
CONOE	Consortium for the collection and treatment of waste oils and fats

Statement of novelty

The study was developed through a targeted literature review on the production and consumption of cooked oil innational and European contexts. However, real characterization data for oils discharged into sewer systems are notavailable in the existing literature, nor is there a systematic overview of their quality and quantity. To address thisgap, qualitative characteristics were obtained from real collected samples. Territorial scenarios were then defined,considering different proper and improper end-of-life pathways for treated oil. Unlike most previous studies, whichtypically do not assess environmental impacts, the present work evaluates the environmental consequencesassociated with the different management configurations.

Introduction

To address the critical challenges of climate change, pollution and dependence on fossil fuels, the European Union has adopted the European Green Deal as a strategic framework to address environmental challenges [16]. This comprehensive policy initiative aims to achieve climate neutrality by 2050 while promoting sustainability and the transition towards a circular economy. An important challenge for environmental sustainability is the efficient management of organic waste, whose volumes keep increasing as a result of population growth, urbanization, and industrial development [3]. Within this framework, the Circular Economy Action Plan reinforces the objectives of the European Green Deal by promoting resource efficiency, waste prevention, and the valorization of secondary raw materials across the European Union [1]. In line with these objectives, life cycle thinking [24] represents a fundamental approach for assessing sustainability, as it enables the evaluation of environmental impacts across the entire life cycle of products and waste management systems, thereby avoiding burden shifting between life cycle stages.

In terms of sustainability initiatives promoted by the European Union, the National Consortium for the Collection and Treatment of Waste Oils and Fats (CONOE) plays a central role in the management and valorization of used oils and fats in Italy. Although the organizational structure of such consortia is defined at the national level, their activities are aligned with the principles established by Directive 2008/98/EC on waste, which provides the legal framework for waste prevention, reuse, recycling, and recovery across the European Union. The treatment and discharge of wastewater containing oils and fats are also regulated by Directive 91/271/EEC on urban wastewater treatment, which sets quality standards and operational guidelines for wastewater collection and treatment systems, particularly with regard to minimizing the environmental impacts of fats, oils, and grease discharged into municipal sewer networks. Despite the existing guidelines and established measures, only a small portion of the oil appears to be effectively recovered through appropriate plants. However, there is a notable lack of systematic studies that quantitatively and qualitatively describe the domestic flows of vegetable and animal oils generated by human activities, as well as their specific final destinations. The recovery of used cooked oil is a key practice for environmental protection and the promotion of sustainability. Recycling cooked oil into a useful resource (RUCO) helps to reduce the dispersion of oil in the environment, preventing damage to ecosystems and decreasing dependence on raw materials. This process not only reduces waste, but also decreases greenhouse gas emissions, supporting a more responsible and eco-friendly production cycle. Within the circular economy framework, UCO can be converted into renewable energy through cogeneration plants or valorized into several products, including biolubricants, cosmetics, industrial soaps, inks, and especially biodiesel [37], which is widely recognized as a viable alternative to fossil-derived diesel due to its comparable fuel properties [22]. The economic sustainability of biodiesel production relies on minimizing feedstock costs through efficient, low-energy extraction technologies that enhance overall profitability [30]. Biodiesel can be blended with fossil fuels, contribuiting to CO_2 emissions reduction in the transport sector. In the CONOE perspective, 90 per cent of used vegetable oils is used for the production of biodiesel, thanks to the influence of European directives promoting recycling and the use of renewable energies [9]. Biodiesel is produced via FAME (Fatty Acid Methyl Esters) or HVO (Hydrotreated Vegetable Oil) processes. FAME allows blending with fossil diesel but has some limitations. HVO, developed by ENI and Honeywell, uses hydrogenation to produce a high-quality, energy-rich renewable fuel, addressing FAME's drawbacks [33].

On the other hand, the improper disposal of used cooking oil, particularly its release into sewer systems, results in significant operational challenges and elevated maintenance expenditures. Oil residues stick to pipeline walls through a phenomenon called saponification, reducing pipe diameters and forming granular deposits requiring high-pressure cleaning to be removed [28]. Furthermore, waste oil can degrade and corrode metal and concrete elements of wastewater treatment plants [12]. From the environmental point of view, UCO forms surface films that block oxygen exchange, harming aquatic life and contributing to eutrophication, often with toxic algal blooms. In soil, it alters pH and contaminates water used in agriculture, increasing fertiliser demand and worsening eutrophication [23, 29]. This issue is expected to gain increasing attention in the coming years, particularly in light of the new European Urban Wastewater Directive (EU Directive 2024/3019)[30], which address the need of the development of territorial risk management plans. These plans will require a deeper analysis of non-conventional domestic-origin pollutants, including waste oils, to address their environmental and infrastructural impacts comprehensively. In this context, the integration of used cooking oil into circular economy models, particularly through its conversion into bio-based products, represents a sustainable alternative to conventional disposal practices. The novelty of this study lies in the quantitative assessment and quality characterization of used cooking oil flows and in the evaluation of the environmental implications of alternative technological discharge and recovery pathways providing life cycle–based evidence to support technology-oriented decision-making. It also provides a focused literature review on cooking oil production and consumption at both national and European levels, highlighting that no comprehensive cycle-level data are currently available in the existing literature. Overall, the study contributes to the development of resource-oriented wastewater management and supports the transition toward sustainable waste-valorization strategies.

