Sustainability of Prevalent Waste Cooking Oils as a Biodiesel Feedstock: A multi-criteria comparison

February 10, 2026

Abstract

The growing concerns about the scarcity of fossil fuels and associated greenhouse gas emissions encourage humanity to develop renewable and environmentally safe alternatives. Over the past 20 years, the field of biofuels has sparked significant investigations, especially biodiesel as a substitute for non-renewable sources in the transport sector. The purpose of the present work is to analyse to what extent the life-cycle environmental impacts of biodiesel from diverse used cooking oils(UCOs) differ when evaluated using a standardized, multi-criteria comparison that covers the entire life-cycle of every investigated oil. This article provides guidelines on which cooking oil to choose if one wants to maximize the sustainability of biodiesel production. Several life cycle assessments and other types of analyses have been conducted to determine the sustainability of various virgin cooking oils and UCOs as biodiesel sources. However, no distinguishing of the different types of UCOs has been mentioned. This paper tries to shed light on this aspect and proves that there is a need to distinguish between different kinds of UCOs. A list of the most efficient and sustainable UCOs to use is also proposed, highlighting sunflower UCO as a leader and coconut UCO as an outsider. Based on a review of literature for the most common UCOs and a multi-criteria comparison approach, the insights are provided for stakeholders in the biodiesel industry with the aim of supporting the transition to less polluting energy generation.

Keywords: sustainability, used cooking oil, life cycle, biodiesel, biofuel, multi-criteria comparison

1 Introduction

The rapidly growing population and its energy needs emphasize the necessity for a wider range of feedstocks to be deployed. In 2024, a 2.2% rise in global energy demand was recorded, which is almost twice the annual average increase over the past 10 years. This significant increase is partially based on global warming conditions that accounted for approximately 13.6% of this overall 2.2% growth. Moreover, 2024 was the warmest year on record with the temperature exceeding pre-industrial levels by 1.5 °C.(International Energy Agency, 2025) Figure 1 demonstrates the breakdown of the current global primary energy mix for sources.(Ritchie et al., 2020) In 2025, more than half of global energy was still derived from coal (24.6%), gas (21%), and oil (31.2%), which are all carbon-based fuels.(Ritchie et al., 2020) These hazardous trends require thorough control, as well as a determined and prompt transition to alternatives, such as solar, wind, nuclear, hydro, and biomass energies. In this context, biofuels appear to be a promising and affordable source of green energy. Within the transport sector, the crucial branch of biofuels is biodiesel, as an efficient substitute fuel for diesel engines. Biodiesel can be generated via a chemical reaction between a vegetable oil (including used cooking oils) or animal fat and an alcohol, involving a strong base as a catalyst and resulting in the production of methyl esters, which constitute biodiesel.(Van Gerpen, 2005) While numerous biodiesel feedstocks exist, the maximum sustainable resource management can be achieved by attracting used cooking oils(UCOs), as a source of production. The reason lies in the of used cooking oil (UCO), which society is currently confronting because of the influence on the environment. UCOs are used cooking oils collected from restaurants and industrial sectors that are no longer suitable for consumption(Beghetto, 2025). In some literature the term Waste Cooking Oil(WCO) is used when referring to the same feedstock of biodiesel as UCO. In this work only the term UCO, a synonym for WCO, is used to avoid misunderstandings. In 2020, the main UCO disposal route was sewage, resulting in sanitary sewer overflows, property flooding, contamination of water bodies with sewage, water, and soil pollution. Consequently, incurring additional costs on water treatment facilities is inevitable, if UCOs are not recycled.(Foteinis et al., 2020). As cooking oil consumption and the population of the planet rise every year and oils make up 10% of global caloric consumption(Beghetto, 2025), the issue of UCOs utilization becomes increasingly topical. Even though existing literature presents other applications for UCO, such as biolubricants, biosolvents, animal feed, asphalt additives, biodiesel remains the most demanded and efficient option, considering the growing need for alternative and sustainable non-fossil fuels.(Beghetto, 2025) The rise of UCO supplies from current 3.7 billion gallons to between five and ten billion gallons in 2030 is expected. As a result, this creates a space for biodiesel production that could reach 5.8 billion gallons within the next four years.(GlobalData, 2023) Additionally, the global consumption of vegetable oils has almost tripled from 2000 (83 million tons) to 2023 (217 million tons) with 167 million tons utilized in the biodiesel industry, signaling a high number of potential new production feedstock.(Beghetto, 2025) Modern studies investigate the field of UCO biodiesel through life cycle assessment (LCA)(Musharavati et al., 2023; Nogales-Delgado, 2025), sustainable business assessment (Abdullah & Glasscock, 2025), comparative studies (Paschou et al., 2025), economic (Yang et al., 2025) and bibliometric (Chen et al., 2021) analyses. Although a great amount of research is conducted on UCOs and separate edible oils that were grown only to be recycled to biodiesel, authors rarely distinguish between types of UCOs derived from different vegetable cooking oils(Bouaid et al., 2024; Intarapong et al., 2016). This paper investigates whether the mentioned difference exists and if so, what exactly these differences are in the use of UCO from the ten most popular cooking oils, comparing them quantitatively through a Multi-Criteria Decision Analysis (MCDA) approach. The criteria cover the entire life cycle of investigated materials, considering main areas of impact: (i)Environmental; (ii)Social; (iii)Economical; (iv)Technical. Every field includes subtopics for comprehensive data analysis and comparison of the most produced vegetable oils in 2022, presented in Figure 2.(Ritchie, Roser, & Rosado, 2024) The choice of compared oils is discussed in detail in the methodology. In the discussion section,all results are assessed and the ranking of oils is presented, starting from the most suitable and ending with the least appropriate, for UCO biodiesel creation. In this way the work discusses to what extent the life-cycle environmental impacts of biodiesel from diverse UCOs differ when evaluated using a multi-criteria comparison. The criteria cover the entire life cycle of UCOs.

2 Materials and Methods

2.1 Formulation of Alternatives

Figure 2 illustrates thirteen of the most produced vegetable oils in 2022.(Ritchie, Roser, & Rosado, 2024) However, linseed, sesame, and safflower oils were found inappropriate for cooking due to the reasons discussed below in this section. Therefore, this research only evaluates 10 remaining oils from Figure 2:

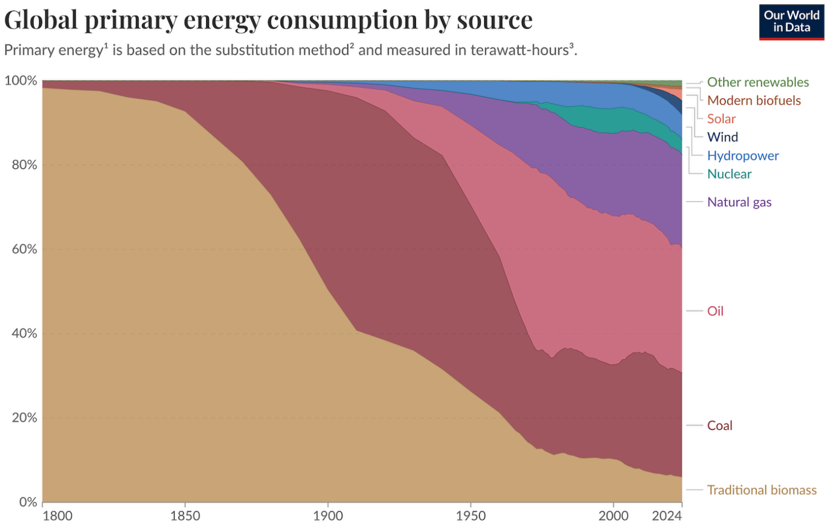

Figure 1: A demonstration of global primary energy consumption by source within the last 2024 years.Adapted from:(Ritchie et al., 2020)

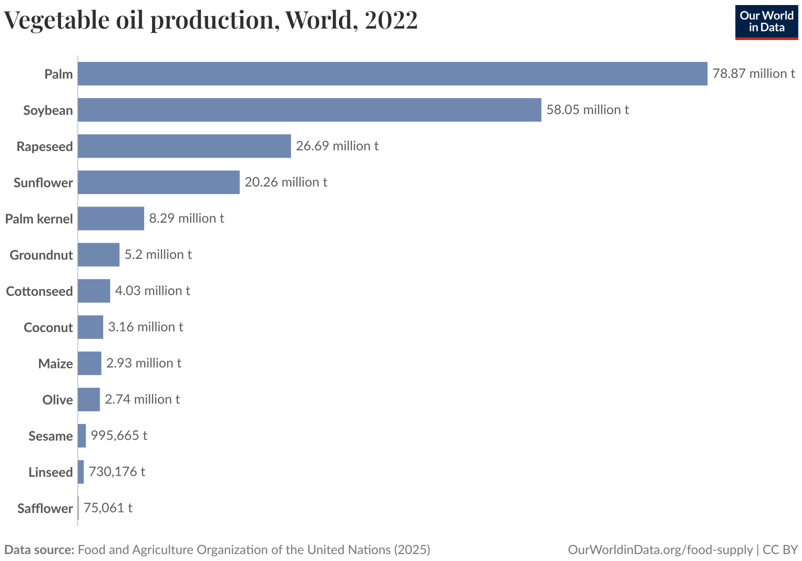

Figure 2: A bar chart showing global vegetable oil production, broken down by oil type.Adapted from:(Ritchie, Roser, & Rosado, 2024)

2.1.1 Linseed oil

Several studies were conducted on the quality properties of the linseed oil.(Eastern Connecticut State University, 2015; Nykter et al., 2006) The smoke point appeared to be comparatively low, resulting in diminished quality of the fried food. A high level of α-linoleic acid causes faster oxidation during heating, which leads to a huge content of Free Fatty Acids (FFA).(Tripathi et al., 2013) These facts negatively influence the ability of oil to be converted into biodiesel, as the sustainability of the final product would be lower than that of already developed substitutes.

2.1.2 Sesame oil

While the sesame oil is extremely stable, it is considered to be high-priced, as the seed harvesting remains an arduous task that requires an enormous amount of labor.(Hwang et al., 2026) In the present time, this oil is referred to ”luxury oil”. Moreover, its production is not extensive enough to consider it as a potential large-scale source of biodiesel.

2.1.3 Safflower oil

The main fatty acid in safflower oil is linoleic acid. Therefore, after heating, the amount of FFA increases significantly, leading to challenges during biodiesel operation, such as the risk of soap formation during transesterification or within the engine system.(Lee et al., 2004; Rubel et al., 2026)

2.2 Multi-Criteria Decision Analysis (MCDA) Development

MCDA is defined as an approach for choosing a well-balanced compromise for complex problems characterized by conflicting objectives and stakeholders with different needs. The tool includes transparent, often mathematical decision-support processes, engaging actors in the procedure.(Gallazzi et al., 2025)

The analysis is conducted as follows: all substitutes are compared using every stated criteria, which are evaluated by significance.(De Feo et al., 2023) The present MCDA procedure includes the following phases: (i) Criteria tree; (ii) The set of indicators; (iii) Relative importance factors elicitation; (iv) Rate creation.

2.2.1 Criteria and the set of indicators

Figure 3 presents criteria tree as the part of the criteria finalization process. Three pillars of sustainability(economic, environmental, and social)(Purvis et al., 2019) and technical aspects are covered as 4 distinct groups, each including relative criteria. Table 1 holds the final 10 criteria for assessment. For every investigated UCO, each criterion is described by three levels of

performance with 1 as the most unsatisfied grade, 2 as acceptable or standard, and 3 standing for the optimal.

2.2.2 Relative importance factors elicitation

In (Wulf et al., 2025) two main ways of weighting factors are presented: trade-off weights and importance coefficients. The first type is more case-specific and describes the relative importance of two or more criteria, while importance coefficients are absolute and non-case-specific. On the other hand, the employment of equal weights in hierarchical structure, if required, is mentioned as a popular alternative.