Materials and Methods

Qualitative and Quantitative Data Collection of Oil Production

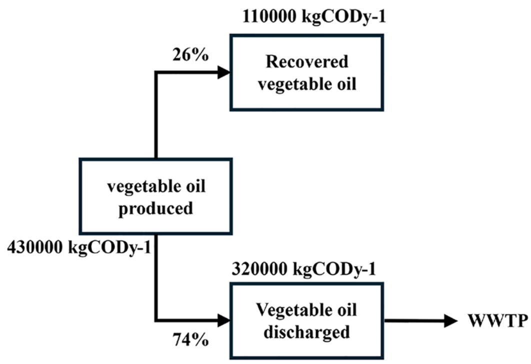
The study assesses the production, consumption and disposal of vegetable oils, with a particular focus on used cooking oil, in Italy and Europe. Different sources included the CONOE Annual Report 2018, the Statista portal, the [20] report, "L'Italia del riciclo" 2021, "Riciclo in Italia" [36], and the CE Delft report titled "Used Cooking Oil as biofuel feedstock in the EU" [42] were taken to account for the extrapolation of data. The selected time frame for the data ranged from 2010 to 2021 to investigate recent trends and changes in practices. Specific attention was given to per capita results to allow for standardized comparisons. Qualitative data of oil primarily comes from restaurant sector in central Italy area, with average production data and physico-chemical characterization provided by a local company specializing in waste oil treatment and recovery. The quantitative and qualitative characterization results were used to establish the UCO mass flow, expressed as COD, in the investigated Scenarios. By combining the average per-capita production of waste cooking oil in Italy with the COD characterization of the UCO sample, it was possible to quantify the mass flows assessed in this study.

Life Cycle Inventory and Identification of Scenarios

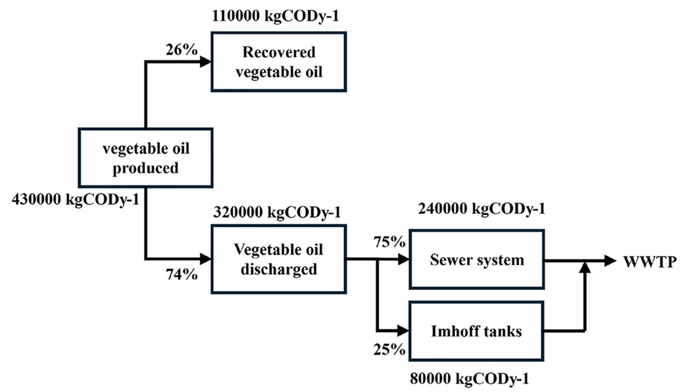
The core of the research regards an oil treatement plant in the central Italy and its capacity to convert UCO in RUCO investigating different Scenarios. This study includes also two additional steps more than the oil treatment plant, the wastewater treatment plant and the sewer network. Four different Scenarios was investigated to allow the comparison of different framework changing the amount of used oil recovered and treated by the plant. Finally, a domestic water supply of 250 lAE-1d-1, a spillage coefficient of 0.9 [31] and a nominal capacity of 100,000 AE were considered to identify the impacts of a typical wastewater plant in order to have an overall view of the whole scheme. In Table 1, a summary of the different Scenarios are presented considering the mass balance in term of COD load. The concentration of COD is equal to 1 $kgCODkgUCO^{-1}$ (see section "Qualitative Parameters of Oil: UCO and RUCO Characterization") and the inhabitants considered are 100,000 AE. The choice of expressing impacts per 100,000 population equivalents is motivated by the possibility of directly retrieving the environmental burden of a wastewater treatment plant with a comparable capacity (1E09 ly^{-1}) from the Ecoinvent database (Ecoinvent 3.6). This enables a consistent and straightforward comparison between the impacts of the UCO treatment process and those associated with a conventional wastewater treatment system of equivalent scale.

This section presents the methodologies for quantifying the environmental impacts of the intervention. In this sense, it is specified that the object of comparison and analysis of the sustainability aspects are the Scenarios 1 and 2 shown in Table 1. In addition, the carbon footprint ($kgCO_2eqy^{-1}$) was also determined for Scenarios 1B and 1C in parametric way. In the biofuel-based electricity Scenario, the avoided burden approach was applied by subtracting the CO_2eq emissions associated with an equivalent amount of fossil-based electricity from the initial carbon footprint. The environmental assessment was carried out by LCA methodology. LCA stands for Life Cycle Assessment and is a tool for assessing the possible environmental impacts of a product, activity or process along all stages of the life cycle [17]. The structure of LCA, following the ISO 14044 [25], is summarised in 4 different steps. Initially, the definition of aims and objectives where objectives, functional unit, system boundaries, assumptions and limits are defined [11],In this case, the objective of the project is the environmental assessment of the different Scenarios shown in Table 1 with a particular

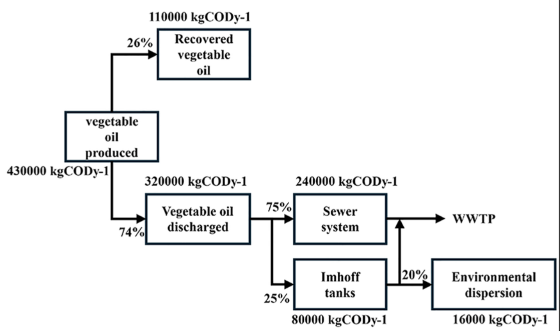
Table 1 System boundary definition and Scenario description