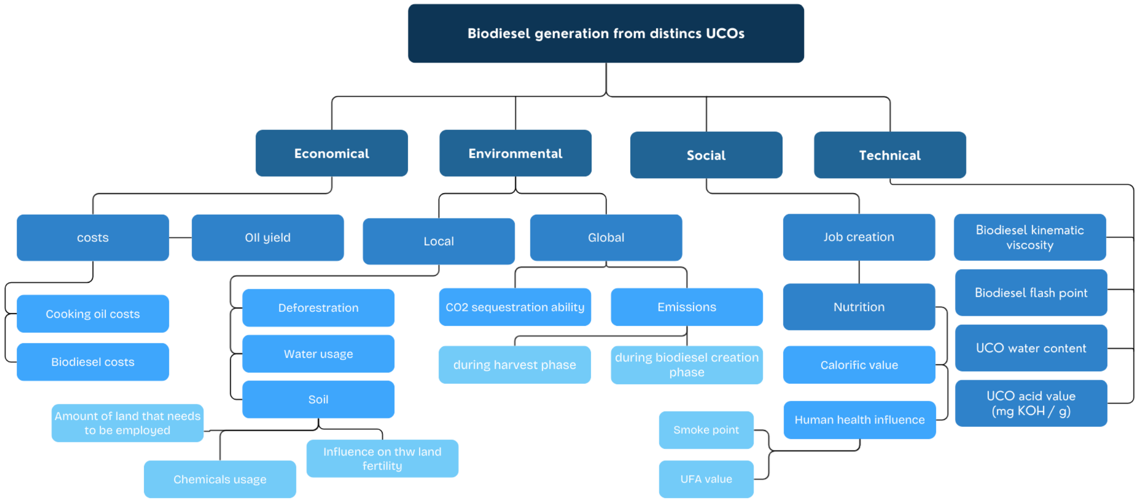

Figure 3: Criteria tree

This study focuses on the equal weights approach, as it ensures clear and unbiased evaluation. Within the hierarchical structure, this method initially considers four main areas as equally important. For every criteria in the mentioned sections the same equal weight distribution is applied.

2.2.3 Rate creation

The rate includes all ten examined UCOs, presenting oils with the highest average results from all criteria at the top and materials with lower values below.

2.3 MCDA Methods

3 Literature Review and Comparative Analysis Beginning

3.1 Economic aspect

3.1.1 Cooking oil prices

Figure 4 presents the prices for 10 vegetable oils in 2022 (Ozbun, 2025; Shanbhag, 2022; Tridge, 2026). A Metric Ton of maize cost 319 US dollars in 2022, considering the information from (Ozbun, 2025). On the contrary, cottonseed oil prices in 2022 were reported to vary from \$760 to \$1660 per Metric Ton. For the figure 4 the average value of \$1210 per Metric Ton was taken(Tridge, 2026).

The average value per metric ton was calculated to be \$1646.6, using formula (1):

$$a_{\text{avg}} = \frac{a_1 + a_2 + a_3 + \cdots + a_n}{n} \tag{1}$$

The grading values for each oil are presented in the result section.

Table 1: Grading criteria for oil evaluation

Aspect	Criteria	Grading Scale
Economic	Cooking oil prices	1 = above average; 2 = approx. average; 3 = below average
	Oil yield	1 = above average; 2 = approx. average; 3 = below average
Environmental	Chemical usage	1 = highest rates; 2 = middle rates; 3 = lowest rates
	Land employed	1 = significantly < 0.6; 2 = approx. 0.6; 3 = significantly > 0.6
Social	Calorific value	1 = less than average; 2 = approx. average; 3 = greater than average
	Smoke point	1 = < 400; 2 = $400 - 450$; 3 = > 450
	UFA value	1 = $< 30\%$ or $> 50\%$; 2 = $30\% - 35\%$ or $45\% - 50\%$; 3 = $35\% - 45\%$
Technical	UCO acid value	1 = > 0.5; 2 = $0.45 - 0.5$; 3 = < 0.45 (mg KOH/g)
	UCO water content	1 = $> 0.15\%$; 2 = $0.1\% - 0.15\%$; 3 = $< 0.1\%$
	Biodiesel flash point	1 = $< 120°C$; 2 = $120°C$ - $170°C$; 3 = $> 170°C$
	Kinematic viscosity	1 = < 1.9 or > 6.0; 2 = $1.9 - 3.5$ or $5.0 - 6.0$; 3 = $3.5 - 5.0$ (mm^2/s)

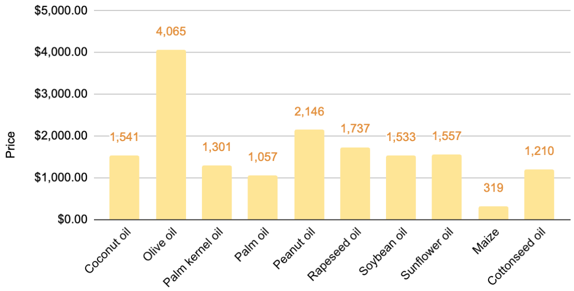

Figure 4: A line chart demonstrates historical price data of 10 edible oils in July 2022. Price in US Dollars per Metric Ton. Data taken from (Ozbun, 2025; Shanbhag, 2022; Tridge, 2026).

3.1.2 Oil yield

Oil yield is known to be a crucial oil efficiency aspect. Apart from maize and palm kernel oil, all data was available in direct values(Ritchie, Rosado, & Roser, 2024). Initially, for both materials oil content percentages were found to be 4%(Singh et al., 2014) and 37.5%(Alshafea et al., 2025) respectively. Thereafter percentages were converted to oil yield, using global vegetable oil production data from Figure 2 and the following formula:

$$Y_{\text{oil}} = Y_{\text{crop}} \times \frac{C\%}{100} \qquad (2)$$

where:

- Y_{oil} — oil yield (t/ha);
- Y_{crop} — total crop yield (t/ha);
- $C\%$ — oil content percentage.

Calculations resulted in 0.12 t for maize and 3.1 t for palm kernel oil. Figure 5 includes the average amount of oil in tonnes produced per hectare of land for 10 analyzed oils.

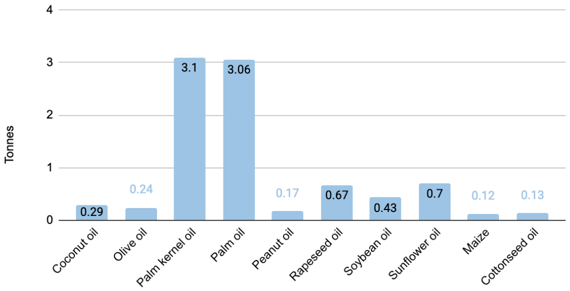

Figure 5: A bar chart depicting global oil yields in tonnes per hectare of land by crop type, evaluating data from(Alshafea et al., 2025; Ritchie, Rosado, & Roser, 2024; Singh et al., 2014).

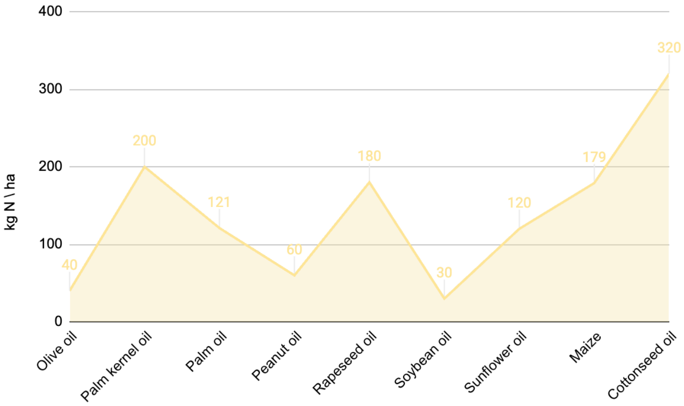

Figure 6: A stacked area chart compares average amount of Nitrogen required for harvest of each oil within last 20 years.

3.2 Environmental aspect

3.2.1 Chemicals usage during harvesting

As the human population continues to grow, an instantly increasing demand on crops is inevitable. To cope with rapidly rising consumption, suppliers resort to using agrochemistry to enhance properties of good, such as temps of growing, quality, and sizes. However, the agricultural sector is in charge of over 80% of anthropogenic N2O emissions, 70% of anthropogenic NH3 emissions, and approximately 40% of anthropogenic CH4 emissions.(Sokal & Kachel, 2025)

Nitrogen fertilizers contribute significantly to the overall GHG emission, several investigations recorded that increasing N fertilizer rates leads to greater than proportional N2O emissions. With this said, this research focuses on analysis of the urea usage during harvesting, which is considered the cheapest and richest(46% of N) primary global nitrogenous fertilizer.(Swify et al., 2024) For all Oil crops values were taken no later than in 2004: (i)Palm Oil - 108-134 kg N $\times$ ha^{-1} (Mohd Kusin et al., 2015); (ii)Sunflower oil - 120 kg N $\times$ ha^{-1}(Özer et al., 2004); (iii)Soybean oil - 30 kg N $\times$ha^{-1}(Wysokiński et al., 2024); (iv)Cottonseed oil - 320 kg N $\times$ha^{-1}(Jing et al., 2023); (v)Maize - 179 kg N $\times$ ha^{-1}(Zhang et al., 2018); (vi)Coconut oil - lack of culture response to N application has been recorded in several studies. (Lins et al., 2021); (vii)Olive oil - 40 kg N $\times$ ha^{-1}(Fernández-Escobar et al., 2002); (viii)Rapeseed oil - 180 kg N $\times$ ha^{-1}(Zhu et al., 2023); (ix)Palm Kernel oil - 260 kg N $\times$ ha^{-1}(Woittiez et al., 2017); (x)Peanut oil- 60 kg N $\times$ ha^{-1}(Li et al., 2024).

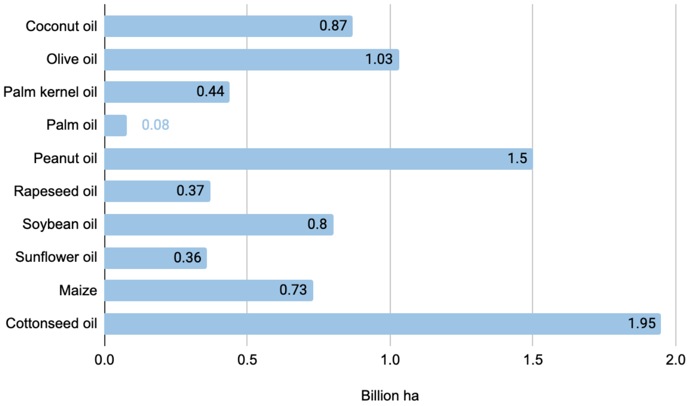

Figure 7: A bar chart demonstrates area of land in billions needed to satisfy global vegetable oil demand using only 1 oil in 2022

3.2.2 Land employment

Statistics(Ritchie, 2021) suggests that global vegetable oil demand in 2022 was equal to 218 million tonnes of oil. This criteria examines 10 evaluated oils for the land area in ha needed to fulfill the global vegetable oil demand in 2022. For palm oil and palm kernel oil together, the researchers argue that the global average yield of 3.5 tons of oil per hectare.(Barcelos et al., 2015) However, taking plain kernel oil, productivity drops to approximately 0.5 tonnes per hectare. Worldwide, corn has an average productivity of 0,3 tonnes per hectare (da Silva & da Costa, 2025). The 218 million tonnes divided separately by the mentioned numbers result in 436 and 726 million hectares accordingly. The rest of the data was taken from(Ritchie, 2021). Figure 6 collects all information explained here together for further evaluation in the discussion section.

Even though oil yield criteria, expanded earlier, is mathematically connected to land employment, this study aims to highlight the importance of sustainability considerations. Therefore, oil yield criteria is related to economic aspect, while land employment is presented in the environmental part.