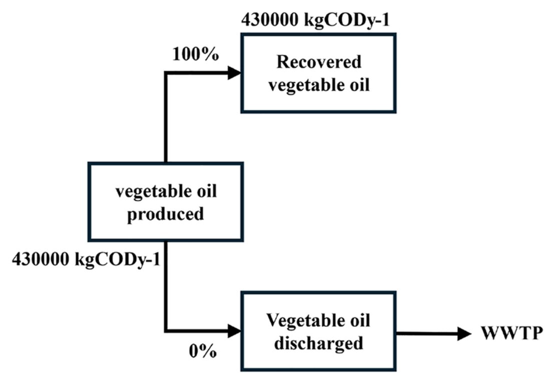
Scenario 1A



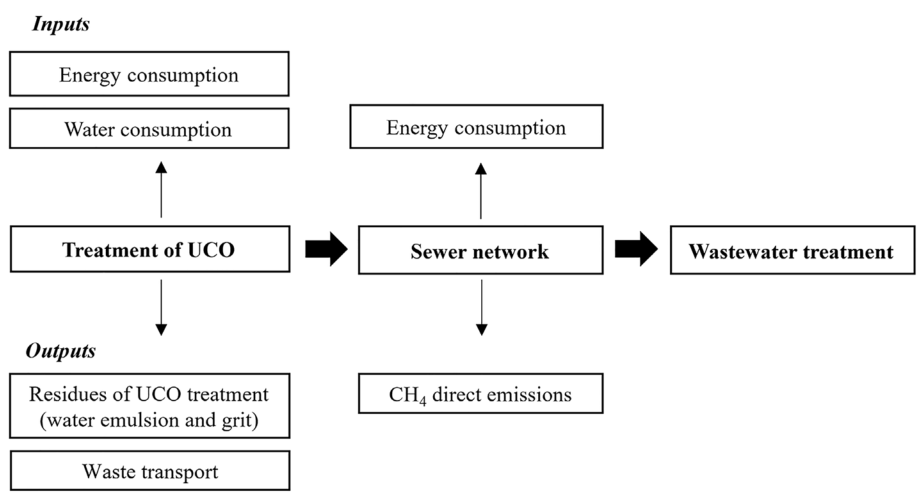
Scenario 1B



Scenario 1C



Scenario 2



SYSTEM BOUNDARIES

focus on carbon footprint. In this study, the functional unit corresponds to the yearly inputs associated with 100,000 population equivalents. This choice provides a representative scale for assessing environmental impacts and facilitates comparison with similar systems. The boundary of the system, presented in Table 1, involves the UCO treatment, the sewer network and the wastewater treatment plant. For each investigated Scenario presented in Table 1, the mass flows also vary accordingly. The initial partition among recovered and discharged vegetable cooked oil derived from the results of the literature research presented in section "Production and Consumption of Cooked Oil in Italy and Europe". However, the system boundaries of the units remain unchanged across all Scenarios. The sewerage system was modelled considering only the environmental impact due to electricity consumption evaluated on the basis of the AE connected to the network and estimated to be 14.5 $kWhy^{-1}AE^{-1}$ following a territorial analysis (in the same order of [34]). Finally, in Table 1, all the Scenarios and the boundary of the system are presented.

Following the definition of the objectives, the inventory analysis phase, where input and output flows are listed, [10] was developed. Data for the LCI were collected from multiple sources, including operational data from the oil treatment plant (eg. energy and water consumption, waste produced and its transportation considering the distance from the production to the disposal site), technical specifications and literature data. The LCA analysis was conducted using the Umberto® LCA + v10 software and the Ecoinvent v3.6 database. All the inputs and outputs collected in this study are presented in Table 2.

The next phase is the Life cycle impact assessment (LCIA) where life cycle inventory's information on elementary flows is translated into environmental impact score [38]. The methodology used for the impact assessment was ReCiPe 2008 H [19]. The environmental impacts were assessed considering each impact categories of the method. The assessment can be evaluated at midpoint level, as in this case, or to endpoint level. The midpoint approach provides results for different impact indicators while the Table 1 approach features simple and easily understandable damage categories, providing results with a lower level of interpretive uncertainty compared to the midpoint approach [45].

The last section of LCA relates with the interpetretation of the results in which an overall comparison of the main findings are carried out, evaluating the differences and possible improvements among different Scenarios.

Table 2 Life cycle inventory for both investigated Scenarios

	Parameter	Scenario 1	Scenario 2	Ecoinvent 3.6 Database
UCO treatment	*Input*			
	Electricity [$kWhy^{-1}$]	3764	14,715	electricity, medium voltage, Italy (2014–2019)
	Methane [sm^3y^{-1}]	241	942	market for methane, 96% by volume [RoW], (2011–2019)
	Water [m^3y^{-1}]	14,458	56,518	market for tap water [RoW], (2012–2019)
	Output			
	Grit [kgy^{-1}]	740	2896	sewage sludge, dried [RoW], (2009–2019)
	Water emulsion [kgy^{-1}]	10.84	42.4	market for wastewater, average [Row], (2011–2019)
	Grit transport [$kgkmy^{-1}$]	20,817	81,377	market for transport, freight, lorry 3.5–7.5 metric ton, EURO4 [RoW], (2009–2019)
	Water emulsion transport [$kgkmy^{-1}$]	2287	8940	market for transport, freight, lorry 3.5–7.5 metric ton, EURO4 [RoW], (2009–2019)
Sewer network	*Input*			
	Electricity [$kWhy^{-1}$]	1,450,000	1,450,000	electricity, medium voltage, Italy (2014–2019)
Wastewater treatment	Wastewater treatment plant [m^3y^{-1}]	10,012,500 (8,212,500 + 1,800,000*)	9,772,970 (8,212,500 + 1,560,470*)	treatment of wastewater, average, capacity 1E9l/year [Europe without Switzerland], (1994–2019)

*Quantity of waste (CER 200306) discharged into the sewerage system and subsequently treated by the treatment plant

Results and Discussion

Production and Consumption of Cooked Oil in Italy and Europe

According to the [9] Annual Report, the average annual consumption of vegetable oils in 2017 was 1.4 million tonnes, divided almost equally between seed oils and olive oil. Based on the Italian population, this corresponds to a per-capita consumption of 23 kg of oil per year. With regard to used cooking oil, approximately 260 thousand tonnes are generated annually, equivalent to 4.3 kg per person per year, as confirmed by [21]. In 2017, the amount of collected used cooking oil was 72 thousand tonnes, corresponding to 1.2 kg per person. The quantity not collected amounted to 188 thousand tonnes, or 3.1 kg per person per year. Furthermore, approximately 90% of the collected oil is recovered, while the remaining 10% is sent for disposal [9]. The 2017 report by Greenea, a French company involved in waste management and renewable energy production, indicates that 156,000 tonnes of used oil are produced from the domestic sector, while only 15,000 tonnes are collected. Assuming that used oil from domestic activities accounts for 64%, the total amount of used oil produced would be approximately 240,000 tonnes, corresponding to 4 kg per person per year [20].

In the reports "L'Italia del riciclo 2021 and "[36]", the amounts of used oil produced in 2020 and 2021 are reported: 290,000 tonnes in 2020 and 260,000 tonnes in 2021, corresponding to 4.9 kg per person and 4.4 kg per person per year, respectively. Additionally, the reports indicate that the amount of used oil collected increased by 18% from 2016 to 2021 [18, 36]. The CE Delft report provides data on the amount of used oil produced and collected in 2015 [42]. The amounts of used oil produced is equivalent to 3.8 kg per person per year while the recovered correspond to 1.1 kg per person per year.

The literature review was also enlarged in European terms and all the data provided are summarised in Table 3.

In terms of percentage contribution of each category in Italy, considering the average value of the results, the produced vegetable cooked oil is the 27% of the total vegetable oil consumed while the collected vegetable cooked oil is the 26% of the produced. The remaining portion (76%) is discharged into the sewer network. The partition of produced and collected vegetable cooked oil was used to implement the Scenarios presented in Table 1. In the collected cooked vegetable oil the major amount is recovered (89%) while the 11% is disposed in a proper manner. The remaining part of the cooked vegetable oil which is not collected was probably discharged in the sewer network. About the European framework, it shows the consumed vegetable oil is 47.89 ± 1.95 $kgPE^{-1}y^{-1}$while the produced vegetable cooked oil is around 4.96 ± 1.95 $kgPE^{-1}y^{-1}$. The collected and discharged vegetable cooked oil are respectively 1.62 ± 0.65 $kgPE^{-1}y^{-1}$ and 1.96 ± 0.25 $kgPE^{-1}y^{-1}$. Compared to the European average, Italy reports substantially lower values for consumed vegetable oil (16.1 ± 3.3 vs. 47.89 ± 1.90 $kgPE^{-1}y^{-1}$). On the other hand, the research shows similar results for produced vegetable cooked oil (4.29 ± 0.25 vs. 4.96 ± 1.95 $kgPE^{-1}y^{-1}$) but lower values in term of collected vegetable cooked oil (0.94 ± 0.25 vs. 1.62 ± 0.65 $kgPE^{-1}y^{-1}$). About the amount of oil discharged into the sewer network Italy show higher values in comparison with the European framework (0.10 ± 0.03 vs. 1.96 ± 0.25 $kgPE^{-1}y^{-1}$).

Qualitative Parameters of Oil: UCO and RUCO Characterization

Qualitative characterization of Used Cooked Oil (UCO) and Reused Cooked Oil (RUCO) was carried out by standard methodologies. The analysis covers various chemical parameters to assess the quality and properties of both UCO and RUCO. Three samples (S1, S2, S3) of UCO (21/12/2022; 27/04/2023; 31/08/2023) and three samples of RUCO (28/04/2023; 10/08/2023; 28/09/2023) were assessed. The results of the analysis are reported in Table 4 and in the supplementary material.

The analysis of the UCO characterization indicates that barium, chromium, and nickel are the most prevalent metals. The COD concentration results to be > 1 $kgCODkg^{-1}$ of oil. Additional characterization parameters, including TS%, TVS/TS%, and oil and fat content, were also evaluated, with respective values of $97.3 \pm 1.3\%$, 99%, and $83.3 \pm 5.4\%$.

The analysis of the RUCO indicates that sulfur and potassium are the most prevalent compounds. The results also shows the LHV and the water content that correspond respectively to to 37.16 ± 1.54 $MJkg^{-1}$ and $22 \pm 2\%$.