3.3 Social aspect

3.3.1 Calorific value

Calorific value is the energy outcome after complete combustion of 1 g of fuel in the presence of oxygen. This value can be expressed in kJ/kg and determined using the next equation:

$$\text{Calorific value} = \frac{\text{heat produced}}{\text{amount of fuel}} \tag{3}$$

The produced heat is found experimentally or via a calculation by thermodynamics methodology:

$$Q = nC_P\Delta T \tag{4}$$

where Q is heat produced, n is no. of moles of fuel, C_P is heat capacity at constant pressure (1 bar), and ΔT is the difference in final and initial temperatures.(Wan Ghazali et al., 2015)

On the one hand, for nutritional purposes higher calorific value means less mass of oil is needed to satisfy certain energy level for the human. On the other hand, the energy content of feedstock indicates the efficiency capacity of the biodiesel. Process of oil conversion into biodiesel increases the amount of oxygen, which leads to lower combustion heat. However, the

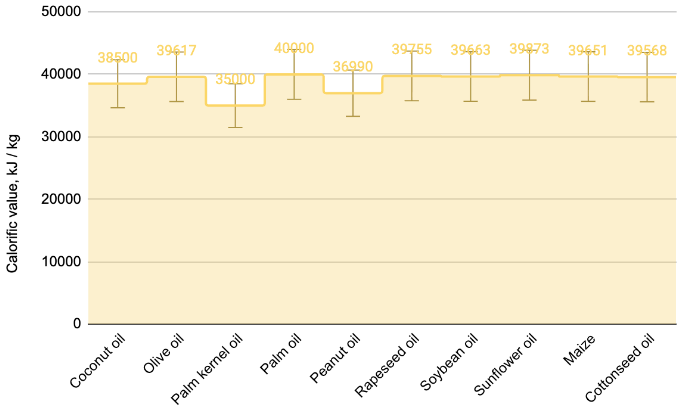

Figure 8: A stepped area chart compares energy values of evaluated oils in kJ per kg

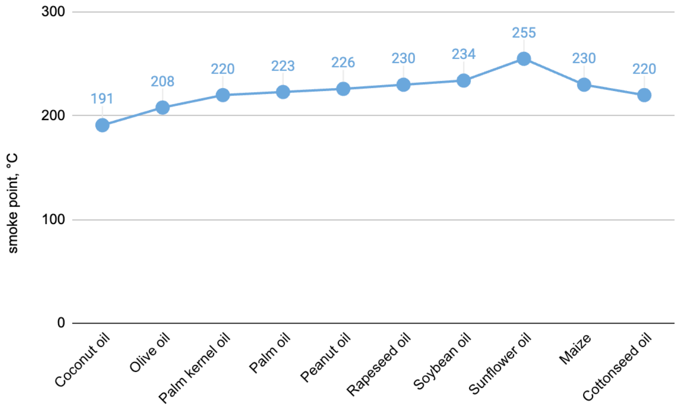

Figure 9: A line chart presents smoke points of 10 examined oils(Benexia, 2022; Redmond, 2024).

initial differences between distinct vegetable oils remain same even after several operations on material.(Plata et al., 2022) Therefore, calorific value steps in as a crucial criteria from two instantaneous perspectives.Figure 7 breaks down the energy content of analysed vegetable oils, containing data from(Batomayena et al., 2019; Sanli, 2025).

3.3.2 Smoke point

Since this research aims to consider the best UCOs for biodiesel production, it is crucial to know which feedstock will be undoubtedly suitable for domestic cooking utilization.

Frying, a widely used cooking method, involves immersing food in hot oil at a temperature range of 150°C to 180°C. Frequently, during this process hydrolysis, thermal oxidation, and polymerization occur. These reactions are undesirable, as they result in worse quality of the frying medium. Therefore, smoke point directly influences the taste of the food and health of the consumers(Ng & Choo, 2017). Figure 8 compares smoke points of 10 vegetable oils, taking data from(Benexia, 2022; Redmond, 2024).

3.3.3 Unsaturated fatty acid (UFA) value

Epidemiologists claim the higher ratio of UFA in vegetable oils, especially 6 polyunsaturated fatty acids (linoleic acid), lowers risks of cardiological problems, type 2 diabetes mellitus and does not

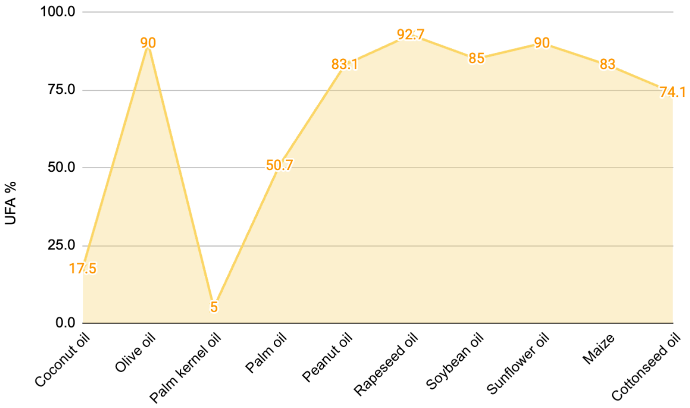

Figure 10: A staked area chart shows UFA content percentage in every oil(Abrante-Pascual et al., 2024; Benexia, 2022; Frančáková et al., 2015; Redmond, 2024).

increase markers of inflammation or oxidative stress. Authoritative health and scientific organizations recommend consumption of oils rich in UFA instead of alternatives with high contamination of saturated fatty acid, for instance, palm and coconut oils(Petersen et al., 2024).

However, high values of UFA negatively influence biodiesel generation process, as they are responsible for faster free fatty acids occurrence during oil frying. Since UCOs with FFA level above 5 percent are inappropriate for biodiesel production, producers often need to spend extra resources and time on lowering FFA rates.

Considering all perspectives, materials with too low or extremely high UFA levels were graded for 1 point, whereas oils with UFA around 40 percent were rated for 3 points. Figure 9 illustrates percentage of UFA in every oil(Abrante-Pascual et al., 2024; Benexia, 2022; Frančáková et al., 2015; Redmond, 2024).

3.4 Technical aspect

3.4.1 UCO acid value mg KOH/g

Acid value refers to the number of potassium hydroxide in milligrams needed to neutralize the amout of FFA in UCO. There exists a straight correlation between the free fatty acid amount and the acid value. High acid value could reduce the oil's quality by slowing its reaction rate. The steady increase of acid value arises with the rise of oil's frying time. The European Standard of a maximum acidity value of 0.50 mg KOH/g was taken into account during grading, meaning that every oil with a higher result was given 1 out of 3. (Bong et al., 2020; Paschou et al., 2025)

The acid value for fresh palm kernel oil was measured as 17.95 mg KOH / g(Bong et al., 2020), signalizing that for UCO this number would probably be even higher. The same applies for fresh rapeseed oil, which acid value was stated as 2 mg KOH / g Additionally, value for maize from the graph is worth highlighting, as it represents a combined average number of 0.745 mg KOH/ g: data was provided for heavily used maize oil and simply used(Cordero-Ravelo & Schallenberg-Rodriguez, 2018). For the rest exact UCOs acid numbers where found(Arawandea et al., 2018; Awogbemi et al., 2021; Ling et al., 2016; Mardiana & Santoso, 2020; Marso et al., 2021; Nježić et al., 2023; Paschou et al., 2025)

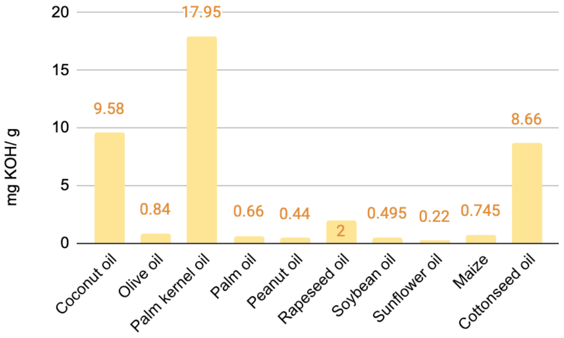

Figure 11: A line chart provides acid values for 8 UCOs and fresh plam kernel, rapeseed oils in mg KOH / g(Arawandea et al., 2018; Awogbemi et al., 2021; Ling et al., 2016; Mardiana & Santoso, 2020; Marso et al., 2021; Nježić et al., 2023; Paschou et al., 2025)

3.4.2 UCO water content

An excess number of water in the biodiesel feedstock can lead to the hydrolysis of fatty acid methyl esters into free fatty acids, resulting in soap formation, reducing biodiesel yield. Moreover, water lowers the catalyst's activity, slowing down or stopping the reaction. In addition, high moisture content can cause emulsion and a complicated separation process of biodiesel and glycerol. Water content not exceeding 0.15% is recommended for biodiesel feedstock to ensure successful transesterification.(Koirala et al., 2024; Paschou et al., 2025)

This criteria shows that deeper and more organized research is needed regarding the correlation between UCOs water content and fried in it products. The data for moisture content were not considered during overall grading, as values for every evaluated material were measured in no equal circumstances. For instance, the highest moisture content can be noticed in used sunflower oil and used olive oil, as they were used for frying potatoes, which have high water content.(Paschou et al., 2025) For the rest values are lower, as they were used for other cooking purposes.(Koirala et al., 2024; Mardiana & Santoso, 2020; Sangkharak et al., 2019; Tilinti et al., 2024; Ubaidah et al., 2018) All found data are provided via Table 2.

Table 2: Moisture Content: Comparison Between Raw Seeds,Refined/Virgin Oils and Used Cooking Oils (UCO)

Category / Source	**Moisture/Water (%)**	**Reference**
Moisture content in raw seeds:		
Maize seeds	11.00	(Xue et al., 2024)
Soybean seeds	≈ 11.00	(Flores et al., 2025)
Water content in Used Cooking Oils (UCO):		
Waste Sunflower (post-frying)	45.32	(Paschou et al., 2025)
Waste Olive (post-frying)	23.16	(Koirala et al., 2024)
Cottonseed UCO	0.32	(Tilinti et al., 2024)
Peanut UCO	0.19	(Mardiana & Santoso, 2020)
Waste Coconut Oil	0.10	(Sangkharak et al., 2019)
Waste Palm Oil	0.0011	(Ubaidah et al., 2018)
Refined/Virgin Oils:		
Kernel Palm oil	0.44	(Novita et al., 2020)
Rapeseed oil	0.07	(Bąkowska et al., 2021)

3.4.3 Flash point

The flash point ensures safe transportation and handling of biofuels, as it limits the amount of residual alcohol present there. The European standard EN 14214 states that a flash point of biodiesel for heating oil must be greater than 120°C.Sunflower cooking oil and olive cooking oil satisfied this condition(Paschou et al., 2025).

For this criteria, the grading system is as follows: 1 for rates lower than 120, 2 for rates higher than this number but lower than 170, and 3 for the rest.

As a result of lacking data, flash points for fresh rapeseed and palm kernel oils are presented in the table. Research shows that there is a trend for the flash point to drop with an increasing percentage of waste cooking oil biodiesel(Wahyudi et al., 2024). Since the value for even fresh palm kernel oil biodiesel is lower than required minimum, this material was graded as 1(Olatundun et al., 2024).

The data on used peanut cooking oil biodiesel was underprovided; the only available information was that the peanut-based biodiesel (5:5) flash point is lower than diesel (63°C) but higher than that of petrol (54°C).(Soni et al., 2022) For used maize and rapeseed cooking oils additional investigation is needed, therefore this research uses available data for fresh oils with the understanding that values for UCOs would be lower than current(Černoch et al., 2010; Yusof et al., 2021).

Table 3: Flash Point Comparison of Biodiesel from Various Feedstocks relative to the 120°C Heating Oil Standard

Biodiesel Feedstock	**Flash Point (°C)**	**Reference**
Safe Range (> 120 °C):		
Rapeseed (Fresh)	195	(Černoch et al., 2010)
Soybean (Waste)	182	(Lin et al., 2021)
Sunflower (Waste)	179	(K et al., 2024)
Maize (Refined)	170	(Yusof et al., 2021)
Cottonseed (Waste)	128	(Sinha & Murugavelh, 2016)
Palm Oil (Used)	127	(Yogeeswara et al., 2020)
Olive Oil (Waste)	>120	(Paschou et al., 2025)
At Risk Range (< 120 °C):		
Coconut Oil (Waste)	110	(K et al., 2024)
Palm Kernel Oil (Fresh)	90	(Olatundun et al., 2024)
Peanut (5:5 Kerosene blend)	<63	(Soni et al., 2022)

3.4.4 Biodiesel kinematic viscosity

Viscosity is the measure of a fluid's resistance to flowing and is inversely proportional to the flow velocity. High viscosity level is assumed to be the main reason for sedimentation in equipment. Moreover, difficulties in evaporation and automatization also arise due to high viscosity. (e Silva et al., 2023; Pham et al., 2018).The American standard ASTM D6751 and the European standard EN 14214 for the biodiesel kinematic viscosity at 40°C are 1.9–6.0 mm2/s and 3.5–5.0 mm2/s respectively(Knothe & Steidley, 2007).