Parametric Environmental Assessment for Scenario 1B and 1C

In this section, the environmental assessment is also extended for Scenario 1B and 1C where 74% of the oil produced is directly discharged in the sewer network. From different study in the field, the emission factors for direct and dissolved emissions for the Imhof pits of 0.125 $kgCH_4$ $kgCOD^{-1}$ and 0.009 $kgCH_4kgCOD^{-1}$ respectively was assumed and then, it was possible to define the CO_2eq emissions for Scenario 1B. In addition, considering the emission factor 0.04 $kgCH_4$ $kgCOD^{-1}$ [35] relative to emissions of imhoff tanks into receiving water bodies (dispersed into the environment) it was also possible to determine the overall emissions for Scenario 1C. The emission in terms

Table 3 Literature review of consumed, produced, collected and discharged vegetable oil

References	Country	Year	Consumed vegetable oil [$kgPE^{-1}y^{-1}$]	Produced vegetable cooked oil [$kgPE^{-1}y^{-1}$]	Collected vegetable cooked oil [$kgPE^{-1}y^{-1}$]		Missed amount of vegetable cooked oil probably discharged in sewer network [$kgPE^{-1}y^{-1}$]
					Recovered	Disposed	
[9]	Italy	2010	–	4.3	0.65	0.07	3.58
	Italy	2011	–	4.3	0.69	0.08	3.53
	Italy	2012	–	4.3	0.7	0.08	3.52
	Italy	2013	–	4.3	0.75	0.08	3.47
	Italy	2014	–	4.3	0.85	0.09	3.36
	Italy	2015	–	4.3	0.93	0.1	3.27
	Italy	2016	–	4.3	0.97	0.11	3.22
	Italy	2017	23	4.3	1.07	0.12	3.11
[20]	Italy	2014	–	4	–	–	–
	Europe	2014	–	1.9	–	–	–
	Europe	2014	–	3.9	–	–	1.8
[40]	Italy	2011	18	–	–	–	–
	Italy	2012	16.3	–	–	–	–
	Italy	2013	18.2	–	–	–	–
	Italy	2014	16.9	–	–	–	–
	Italy	2015	17.2	–	–	–	–
	Italy	2016	13.4	–	–	–	–
	Italy	2017	16.3	–	–	–	–
	Italy	2018	12.9	–	–	–	–
	Italy	2019	12	–	–	–	–
	Italy	2020	12.2	–	–	–	–
Statista (2023 39)	Europe	2017	49	–	–	–	–
	Europe	2018	49	–	–	–	–
	Europe	2019	50	–	–	–	–
	Europe	2020	47	–	–	–	–
	Europe	2021	45	–	–	–	–
[18]	Italy	2016	–	–	1.08	0.12	–
	Italy	2017	–	–	1.17	0.13	–
	Italy	2018	–	–	1.27	0.14	–
	Italy	2019	–	–	1.39	0.15	–
	Italy	2020	–	4.9	1.22	0.14	3.54
[36]	Italy	2021	–	4.4	1.3	0.15	2.95
[42]	Italy	2015	–	3.8	1.1	–	2.70
	Europe	2015	–	3.7	1.60	–	2.1
Italian average			16.1 ± 3.3	4.29 ± 0.25	0.94 ± 0.25	0.10 ± 0.03	3.33 ± 0.31
European average			47.89 ± 1.90	4.96 ± 1.95	1.62 ± 0.65		1.96 ± 0.25

of CO_2eq for Imhoff tanks are in the ranges of values of the [6]. In Scenario 1B, the influent COD load into Imhoff tanks is 80,000 $kgCODy^{-1}$, resulting in an estimated methane production of 10,720 $kgCH_4year^{-1}$. This contributes to 289,440 $kgCO_2$ equivalent emissions from the Imhoff tanks, leading to a total CO_2 emission of 6,215,115 $kgCO_2eqy^{-1}$ for the entire system. In Scenario 1C, 20% of the COD load collected in Imhoff tanks, equal to 16,000 $kgCODy^{-1}$, is directly discharged into the environment. This discharge generates an additional 640 $kgCH_4y^{-1}$, corresponding to 17,280 $kgCO_2eqy^{-1}$. Consequently, the total CO_2 emissions from both Imhoff tanks and environmental dispersion reach 306,720 $kgCO_2eqy^{-1}$, increasing the overall system's CO_2 emissions to 6,232,295 $kgCO_2eqy^{-1}$.

The impacts in terms of equivalent person per year of Scenario 1B and 1C result comparable and respectively equal to 778 PEy^{-1} and 780 PEy^{-1}, slightly increasing the impact of climate change by 5% in respect to Scenario 1 (742 PEy^{-1}).

Table 4 UCO/RUCO characterization

UCO	pH	Dry residue at 105 °C [%] TS%	Dry residue at 600° [%] TFS%	TVS %	TVS/TS	Flash point [°C]	COD [mgkg^{-1}]	Barium [mgkg^{-1}]	Cadmium [mgkg^{-1}]	Total Chromium [mgkg^{-1}]	Nickel [mgkg^{-1}]	Lead [mgkg^{-1}]	Copper [mgkg^{-1}]	Zinc [mgkg^{-1}]	Hydrocarbons C5–C8 [mgkg^{-1}]	Hydrocarbons C10−C40 [mgkg^{-1}]	Total Hydrocarbons [mgkg^{-1}]	Animal fats and oils [%]
S1	6.8	96.8	< 1	95.8	0.99	> 60	> 1,000,000	< 10	<0.2	< 10	< 10	< 2	< 1	< 5	< 1	< 5	< 5	89.5
S2	6.9	> 99	< 1	98	0.99	> 60	> 1,000,000	< 10	<0.2	< 10	< 10	< 2	< 1	< 5			1364	79.9
S3	6.9	> 99	< 1	98	0.99	> 60	> 1,000,000	< 10	<0.2	< 10	< 10	< 2	< 1	< 5			1470	80.4
average	6.9	98.3	< 1.0	97.3	1.0	> 60.0	> 1,000,000	< 10.0	<0.2	< 10.0	< 10.0	< 2.0	< 1.0	< 5.0	< 1.0	< 5.0	< 946.3	83
dev.std	0.1	1.3	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–	–	816.9	5.4
RUCO																		
	LHV [MJkg^{-1}]	Total Chlorides [ppm]	Unsaponifiable Matter (normal fats) [%]	Water Content [mass%]	Sodium [mgkg^{-1}]	Potassium [mgkg^{-1}]	Density at 15 °C [kgm3−1]	Density at 60 °C [kgm3−1]	Kinematic Viscosity at 122°F/50 °C [mm^{2}s^{-1}]	Kinematic Viscosity at 176°F/80 °C [mm^{2}s^{-1}]	Water Content [%mm^{-1}]	Ash Content [%mm^{-1}]	Total Free Fatty Acids [mass%]	Melting Point [°C]	Acid Value [mg KOHg^{-1}]	Total Acid Number [mg KOHg^{-1}]	Total Sulfur Content [mgkg^{-1}]	Phosphorus [mgkg^{-1}]
S1	36	14	0.5	0.21	1.2		923	892.7	27.91	12.59	0.2	0.009	1.1	12	2.1	2.2	14.3	< 0.1
S2	36.3	24	0.69	0.2	< 1		923.5	893.5	29.39	13.34	0.205	0.002	1.8	10	3.7	3.6	22	< 1
S3	39.389–36.970				7.6	7.4	924	893.4	28.11	13	0.24	< 0.01			< 0.01	2.71	< 3	3.5
average	37.16	19	0.60	0.21	< 3.27	7.40	923.5	893.2	28.47	12.98	0.22	0.01	1.45	11.00	1.94	2.84	13.10	< 1.53
dev.std	1.54	7.07	0.13	0.01	3.75	–	0.50	0.44	0.80	0.38	0.02	0.00	0.49	1.41	1.85	0.71	9.56	1.76

Table 5 Life cycle impact assessment results are consistent across both Scenarios analysed

category		u.m	Scenario 1		Scenario 2	
			Absolute value	PE	Absolute value	PE
ALO	agricultural land occupation	m^2y^{-1}	346,027	56	339,179	55
CC	climate change	$kgCO_2$-Eqy^{-1}	5,925,675	742	5,817,558	728
FD	fossil fuel depletion	kgoil-Eqy^{-1}	1,464,342	1489	1,438,816	1463
FE	freshwater eutrophication	kgP-Eqy^{-1}	9431	14,511	9207	14,167
FET	freshwater ecotoxicity	kg1,4-DCB-Eqy^{-1}	23,191	921	22,662	900
HT	human toxicity	kg1,4-DCB-Eqy^{-1}	1,542,640	49	1,507,608	48
IR	ionising radiation	kgU235-Eqy^{-1}	320,718	668	315,003	656
ME	marine eutrophication	kgN-Eqy^{-1}	205,782	44,563	200,863	43,498
MET	marine ecotoxicity	kg1,4-DB-Eqy^{-1}	25,586	589	24,991	575
MRD	mineral resource depletion	kgFe-Eqy^{-1}	675,736	6	659,879	6
OD	ozone depletion	kgCFC11-Eqy^{-1}	1	8	1	8
PMF	particulate matter formation	kgPM10-Eqy^{-1}	20,506	802	20,101	786
POF	photochemicala oxidant formation	kgNMVOC-Eqy^{-1}	25,913	1260	25,380	1234
TA	terrestrial acidification	$kgSO_2$-Eqy^{-1}	48,285	1178	47,272	1154
TET	terrestrial ecotoxicity	kg1,4-DCB-Eqy^{-1}	3324	0	3246	0
ULO	urban land occupation	m^2y^{-1}	1,381,688	224	1,348,792	219
WD	water depletion	m^3y^{-1}	1,048,940	3934	1,024,043	3841
Total				71,000		69,338

Life Cycle Assessment—Scenario 1 and 2

This section presents the results of the life cycle analysis comparing all the investigated categories and the corresponding impact of the entire system for both Scenario 1 and Scenario 2, shown in absolute values and normalized to equivalent person [39] in Table 5.

The final results show that Scenario 2 has a lower overall environmental impact compared to Scenario 1, with a total of 69,338 PEy^{-1} versus 71,000 PEy^{-1} for Scenario 1. This indicates an improvement in environmental sustainability in Scenario 2. To further investigate the Scenarios, climate change, freshwater eutrophication, terrestrial acidification and ozone depletion were selected and analyzed individually. The main source of climate change is human-induced changes in atmospheric composition. These perturbations primarily result from emissions associated with energy use, urbanization and land use changes [27]. The causes include greenhouse gas (GHG) emissions such as CO_2, CH_4, and N_2O, mainly resulting from the burning of fossil fuels. The effects include rising global temperatures, melting glaciers, sea level rise, changes in precipitation patterns, and extreme weather events. In Fig. 1 a comparison of "Climate change" impact is presented for the sewer network, UCO treatment and wastewater treatment plant. It is observed the wastewater treatment plant has a significantly higher impact compared to sewer network and UCO treatment. Regarding the sewer network, since the electricity consumption is estimated on an AE basis it does not vary. In terms of overall impact, CO_2 emission in the Scenario 1 is 5,925,675 CO_2eqy^{-1} while in the Scenario 2 is 5,817,558 CO_2eqy^{-1} resulting in a reduction of 1.82%. The category freshwater eutrophication refers to a water body changing over time from nutrient-poor to nutrient-rich status. More nutrients cause increased aquatic plant growth that negatively influences water quality and especially dissolved oxygen availability [7]. Figure 1 highlights the wastewater treatment plant has a significantly higher impact compared to the other units considered. The UCO treatment process, in this environmental category, appears negligible since it does not produce or release nitrogenous or phosporous components into surface waters.