No vital difference was found in engine performance during engine tests between the biodiesel from fresh oils and UCOs. Therefore, this study believes that it is reasonable to substitute kinematic viscosity values for UCO biodiesel with values from fresh oil biodiesel, when no data about the first type was available(Adhikesavan et al., 2022). These approach was implemented for palm kernel and cottonseed oil biodiesel(Ejeromedoghene, 2021; Tilinti et al., 2024).

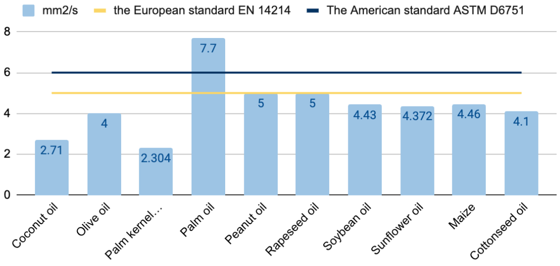

Figure 12: A given line chart depicts the kinematic viscosity of biodiesels in mm2/s from 10 UCOs, comparing values with the American standard ASTM D6751 and the European standard EN 14214. Data taken from:(Cordero-Ravelo & Schallenberg-Rodríguez, 2018; Dabai et al., 2018; Ejeromedoghene, 2021; Khalighi et al., 2025; Köse et al., 2020; Saeed et al., 2019; Tilinti et al., 2024; Ubabuike et al., 2024).

On the contrary, waste peanut and rapeseed oil kinematic viscosities were considered acceptable for biodiesel production.Therefore they were pointed as 5 mm2/s on the graph - the greatest European standard boundary(Khalighi et al., 2025). During multi-criteria comparison in this study, both were graded as 2 out of 3. Since no accurate exact details were found, the field needs additional investigation. In addition, waste olive oil biodiesel was reported to have a value around 4 mm2/s, without a precise number. It was graded as 2 out of 3(Cordero-Ravelo & Schallenberg-Rodríguez, 2018).

Figure 11 shows collected data(Cordero-Ravelo & Schallenberg-Rodríguez, 2018; Dabai et al., 2018; Ejeromedoghene, 2021; Khalighi et al., 2025; Köse et al., 2020; Saeed et al., 2019; Tilinti et al., 2024; Ubabuike et al., 2024) correlation with the American standard ASTM D6751 and the European standard EN 14214 for biodiesel kinematic viscosity values at 40 °C.

4 Discussion

Table 4 summarizes the comparison and grading phase of this study using the MCDA method. The total points range from 16 to 25, demonstrating a significant difference in the impacts of UCOs as biodiesel feedstocks.

The maximum potential grade is 30, while the minimum equals 10. Sunflower oil behaved the best out of all materials, resulting in the closest result to the maximum of 25 total points. Soybean oil received 23 points in total, proving to be the second-best option for sustainable UCO biodiesel production, considering criteria used in this paper. Palm oil is the third best choice out of ten evaluated oils with improvements needed in its acid values and the biodiesel's kinematic viscosity. Maize and rapeseed oil scored 20 out of 30, signaling improvements needed for sustainable biodiesel production.

On the contrary, coconut oil scored one point more than half of the maximum, demonstrating the necessity of strong interventions to produce satisfactory quality biodiesel from it. It received 3 only once for low usage of nitrogen fertilizers, showing potential for its sustainable usage as a biodiesel feedstock. Olive and peanut oils are second worst options with 17 total points each. Oil yield, price, land employment, UFA value were criteria where both scored 1 out of 3, raising the need for severe enhancements. Cottonseed and palm kernel oils were given 18 points each, highlighting the requirement for at least lowering nitrogen fertilization, improving UFA and UCO values to create more sustainable biofuel.

Table 5 represents the final rate of UCOs, starting with sunflower that has the highest score and ending with coconut that received 16 points in total.

Table 4: Final Comprehensive Analysis Table for ten evaluated UCOs

Oil\Criteria	Price	Oil yield	Nitrogen fert.	Land empl.	Calor. value	Smoke point	UFA value	UCO acid value	Flash point	Kin. viscosity	Tot.
Palm oil	3	3	2	3	3	2	2	1	2	1	22
Coconut oil	2	1	3	2	2	1	1	1	1	2	16
Olive oil	1	1	3	1	3	1	1	1	2	3	17
Palm kernel oil	3	3	1	3	1	2	1	1	1	2	18
Peanut oil	1	1	3	1	1	2	1	3	1	3	17
Rapeseed oil	1	2	1	3	3	3	1	1	2	3	20
Soybean oil	2	1	3	2	3	3	1	2	3	3	23
Sunflower oil	2	2	2	3	3	3	1	3	3	3	25
Maize	3	1	1	2	3	3	1	1	2	3	20
Cottonseed oil	3	1	1	1	3	2	1	1	2	3	18

UCO Source	**Total Score**	**Final Rank**
Sunflower	25	1
Soybean	23	2
Palm	22	3
Maize, rapeseed	20	4
Palm kernel, cottonseed	18	5
Peanut, olive	17	6
Coconut	16	7

Table 5: Final ranking of oil types based on aggregate scoring.

Overall, the average rate equals 19.6 points, using formula 1, mentioned before. Considering that the maximum possible number to score was 30 and the mean score is approximately 65%,the deeper research and enhancements are crucial in the field of biodiesel production from UCOs. Moreover, lack of data for certain UCOs was noticed in the literature, signaling the necessity for deeper research for every separate UCO evaluated.

Table 6 presents all criteria in descending order, commencing from those exhibiting the highest summed values across all oil grades. In general, the lowest grades were given for oil's unsaturated fatty acid value, UCO's acid value, and oil yield. These fields require more thorough investigation in general, as great scientific intervention is needed to boost UCO biodiesel's quality and sustainability. On the other hand, values for biodiesel's kinematic viscosity appeared to be pretty high with only 3 oils scoring less than maximum of 3. The same situation was observed for calorific value, with smoke point reaching 3 points less.

5 Conclusions

The selection of the best UCO is crucial for sustainable biodiesel production. Multi-criteria comparison analysis was employed to create the rate of potential sustainable biodiesel feedstocks for the ten most popular worldwide cooking vegetable oils.

A great range of results for ten investigated oils demonstrates that there is a rapid difference between most of them. Therefore, more comparison and empirical work is needed to consider all influential criteria in standardized circumstances.

This study highlights sunflower, soybean, and palm UCOs as three of the most suitable UCO

Criteria	Total Score	Rank
Kinematic viscosity	26	1
Calorific value	25	2
Smoke point	22	3
Price	21	4
Land employment	21	4
Nitrogen fertilizers	20	5
Flash point	19	6
Oil yield	16	7
UCO acid value	15	8
UFA point	11	9

Table 6: Ranking of criteria based on cumulative evaluation scores.

feedstocks for sustainable and efficient biodiesel. Coconut, peanut, and olive UCOs are three with the lowest rates of all analyzed materials. The present paper suggests that they might be used as a biodiesel feedstock, but stakeholders could need to apply more effort and investments than for UCOs with higher rates.

UFA point, UCO acid value, oil yield, flash point, and nitrogen fertilizers are criteria from which the majority of UCOs scored the lowest. From all mentioned here criteria, these fields have great potential for innovative approaches and improvement. They are highly recommended for future work and research. Kinematic viscosity, calorific value, smoke point, price, and land employment scored better; however, any criteria have a maximum of 30. This shows that even in the most successful fields, such as kinematic viscosity, there is still some space for development.

Throughout the data demonstrations for some criteria, the limited information on exact UCOs was noticed. This paper suggests that deeper analysis and research is needed for all UCOs evaluated here, as frequently only data on fresh vegetable oils were available.

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Review: Sustainability of Prevalent Waste Cooking Oils as a Biodiesel Feedstock: A multicriteria comparison.

Decision: Accept with major revisions

Overall Review:

Overall I can tell the author spends a good amount of time reading the literature, understanding the topic and making an effort to synthesize the literature. The main areas for improvement relate to clarity of writing, organization, and strengthening the abstract and conclusions so the key takeaways and practical implications are more clearly communicated. Once the revisions outlined below are addressed, this paper has strong potential to become a solid publication.

The content of the introduction is of good quality. However, the sentence structure needs further work, as several sentences are difficult to read and follow. The abstract provides enough information to understand what the paper is about and what it is trying to achieve. However, the order could be improved to provide a better reading flow. I recommend organizing the abstract in the following order:

- Background / motivation (why biodiesel and UCOs matter)
- Research gap (lack of distinction among UCO types)
- Objective (what this paper analyzes)
- Methods (multi-criteria comparison approach)
- Key results (main findings)
- Implications (why the findings matter)

Currently, the abstract clearly motivates the study and states the objective:

“to analyze to what extent the life-cycle environmental impacts of biodiesel from diverse Used Cooking Oils (UCOs) differ when evaluated using a standardized, multi-criteria comparison” However, the abstract is still missing a clear statement of the main overall result. You mention future directions and discussion points, but the reader should immediately understand the primary takeaway of your study. I recommend adding 1–2 sentences that directly answer your main research question. You conducted a strong literature review, and the paper contains valuable material. At this stage, the main issues are related to organization and clarity of presentation, not the underlying content.

Overall, the manuscript would benefit from:

- breaking up long or run-on sentences
- clarifying transitions between ideas
- tightening the connection between claims and supporting evidence

One additional note: the claim that the study provides a guideline for stakeholders is somewhat strong. This could be appropriate, but it should be more explicitly supported in the discussion. For example, under what conditions should biofuels choose one UCO over another? You briefly mention regional differences (e.g., Europe vs. U.S.); expanding this point would strengthen the practical relevance of the paper.

Individual Comments

- Thank you for including inline numbering. You are the first young scientist in this journal (among the submissions I have reviewed) to include this format, and it is very helpful for the reviewer.
- **[line 11]** Formatting: add a space between *used cooking oils* and the abbreviation (UCOs).
- **[line 31]** The period should appear after the in-text citation, not before. Please check the rest of the manuscript since this is a consistent issue.
- **[lines 43–44]** Please review this sentence. It appears that a word may be missing, and the meaning is currently unclear. When first defining the UCO abbreviation, please capitalize Used Cooking Oils.
- **[line 46]** Please review citation spacing; there are several instances where a space is missing between the text and the citation. Also add a space between Waste Cooking Oil and (WCO). Instead of “in some literature,” consider a more precise phrasing such as:

  In the literature, the terms Waste Cooking Oil (WCO) and Used Cooking Oil (UCO) are often used interchangeably to refer to the same biodiesel feedstock. For consistency and clarity, this study uses the term UCO throughout.

- **[lines 49–50]** The statement about UCO disposal routes in 2020 is interesting and important. Please clarify the geographic context (country or region) of this statistic.
- **[lines 52–53]** This sentence currently contains too many ideas at once. Consider splitting it into two sentences so each point is clearer and easier to process.
- **[lines 57–58]** The sentence structure is somewhat inverted and difficult to follow. Consider rewriting in a more direct subject–verb–object form. Also, please add a citation supporting the projected values.
- **[lines 59–62]** You are presenting very strong supporting statistics, but the current wording makes them harder to follow. Suggested revision:

  Additionally, global vegetable oil consumption has nearly tripled, increasing from 83 million tons in 2000 to 217 million tons in 2023. Of this total, approximately 167 million tons are used in the biodiesel industry, indicating substantial potential for new feedstock production.

- **[line 63]** Please capitalize Life Cycle Assessment (LCA).
- **[lines 63–65]** Good job with the citations. Continue working on sentence flow when integrating in-text citations.
- **[lines 69–71]** This sentence structure works well and is easy to follow, consider using this style more consistently.