In the wastewater treatment plant, the Scenario 2 results in a lower amount of Peq released by the plant of about 225 $kgPEqy^{-1}$ which correspond to a reduction of 2.4% in respect the the Scenario 1.

The increases in soil acidification as a result of accelerating anthropogenic activities is becoming a global issue. High emissions nitrogen, sulfur, and carbon dioxide in the atmosphere are responsible for acid precipitations which play a key role in soil acidification. Long-term application of nitrogen fertilizers is a major contributor in acidification of agricultural soil lowering the soil nutrient availability, and consequently affects the soil biological properties and plant performances [44]. The UCO treatment has a negligible impact as it is a physical treatment with low emissions of nitrogen and sulphur oxides. Also in this case, the wastewater plant impact has orders of magnitude more than the other units of the system. The improvement in Scenario 2 is

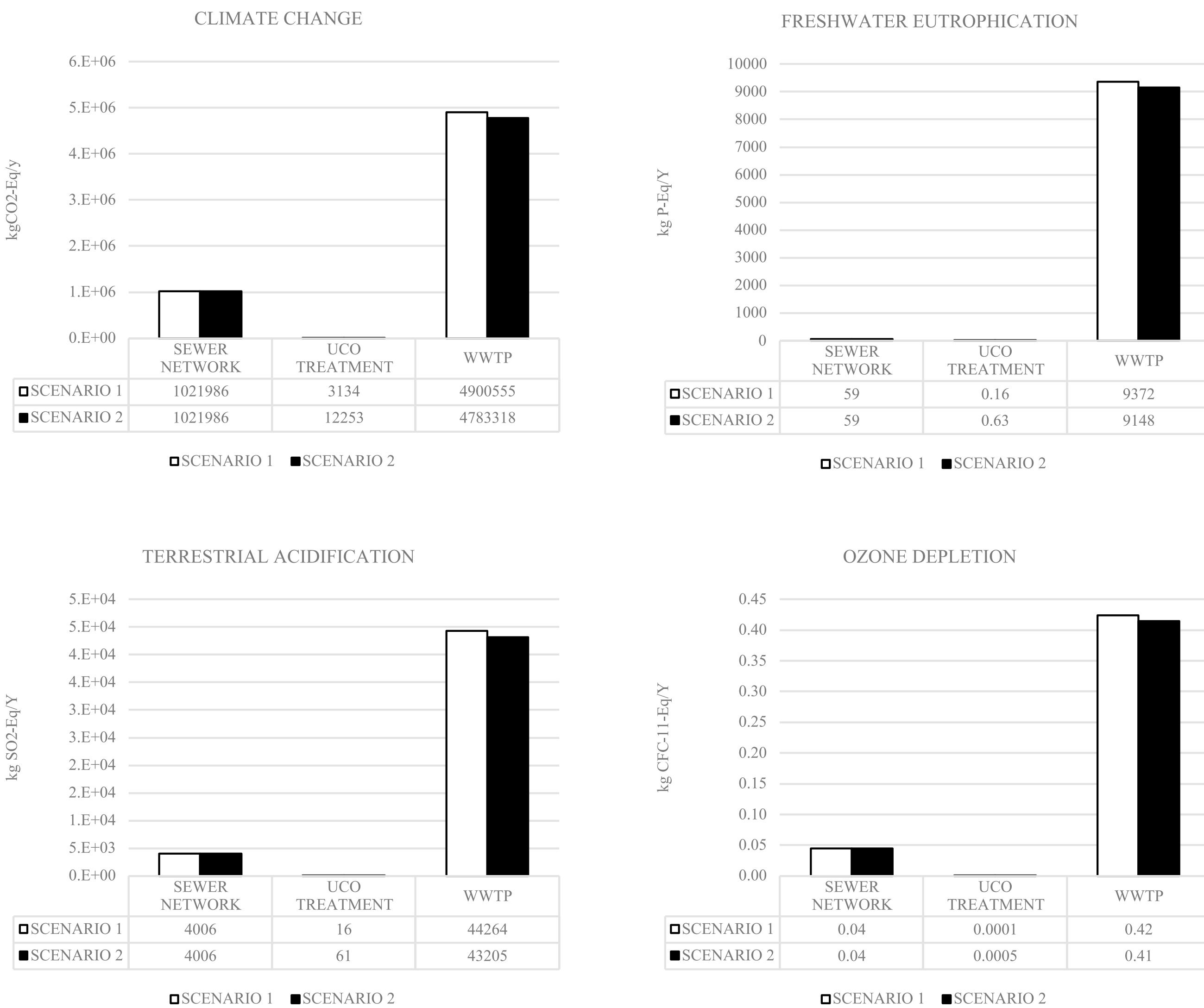


Fig. 1 Life Cycle Impact Assessment results of CC, FE, TA, OD indicators

of a few percentage orders of magnitude and equal to 1059 kgSO2eqy^{-1}. In the overall Scenario, the reduction in the Scenario 2 is equal to 1014 kgSO_2eqy^{-1}).

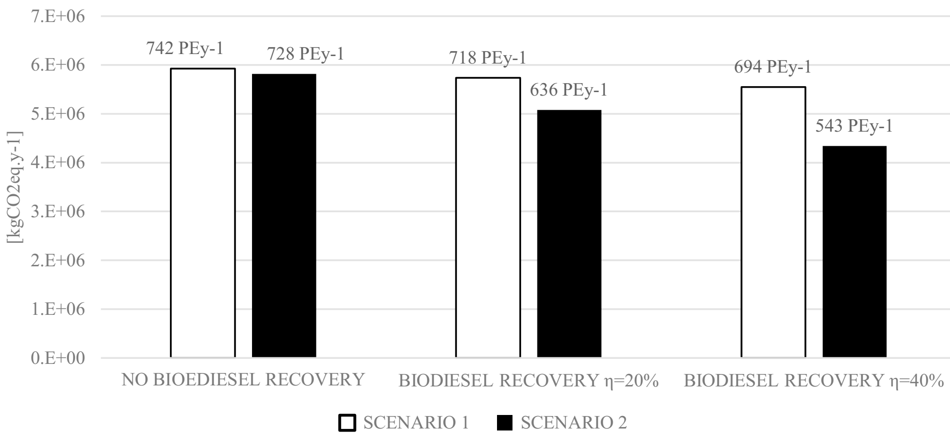
In term of Ozone depletion changes in stratospheric ozone and climate over the past 40-plus years have altered the solar ultraviolet (UV) radiation conditions at the Earth's surface. These changes are interacting to affect human health, food and water security and ecosystem services [4]. Causes include emissions of chemicals such as chlorofluorocarbons (CFCs), halons and other compounds containing chlorine and bromine. Effects include increased levels of UV-B radiation reaching the earth's surface, causing an increased risk of skin cancer, eye damage and negative impacts on marine and terrestrial ecosystems. In Fig. 1, it is shown that the wastewater plant causes the greatest environmental impact in ozone depletion. The impact of the sewage network is an order of magnitude smaller than that of the plant, while the impact of UCO treatment is negligible compared to the other units considered. In Scenario 2 there is a reduction of kgCFC^{-1}1-Eq produced by the plant of 0.01 kgCFC^{-1}1-Eqy^{-1}.

The production of biodiesel was evaluated considering both the HVO process for the production of Green Diesel and the FAME process for the production of biodiesel. Based on the production's yield of biodiesel and green diesel respectively 83% [46] and 89% [5, 22]the production of biofuel was evaluated starting from the RUCO produced by the company. In the next evaluation, biodiesel and green diesel were assumed to be the same product in terms of energy produced. Based on the calorific value of biodiesel, approximately 10.5 kWhkg^{-1} [14], and typical diesel generator efficiencies ranging from 20 to 40% [26], the energy

Table 6 Carbon footprint assessment and reduction potential for both Scenarios

Parameter	Efficiency 20%	Efficiency 40%	SCENARIO
Electricity produced [$kWhy^{-1}$]	184,465	368,930	SCENARIO 1
	721,091	1,442,181	SCENARIO 2
Carbon dioxide reduction CO_2 [$kgCO_2eqy^{-1}$]	188,929	377,858	SCENARIO 1
	738,541	1,477,082	SCENARIO 2
CF—biodiesel recovery [$kgCO_2eqy^{-1}$]	5,736,746	5,547,817	SCENARIO 1
	5,079,016	4,340,475	SCENARIO 2
CF—biodiesel recovery [PEy^{-1}]	718	694	SCENARIO 1
	636	543	SCENARIO 2
% Reduction	3.19%	6.38%	SCENARIO 1
	12.70%	25.39%	SCENARIO 2

SCENARIO 1 VS SCENARIO 2



conversion yields between 2.10 and 4.20 kWh per kilogram of biodiesel consumed.

Considering an emission factor (EF) of 1.0242 $kgCO_2eqkWh^{-1}$ (Ecoinvent n.d.) and an average production of biofuel (green diesel and biodiesel), the results of the electricity produced, the carbon dioxide reduction and the final carbon footprint of both the Scenarios are summarised in Table 6.

According to the following results, the average mitigation of CO_2eqy^{-1} is 188,929–377,858 kg CO_2eqy^{-1} for Scenario 1 and 738,541–1,477,082 kg $CO_2eqy^{-1}$for Scenario 2, which translate respectively into final climate change values of 718–694 PEy^{-1} against the initial 742 PEy^{-1} for SCENARIO 1 and 636–543 PEy^{-1} against 728 PEy^{-1} for Sceanrio 2, resulting in an improvement of 3.19–6.38% for Scenario 1 and 12.70–25.39% in Scenario 2.

Conclusion

Qualitative and quantitative data on used oils are often variable and, in some cases, incomplete or inconsistent across different sources. Nevertheless, the literature review conducted does not report recovery rates exceeding 30%. Preliminary quantification of the impacts across different environmental categories was performed through a life cycle assessment, considering both partial and total oil recovery for biodiesel production. Total recovery of used cooking oil substantially reduces environmental impacts by decreasing the amount of oil requiring treatment in wastewater facilities. Although the scenarios analysed show an increase of approximately 300% in the amount of oil to be treated, the overall comparison indicates improvements in several environmental impact categories (Climate Change, Water Eutrophication, and Terrestrial Acidification). These overall environmental benefits correspond to 1662 person-equivalents across all categories assessed.

Regarding carbon footprint, the presence of Imhoff tanks in the sewer network leads to a slightly more impactful situation compared to the current state, with an increase of about 5% in climate change impact. When electricity generation from biodiesel is considered as a recovered energy source, CO_2 emissions decrease by 14–27% in the scenarios with and without biodiesel recovery. In terms of person-equivalents, this corresponds to a reduction of 48–199 PE.

Furthermore, from the economic perspective, future research could include techno-economic assessments of treatment processes, the design and implementation of strategies to increase public participation in UCO collection programs and the development of advanced catalytic conversion technologies for UCO valorization. Sociocultural acceptance, education and behavioral change are key drivers for the success of sustainable resource management initiatives [2].

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Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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