Additional Comments

- **Figure 1:** Remember the distinction between “sourced from” and “adapted from.”
  - Sourced from = figure reproduced as is
  - Adapted from = figure modified
    If adapted, please briefly describe what was changed.
- **Figure 2:** Same comment regarding *sourced from* vs. *adapted from*.
- **Section 2.1:** Nice work presenting each oil type separately with strengths and weaknesses.
- **Figure 3:** Strong and informative figure. Because it contains a lot of information, consider:
  - switching to a horizontal layout
  - increasing font size for readability

- **Figure 4:** This appears to be a bar chart, not a line chart. Please enlarge the figure and consider sorting bars from highest to lowest for readability.
- **Figure 5:** Please standardize text color across the bars (currently mixed). Also increase figure size and DPI for clarity. This recommendation also applies to Figure 7.
- **Section 3.2.1:** There is excellent information here well done gathering these data. However, the paragraph currently jumps between ideas, which makes the main message harder to follow. Consider:
    - improving logical flow
    - checking spacing around inline numbers (e.g., *richest(46% of N)*)
    - possibly adding a table for nitrogenous fertilizers (might be easier to present data this way)
- **Figure 9:** Line charts are typically best for time series. Consider whether a bar chart may be more appropriate for comparing categories.
- **Figure 10:** The citation is somewhat unclear, are you citing the data source? Also consider whether an area chart is appropriate only if values vary over time.
- **Section 3.3.3 (UFA values):** You present two contrasting interpretations (good for health vs. less ideal for biodiesel). Please clarify the overall takeaway. What does grading imply for biodiesel performance?
- **Figure 11:** This is a bar chart but is labeled as a line chart. Please enlarge for readability and ensure decimal precision is consistent across bars.
- **Tables 2 and 3:** The formatting is very clean, nice work. Try to maintain this consistency throughout the manuscript.
- **Figure 12:** This is a bar chart with line indicators for U.S. and European standards not a line chart
- **All figures:** you want to mention figures more than once, if possible, to make sure they are actually serving a purpose in your manuscript. Also, when you make a graph it's important you mention how it was made. In the caption as well as in the paper the reader knows how to interpret what they are seeing.

Results and Discussion

There is currently not a clear distinction between the Results and Discussion sections. I recommend either:

- clearly separating descriptive results from interpretation, or
- combining them into a single Results and Discussion section.
- It is also uncommon to introduce new tables in the conclusion and discussion sections. Consider moving all tables and figures to the Results section.

- You have a lot of valuable results to discuss, but right now the manuscript does not present a fully consistent narrative about what the reader should take away from the paper. Instead, I recommend selecting two scenarios to really dive into in your discussion and really focus on what is the general message you want to have in the conclusion, so your overall narrative becomes clearer and more focused.

- Thank you for your hard work. I hope these changes help strengthen the manuscript and move it toward publication as a strong article.

Review of Paper: “Sustainability of Prevalent Waste Cooking Oils as a Biodiesel Feedstock: A multi-criteria comparison”

(First Suggestion: To be consistent with writing the title with proper title capitalization, “Multi-Criteria Comparison” should be capitalized as well.

This manuscript is a review article of the literature around the life cycle analysis of used cooking oils, which the author refers to throughout as UCOs, and more broadly the sustainability, suitability, and economics around their use as biodiesel energy sources when replacing more polluting, fossil-fuel counterparts. This is particularly important as it extends the applications of said UCOs and thus might be seen more broadly as a transition towards greater sustainability, but as is investigated, not all UCOs are alike in their properties or potential for broader adoption on a larger scale. This review synthesis methodically and systematically rates 10 UCOs, namely palm oil, coconut oil, olive oil, palm kernel oil, peanut oil, rapeseed oil, soybean oil, sunflower oil, maize, and cottonseed oil in terms of their overall sustainability with regards to maximum biodiesel production, based on 10 different factors, summarized in Table 4 and then ultimately consolidated and ranked in Table 5. This review article purports this overview to be novel in its finding of sunflower, soybean, and palm oils as the preferred oils for sustainable and efficient biofuels.

Overall, this is an interesting and fairly accessible review paper that is quite thorough in terms of its literature evaluation, and I believe this will be worthy of publication, pending some moderate to significant revision, particularly on the stylistic side.

Additionally, while the writing itself is generally acceptable, portions of it are grammatically a little clunky, with many missing definite and indefinite articles throughout and some missing words or confusing sentences elsewhere; in some other cases some general improvement may substantially improve its overall readability. I highly recommend a thorough proofread prior to the next submission – I am providing some grammatical guidance at the end of this review, but it is not a completely comprehensive list and I urge the author to potentially consider additional eyes to improve the editorial element of the paper.

Specific Technical Comments:

1) Figure 3: While I can read all the text in the Criteria Tree, I had to zoom in a bit, and wonder if it is possible to enlarge the text a little bit, especially for the lower boxes. It is okay for this figure to take up a little more space, and for clarity and accessibility purposes, making this figure larger would be helpful.
2) Figure 5: What is the meaning, if any, of the faint blue values denoting oil yields of olive oil, peanut oil, maize, and cottonseed oil? Or are the black bold values for the others simply indicating that they are top six oil yield crops?

3) Figure 8: There is quite a bit of wasted space on the y-axis, especially since none of the UCOs have calorific values lower than about 35,000 kJ/kg. I would suggest perhaps starting the y-axis with this value to better highlight differences. Also, the numbers are nearly impossible to read – please consider changing the font color to black.
4) Table 2: Only three UCOs have the requirements for sufficiently low moisture content. Is there a better way to highlight this in the table?
5) Line 19: Why does soybean oil not appear in the abstract? After all, it ranks overall as the second leading candidate of a UCO for use as a biofuel, but a reader would not know that if only the abstract was consulted.

Specific Grammar, Punctuation, and Specific Readability Concerns:

1) Line 16: I would suggest using “distinguishability” here instead of “distinguishing.”
2) Line 31 (and elsewhere): When a citation is included in parentheses, the period follows *after* the second parenthesis, not before the first of the pair of parentheses. (Other nearby examples of this are on lines 32 and 34.)
3) Line 43: The sentence: “The reason lies in the of used cooking oil …” appears to have a missing word and is unclear. Did the author intend to include “type of” prior to “used cooking oil?”
4) Line 51: There appears to be an extra period not needed (before the parenthesis).
5) First paragraph of page 4: There are once again several instances of periods appearing before parenthesis pairs containing citations.
6) Line 94: “the” is not needed before “sesame”.
7) Lines 95-96: Verbose – change “In the present time” to “Presently,”
8) Line 96: missing article – add “a” before “luxury oil.”
9) Line 113: Missing article – add “a” before “criteria tree”
10) Line 159: “good” should be “goods”
11) Line 160: Suggest changing “is in charge of” to “is responsible for”
12) Line 161: Period should be after the second parenthesis.
13) Line 162: Change “to the overall GHG emission” to “to overall GHG emissions”
14) Line 166: Add a comma after “values”; also, change “no later” to “no earlier.”
15) Lines 176-177: This is an incomplete sentence as written. Change the portion of line 177, which now reads as “global average yield of 3.5 tons of oil” to “global average yields 3.5 tons of oil …”
16) Line 196: The sentence, currently beginning with “Process”, should begin with “The.”
17) Line 235: There is a missing period after “g.”
18) Line 235: There’s a missing article before “value” (should add “the” before “value”).
19) Line 237: I do not understand what “simply used” refers to here.

20) Line 238: Add a comma after “rest”. Also, I believe that “where” should be “were.”
21) Line 242: change “excess number of water” to “excess amount of water”
22) Line 246: Missing article: add “the” before “biodiesel.”
23) Line 249: The phrase “water content and fried in it products” is awkward and needs to be rewritten.
24) Line 252: Missing “a” before “high.”
25) Line 266: Add “the” before “required”.
26) Line 276: Begin the sentence with “A”
27) Line 284: Change “These approach” to “This approach”
28) Line 285: Need a space between biodiesel and the first parenthesis.
29) Line 308: Change “On the contrary” to “In contrast”
30) Line 319: Clunky sentence: Change “that the maximum possible number to score was 30” to “that the maximum possible score was 30”
31) Lines 319-320: Change “the deeper research” to “additional research”
32) Line 328: add “the” before “maximum.”
33) Lines 328-329: add “the” before smoke point”. However, I do not understand what this sentence means … e.g. starting with “The same situation …” Please consider a complete overhaul of this sentence.
34) Line 334: “rapid” is not an appropriate word here; change to “large” or something else.

Sustainability of Prevalent Waste Cooking Oils as a Biodiesel Feedstock: A Multi-Criteria Comparison

March 21, 2026

Abstract

The growing concerns about the scarcity of fossil fuels and associated greenhouse gas emissions encourage humanity to develop renewable and environmentally safe alternatives. Over the past 20 years, the field of biofuels has sparked significant investigations, especially biodiesel as a substitute for non-renewable sources in the transport sector. Several Life Cycle Assessments and other types of analyses have been conducted to determine the sustainability of various virgin cooking oils and UCOs as biodiesel sources. However, no distinguishability of the different types of UCOs has been mentioned. The purpose of the present work is to analyse to what extent the environmental, social, economic, and technical impacts of biodiesel from diverse Used Cooking Oils (UCOs) differ when evaluated using a standardised, multi-criteria comparison that covers the entire life-cycle of every investigated oil. The results show that there is a need to distinguish between different kinds of UCOs. Based on a literature review of the most common UCOs and a multi-criteria comparison approach, 10 UCOs were compared by 10 criteria from different sectors. A list of the most efficient and sustainable UCOs is also proposed, highlighting sunflower, soybean, and palm UCOs as the leaders and peanut, olive, and coconut UCOs as the underperformers. This analysis reveals that the unsaturated fatty acids profile, the acid value of the UCOs, the oil yield, the flash point, and nitrogen fertilizers are the criteria by which the majority of UCOs scored the lowest. This suggests that these fields have great potential for improvement. Almost all UCOs demonstrated appropriate kinematic viscosity and calorific values, meaning that the focus might be switched from them towards more undeveloped criteria. The insights are provided for stakeholders in the biodiesel industry with the aim of supporting the transition to less polluting energy generation.

Keywords: sustainability, used cooking oil, life cycle, biodiesel, biofuel, multi-criteria comparison

1 Introduction

The rapidly growing population and its energy needs emphasize the necessity for a wider range of feedstocks to be deployed. In 2024, a 2.2% rise in global energy demand was recorded, which is almost twice the annual average increase over the past 10 years. This significant increase is partially based on global warming conditions that accounted for approximately 13.6% of this overall 2.2% growth. Moreover, 2024 was the warmest year on record, with the temperature exceeding pre-industrial levels by 1.5 °C (International Energy Agency, 2025). Figure 1 demonstrates the breakdown of the current global primary energy mix for sources (Ritchie et al., 2020). In 2025, more than half of global energy was still derived from coal (24.6%), gas (21%), and oil (31.2%), which are all carbon-based fuels (Ritchie et al., 2020). These hazardous trends require thorough control, as well as a determined and prompt transition to alternatives, such as solar, wind, nuclear, hydro, and biomass energies. In this context, biofuels appear to be a promising and affordable source of green energy.

Within the transport sector, the crucial branch of biofuels is biodiesel, as an efficient substitute fuel for diesel engines. Biodiesel can be generated via a chemical reaction between a vegetable oil (including used cooking oils) or animal fat and an alcohol, involving a strong base as a catalyst and resulting in the production of methyl esters, which constitute biodiesel (Van Gerpen, 2005). While numerous biodiesel feedstocks exist, the maximum sustainable resource management can be achieved by attracting Used Cooking Oils (UCOs) as a source of production. The reason lies in the opportunity to address the UCO disposal issue, which society is currently confronting because of the negative environmental influence. UCOs are used cooking oils collected from restaurants and industrial sectors that are no longer suitable for consumption (Beghetto, 2025). In the literature, the terms Waste Cooking Oil (WCO) and Used Cooking Oil (UCO) are often used interchangeably to refer to the same biodiesel feedstock. For consistency and clarity, this study uses the term UCO only. In 2020, the main UCO disposal route in Greece was sewage, resulting in sanitary sewer overflows, property flooding, contamination of water bodies with sewage, water, and soil pollution. Consequently, incurring additional costs on water treatment facilities is inevitable if UCOs are not recycled (Foteinis et al., 2020). Currently, oils make up 10% of global caloric consumption (Beghetto, 2025). As the global population grows every year, the demand for cooking oil rises accordingly. Consequently, the issue of UCO utilization becomes increasingly topical. Even though existing literature presents other applications for UCO, such as biolubricants, biosolvents, animal feed, asphalt additives, biodiesel remains the most demanded and efficient option, considering the growing need for alternative and sustainable non-fossil fuels (Beghetto, 2025).

The UCO supplies are expected to rise from the current 3.7 billion gallons to between five and ten billion gallons in 2030 (GlobalData, 2023). As a result, this creates a space for biodiesel production that could reach 5.8 billion gallons within the next four years (GlobalData, 2023). Additionally, global vegetable oil consumption has almost tripled from 83 million tons in 2000 to 217 million tons in 2023. Of this total, 167 million tons are utilized in the biodiesel industry, indicating a substantial potential for new feedstock production (Beghetto, 2025).

Modern studies investigate the field of UCO biodiesel through Life Cycle Assessment (LCA) (Musharavati et al., 2023; Nogales-Delgado, 2025), sustainable business assessment (Abdullah & Glasscock, 2025), comparative studies (Paschou et al., 2025), economic (Yang et al., 2025), and bibliometric (Chen et al., 2021) analyses. Although a great amount of research is conducted on UCOs and separate edible oils that were grown only to be recycled to biodiesel, authors rarely distinguish between types of UCOs derived from different vegetable cooking oils (Bouaid et al., 2024; Intarapong et al., 2016). This paper investigates whether the mentioned difference exists and if so, what exactly these differences are in the use of UCO from the ten most popular cooking oils, comparing them quantitatively through a Multi-Criteria Decision Analysis (MCDA) approach. The criteria cover the entire life cycle of investigated materials, considering main areas of impact: (i)Environmental; (ii)Social; (iii)Economic; (iv)Technical. Every field includes subtopics for comprehensive data analysis and comparison of the most produced vegetable oils in 2022, presented in Figure 2 (Ritchie, Roser, & Rosado, 2024). The choice of compared oils is discussed in detail in the methodology. In the results section, all findings are assessed and the ranking of oils is presented, starting from the most suitable and ending with the least appropriate, for UCO biodiesel creation. The discussion section offers recommendations on the most appropriate UCOs, taking into account the primary focuses of stakeholders. In this way, the work discusses to what extent the life-cycle environmental impacts of biodiesel from diverse UCOs differ when evaluated using a multi-criteria comparison. The criteria cover the entire life cycle of UCOs.

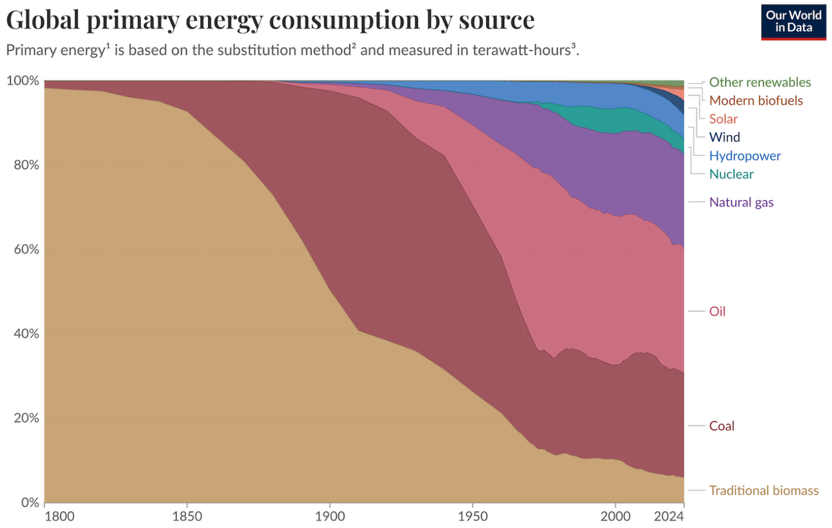

Figure 1: A demonstration of global primary energy consumption by source within the last 2024 years. Sourced from:(Ritchie et al., 2020)

2 Materials and Methods

2.1 Formulation of Alternatives

Figure 2 illustrates thirteen of the most produced vegetable oils in 2022 (Ritchie, Roser, & Rosado, 2024). However, linseed, sesame, and safflower oils were found inappropriate for cooking due to the reasons discussed below in this section. Therefore, this research only evaluates 10 remaining oils from Figure 2:

2.1.1 Linseed oil

Several studies were conducted on the quality properties of the linseed oil (Eastern Connecticut State University, 2015; Nykter et al., 2006). The smoke point appeared to be comparatively low, resulting in diminished quality of the fried food. A high level of α-linoleic acid causes faster oxidation during heating, which leads to a huge content of Free Fatty Acids (FFA) (Tripathi et al., 2013). These facts negatively influence the ability of oil to be converted into biodiesel, as the sustainability of the final product would be lower than that of already developed substitutes.

2.1.2 Sesame oil

While sesame oil is extremely stable, it is considered to be high-priced, as the seed harvesting remains an arduous task that requires an enormous amount of labor (Hwang et al., 2026). Presently, this oil is referred to as a ”luxury oil”. Moreover, its production is not extensive enough to consider it as a potential large-scale source of biodiesel.

2.1.3 Safflower oil

The main fatty acid in safflower oil is linoleic acid. Therefore, after heating, the amount of FFA increases significantly, leading to challenges during biodiesel operation, such as the risk of soap formation during transesterification or within the engine system.(Lee et al., 2004; Rubel et al., 2026)

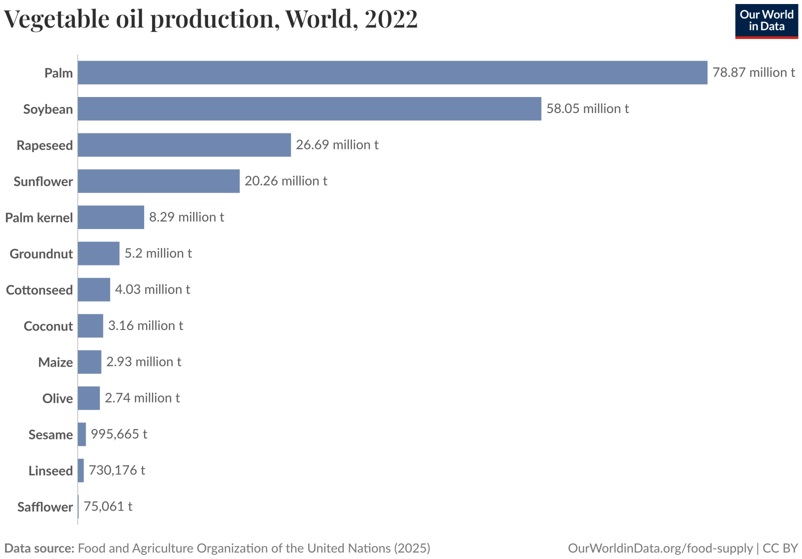

Figure 2: A bar chart showing global vegetable oil production, broken down by oil type. Sourced from:(Ritchie, Roser, & Rosado, 2024)

2.2 Multi-Criteria Decision Analysis (MCDA) Development

MCDA is defined as an approach for choosing a well-balanced compromise for complex problems characterized by conflicting objectives and stakeholders with different needs. The tool includes transparent, often mathematical decision-support processes, engaging actors in the procedure (Gallazzi et al., 2025).

The analysis is conducted as follows: all substitutes are compared using every stated criteria, which are evaluated by significance (De Feo et al., 2023). The present MCDA procedure includes the following phases: (i) A criteria tree; (ii) The set of indicators; (iii) Relative importance factors elicitation; (iv) Rate creation.

2.2.1 Criteria and the set of indicators

Figure 3 presents a criteria tree as part of the criterion finalization process. Three pillars of sustainability(economic, environmental, and social)(Purvis et al., 2019) and technical aspects are covered as 4 distinct groups, each including relative criteria. Table 1 holds the final 10 criteria for assessment. For every investigated UCO, each criterion is described by three levels of performance with 1 as the most unsatisfactory grade, 2 as acceptable or standard, and 3 standing for the optimal.

2.2.2 Relative importance factors elicitation

In (Wulf et al., 2025), two main ways of weighting factors are presented: trade-off weights and importance coefficients. The first type is more case-specific and describes the relative importance of two or more criteria, while importance coefficients are absolute and non-case-specific. On the other hand, the employment of equal weights in a hierarchical structure, if required, is mentioned as a popular alternative.

This study focuses on the equal weights approach, as it ensures a clear and unbiased evaluation. Within the hierarchical structure, this method initially considers four main areas as equally

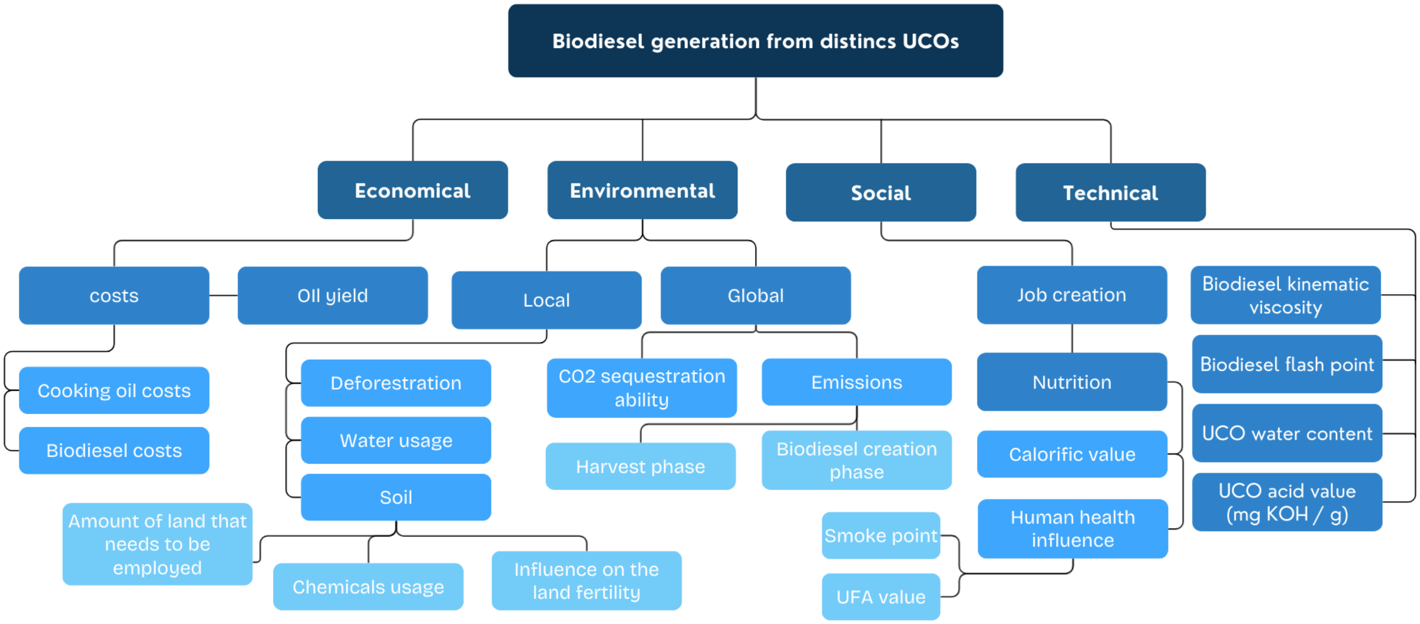

Figure 3: A criteria tree

important. For every criterion in the mentioned sections, the same equal weight distribution is applied.

2.2.3 Rate creation

The rate includes all ten examined UCOs, presenting oils with the highest average results from all criteria at the top and materials with lower values below.

2.3 MCDA Methods

3 Literature Review and Comparative Analysis Beginning

3.1 Economic aspect

3.1.1 Cooking oil prices

Figure 4 presents the prices for 10 vegetable oils in 2022 (Ozbun, 2025; Shanbhag, 2022; Tridge, 2026). A Metric Ton of maize costs 319 US dollars in 2022, considering the information from (Ozbun, 2025). On the contrary, cottonseed oil prices in 2022 were reported to vary from $760 to $1660 per Metric Ton. For Figure 4, the average value of $1210 per Metric Ton was taken (Tridge, 2026).

The average value per metric ton was calculated to be $1646.6, using formula (1):

$$a_{\text{avg}} = \frac{a_1 + a_2 + a_3 + \cdots + a_n}{n} \quad (1)$$

Table 1: Grading criteria for oil evaluation

Aspect	**Criteria**	**Grading Scale**
Economic	Cooking oil prices	1 = above average; 2 = approx. average; 3 = below average
	Oil yield	1 = above average; 2 = approx. average; 3 = below average
Environmental	Chemical usage	1 = highest rates; 2 = middle rates; 3 = lowest rates
	Land employed	1 = significantly < 0.6; 2 = approx. 0.6; 3 = significantly > 0.6
Social	Calorific value	1 = less than average; 2 = approx. average; 3 = greater than average
	Smoke point	1 = < 400; 2 = $400 - 450$; 3 = > 450
	UFA value	1 = $< 30\%$ or $> 50\%$; 2 = $30\% - 35\%$ or $45\% - 50\%$; 3 = $35\% - 45\%$
Technical	UCO acid value	1 = > 0.5; 2 = $0.45 - 0.5$; 3 = < 0.45 (mg KOH/g)
	UCO water content	1 = $> 0.15\%$; 2 = $0.1\% - 0.15\%$; 3 = $< 0.1\%$
	Biodiesel flash point	1 = $< 120°C$; 2 = $120°C$ - $170°C$; 3 = $> 170°C$
	Kinematic viscosity	1 = < 1.9 or > 6.0; 2 = $1.9 - 3.5$ or $5.0 - 6.0$; 3 = $3.5 - 5.0$ (mm^2/s)

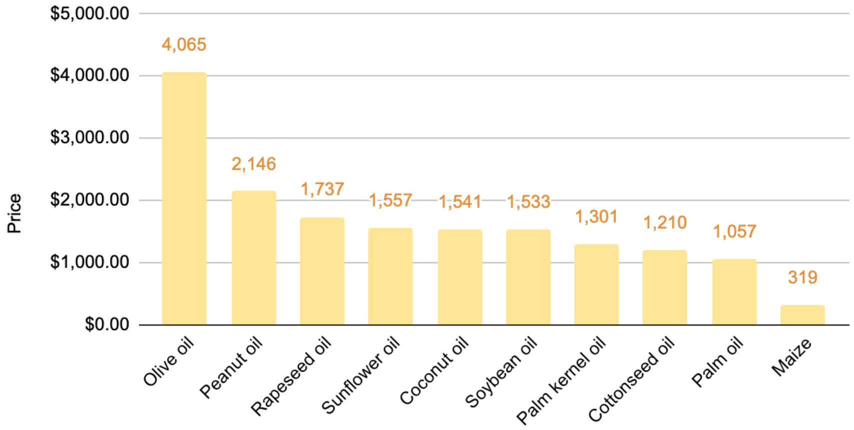

Figure 4: A bar chart demonstrates historical price data of 10 edible oils in July 2022. Price in US Dollars per Metric Ton. Data taken from (Ozbun, 2025; Shanbhag, 2022; Tridge, 2026).

The grading values for each oil are presented in the result section.

3.1.2 Oil yield

Oil yield is known to be a crucial oil efficiency aspect. Apart from maize and palm kernel oil, all data were available in direct values (Ritchie, Rosado, & Roser, 2024). Initially, for both materials, oil content percentages were found to be 4% (Singh et al., 2014) and 37.5% (Alshafea et al., 2025), respectively. Thereafter, percentages were converted to oil yield, using global vegetable oil production data from Figure 2 and the following formula:

$$Y_{\text{oil}} = Y_{\text{crop}} \times \frac{C\%}{100} \tag{2}$$

where:

- Y_{oil} — oil yield (t/ha);
- Y_{crop} — total crop yield (t/ha);
- $C\%$ — oil content percentage.

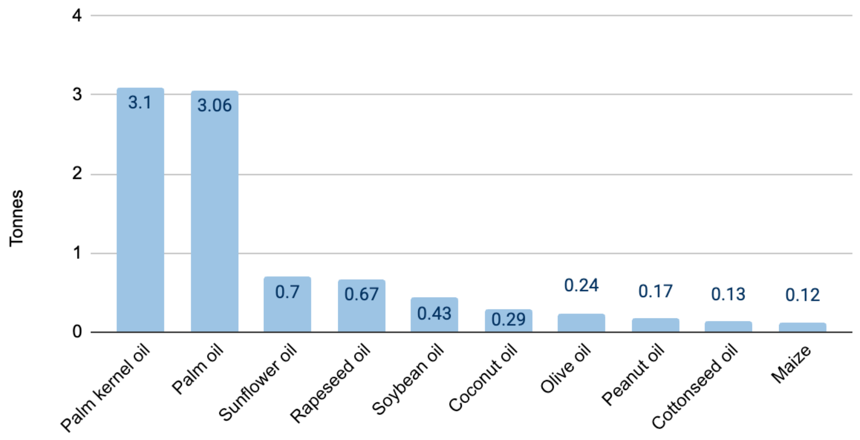

Figure 5: A bar chart depicting global oil yields in tonnes per hectare of land by crop type, evaluating data from (Alshafea et al., 2025; Ritchie, Rosado, & Roser, 2024; Singh et al., 2014).

Calculations resulted in 0.12 t for maize and 3.1 t for palm kernel oil. Figure 5 includes the average amount of oil in tonnes produced per hectare of land for 10 analyzed oils.

3.2 Environmental aspect

3.2.1 Chemicals usage during harvesting

As the human population continues to grow, an instantly increasing demand for crops is inevitable. To cope with rapidly rising consumption, suppliers resort to using agrochemistry to enhance properties of goods, such as temps of growing, quality, and sizes. However, the agricultural sector is responsible for more than 80% of anthropogenic N2O emissions, 70% of anthropogenic NH3 emissions and approximately 40% of anthropogenic CH4 emissions (Sokal & Kachel, 2025).

Nitrogen (N) fertilizers are the ones that contribute significantly to overall GHG emissions. Several investigations recorded that increasing N fertilizer rates leads to greater than proportional N2O emissions. With this said, this research focuses on the analysis of the urea usage during harvesting, which is considered the cheapest and richest (46% of N) primary global nitrogenous fertilizer (Swify et al., 2024). The average nitrogen employment rates are presented in Table 2 for the harvest of each oil crop. All compared values were taken from sources published no earlier than from 2004 for information to remain accurate nowadays. Figure 6 visualizes data from Table 2.

3.2.2 Land employment

Statistics(Ritchie, 2021) suggest that global vegetable oil demand in 2022 was equal to 218 million tonnes of oil. This criterion examines 10 evaluated oils for the land area in ha needed to fulfill the global vegetable oil demand in 2022. For palm oil and palm kernel oil together, the researchers argue that the global average yields 3.5 tons of oil per hectare (Barcelos et al., 2015). However, taking plain kernel oil, productivity drops to approximately 0.5 tonnes per hectare. Worldwide, corn has an average productivity of 0,3 tonnes per hectare (da Silva & da Costa, 2025). The 218 million tonnes divided separately by the mentioned numbers result in 436 and 726 million hectares accordingly. The rest of the data was taken from (Ritchie, 2021). Figure 6 collects all the information explained here together for further evaluation in the discussion section.

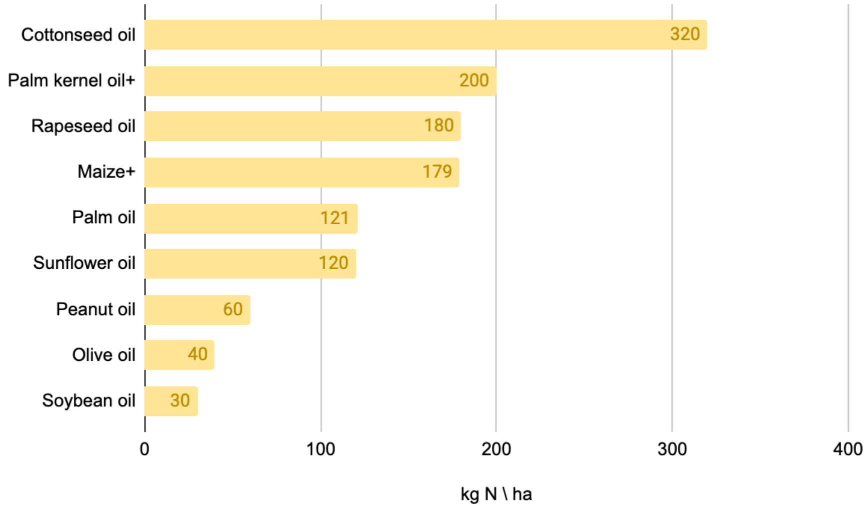

Figure 6: A bar chart compares the average amount of Nitrogen required for the harvest of each oil within the last 20 years.

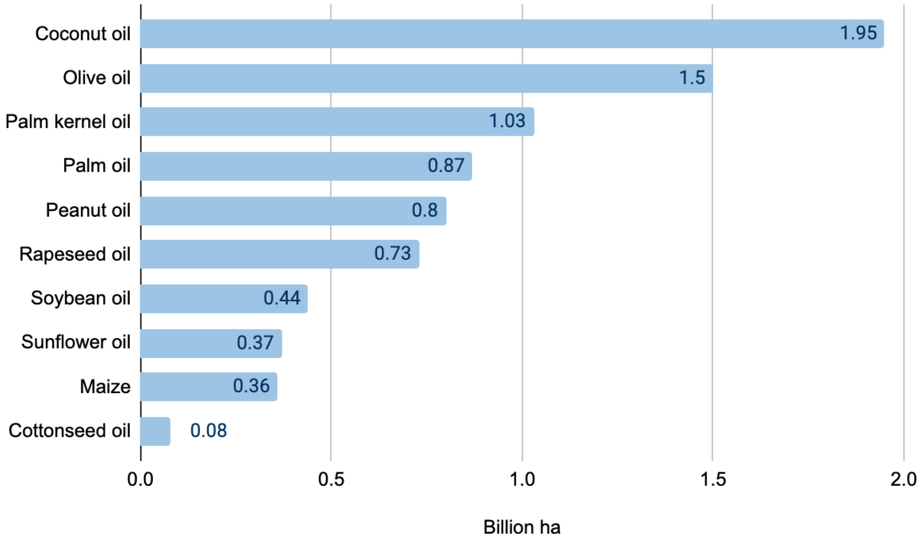

Figure 7: A bar chart demonstrates the area of land in billions needed to satisfy global vegetable oil demand using only 1 oil in 2022

Table 2: Standard nitrogen application rates for various oil crops

Oil Crop	**Nitrogen Rate (kg N $\times$ ha^{-1})**	**Source**
Palm Oil	108–134	(Mohd Kusin et al., 2015)
Sunflower Oil	120	(Özer et al., 2004)
Soybean Oil	30	(Wysokiński et al., 2024)
Cottonseed Oil	320	(Jing et al., 2023)
Maize	179	(Zhang et al., 2018)
Coconut Oil	Lack of culture response	(Lins et al., 2021)
Olive Oil	40	(Fernández-Escobar et al., 2002)
Rapeseed Oil	180	(Zhu et al., 2023)
Palm Kernel Oil	260	(Woittiez et al., 2017)
Peanut Oil	60	(Li et al., 2024)

Even though the oil yield criteria, expanded earlier, is mathematically connected to land employment, this study aims to highlight the importance of sustainability considerations. Therefore, the oil yield criteria is related to the economic aspect, while land employment is presented in the environmental part.

3.3 Social aspect

3.3.1 Calorific value

Calorific value is the energy outcome after complete combustion of 1 g of fuel in the presence of oxygen. This value can be expressed in kJ/kg and determined using the following equation:

$$\text{Calorific value} = \frac{\text{heat produced}}{\text{amount of fuel}} \tag{3}$$

The produced heat is found experimentally or via a calculation by thermodynamic methodology:

$$Q = nC_P\Delta T \tag{4}$$

where Q is heat produced, n is no. of moles of fuel, C_P is heat capacity at constant pressure (1 bar), and ΔT is the difference in final and initial temperatures (Wan Ghazali et al., 2015).

On the one hand, for nutritional purposes, a higher calorific value means less mass of oil is needed to satisfy a certain energy level for humans. On the other hand, the energy content of the feedstock indicates the efficiency capacity of the biodiesel. The process of oil conversion into biodiesel increases the amount of oxygen, which leads to lower combustion heat. However, the initial differences between distinct vegetable oils remain the same even after several operations on material (Plata et al., 2022). Therefore, calorific value steps in as a crucial criterion from two instantaneous perspectives. Figure 7 breaks down the energy content of analyzed vegetable oils, containing data from (Batomayena et al., 2019; Sanli, 2025).

3.3.2 Smoke point

Since this research aims to consider the best UCOs for biodiesel production, it is crucial to know which feedstock will be undoubtedly suitable for domestic cooking utilization.

Frying, a widely used cooking method, involves immersing food in hot oil at a temperature range of 150°C to 180°C. Frequently, during this process hydrolysis, thermal oxidation, and polymerization occur. These reactions are undesirable, as they result in a worse quality of the frying medium. Therefore, smoke point directly influences the taste of the food and the health of the

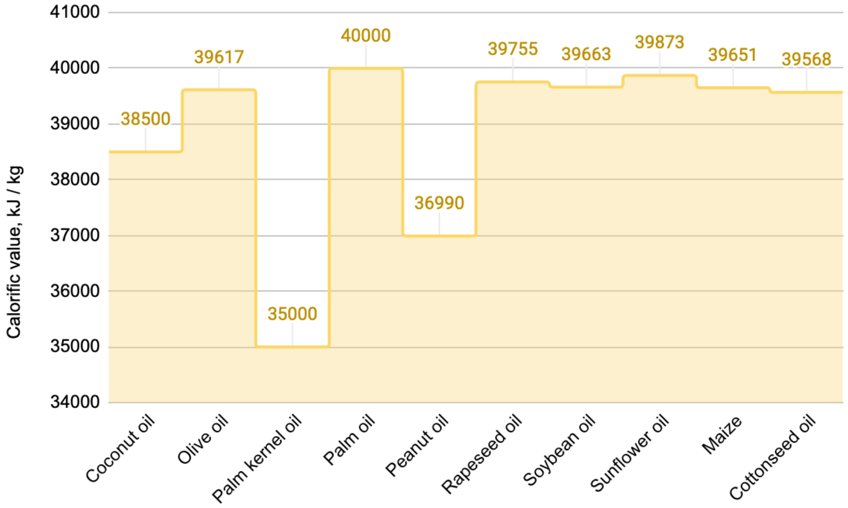

Figure 8: A stepped area chart compares energy values of evaluated oils in kJ per kg

consumers (Ng & Choo, 2017). Figure 8 compares smoke points of 10 vegetable oils, taking data from (Benexia, 2022; Redmond, 2024).

3.3.3 Unsaturated fatty acid (UFA) value

Epidemiologists claim the higher ratio of UFA in vegetable oils, especially 6 polyunsaturated fatty acids (linoleic acid), lowers risks of cardiological problems, type 2 diabetes mellitus and does not increase markers of inflammation or oxidative stress. Authoritative health and scientific organizations recommend consumption of oils rich in UFA instead of alternatives with high contamination of saturated fatty acid, for instance, palm and coconut oils (Petersen et al., 2024).

However, high values of UFA negatively influence the biodiesel generation process, as they are responsible for faster free fatty acids occurrence during oil frying. Since UCOs with FFA level above 5 percent are inappropriate for biodiesel production, producers often need to spend extra resources and time on lowering FFA levels.

To balance these opposing criteria, a compromise grading system was employed. Materials with either too low or extremely high UFA levels were graded 1 point, whereas oils with a UFA content around 40 % were rated 3 points. Figure 9 illustrates the percentage of UFA in each oil (Abrante-Pascual et al., 2024; Benexia, 2022; Frančáková et al., 2015; Redmond, 2024).

3.4 Technical aspect

3.4.1 UCO acid value mg KOH/g

Acid value refers to the number of milligrams of potassium hydroxide needed to neutralize the amount of FFA in UCO. There exists a straight correlation between the free fatty acid amount and the acid value. High acid value could reduce the oil's quality by slowing its reaction rate. The steady increase of acid value arises with the rise of the oil's frying time. The European Standard of a maximum acidity value of 0.50 mg KOH/g was taken into account during grading, meaning that every oil with a higher result was given 1 out of 3 (Bong et al., 2020; Paschou et al., 2025).

The acid value for fresh palm kernel oil was measured as 17.95 mg KOH / g (Bong et al., 2020), signalizing that for UCO this number would probably be even higher. The same applies for fresh rapeseed oil, which acid value was stated as 2 mg KOH / g. Additionally, the value of maize on the

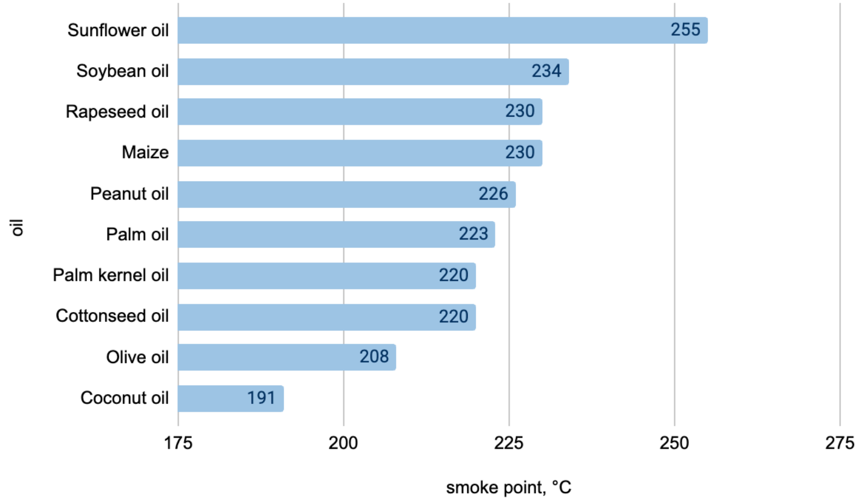

Figure 9: A bar chart presents smoke points of 10 examined oils(Benexia, 2022; Redmond, 2024).

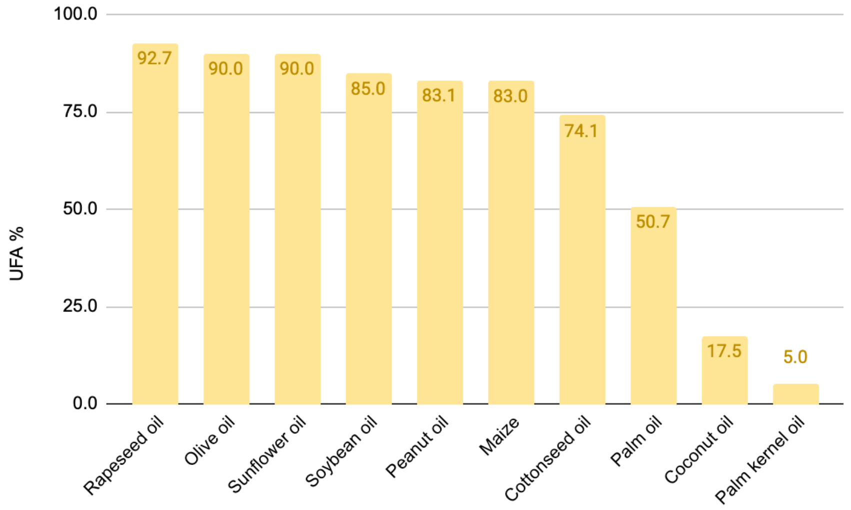

Figure 10: A bar chart shows UFA content percentage in every oil. Based on the data from(Abrante-Pascual et al., 2024; Benexia, 2022; Frančáková et al., 2015; Redmond, 2024).

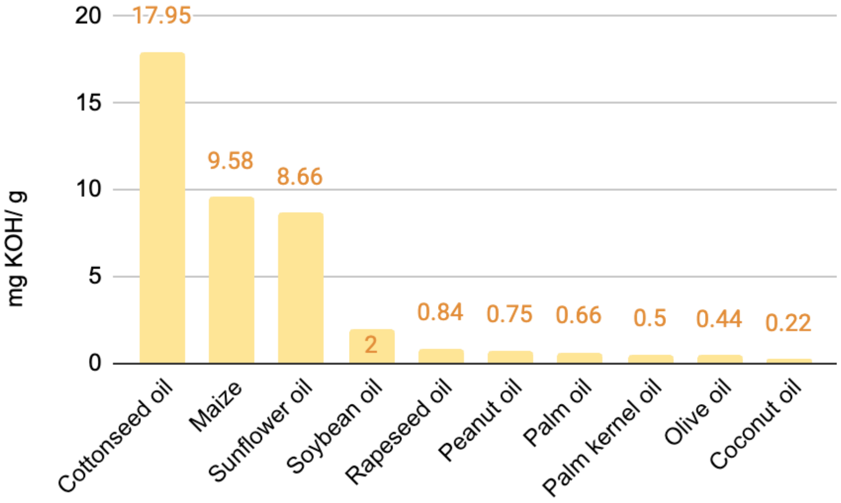

Figure 11: A bar chart provides acid values for 8 UCOs and fresh palm kernel, rapeseed oils in mg KOH / g(Arawandea et al., 2018; Awogbemi et al., 2021; Ling et al., 2016; Mardiana & Santoso, 2020; Marso et al., 2021; Nježić et al., 2023; Paschou et al., 2025)

graph is worth highlighting, as it represents a combined average number of 0.745 mg KOH/ g: data were provided for heavily and moderately used maize oils (Cordero-Ravelo & Schallenberg-Rodriguez, 2018). For the rest, exact UCOs acid numbers were found (Arawandea et al., 2018; Awogbemi et al., 2021; Ling et al., 2016; Mardiana & Santoso, 2020; Marso et al., 2021; Nježić et al., 2023; Paschou et al., 2025).

3.4.2 UCO water content

An excess amount of water in the biodiesel feedstock can lead to the hydrolysis of fatty acid methyl esters into free fatty acids, resulting in soap formation, reducing biodiesel yield. Moreover, water lowers the catalyst's activity, slowing down or stopping the reaction. In addition, high moisture content can cause emulsion and a complicated separation process of biodiesel and glycerol. Water content not exceeding 0.15% is recommended for biodiesel feedstock to ensure successful transesterification (Koirala et al., 2024; Paschou et al., 2025).

This criterion shows that deeper and more organized research is needed regarding the correlation between the moisture content of UCOs and the food products previously fried in the oil. The data for moisture content were not considered during overall grading, as values for every evaluated material were measured under unequal circumstances. For instance, the highest moisture content can be noticed in used sunflower oil and used olive oil, as they were used for frying potatoes, which have a high water content (Paschou et al., 2025). For the rest, values are lower, as they were used for other cooking purposes (Koirala et al., 2024; Mardiana & Santoso, 2020; Sangkharak et al., 2019; Tilinti et al., 2024; Ubaidah et al., 2018). All found data are provided via Table 3.

3.4.3 Flash point

The flash point ensures safe transportation and handling of biofuels, as it limits the amount of residual alcohol present. The European standard EN 14214 states that the flash point of biodiesel for heating oil must be greater than 120°C. Sunflower cooking oil and olive cooking oil satisfied this condition (Paschou et al., 2025).

Table 3: Moisture Content: Comparison Between Raw Seeds, Refined/Virgin Oils and Used Cooking Oils (UCO)

Category / Source	Moisture/Water (%)	Reference
Moisture content in raw seeds:		
Maize seeds	11.00	(Xue et al., 2024)
Soybean seeds	≈ 11.00	(Flores et al., 2025)
Water content in Used Cooking Oils (UCO):		
Waste Sunflower (post-frying)	45.32	(Paschou et al., 2025)
Waste Olive (post-frying)	23.16	(Koirala et al., 2024)
Cottonseed UCO	0.32	(Tilinti et al., 2024)
Peanut UCO	0.19	(Mardiana & Santoso, 2020)
Waste Coconut Oil	**0.10***	(Sangkharak et al., 2019)
Waste Palm Oil	**0.0011***	(Ubaidah et al., 2018)
Refined/Virgin Oils:		
Kernel Palm oil	0.44	(Novita et al., 2020)
Rapeseed oil	**0.07***	(Bąkowska et al., 2021)

* *Meets the recommended requirement of $\leq$ 0.15% for biodiesel feedstock.*

For this criterion, the grading system is as follows: 1 for rates lower than 120, 2 for rates higher than this number but lower than 170, and 3 for the rest.

As a result of a lack of data, flash points for fresh rapeseed and palm kernel oils are presented in the table. Research shows that there is a trend for the flash point to drop with an increasing percentage of waste cooking oil biodiesel (Wahyudi et al., 2024). Since the value for even fresh palm kernel oil biodiesel is lower than the required minimum, this material was graded as 1 (Olatundun et al., 2024).

The data on used peanut cooking oil biodiesel was underprovided; the only available information was that the peanut-based biodiesel (5:5) flash point is lower than diesel (63°C) but higher than that of petrol (54°C) (Soni et al., 2022). For used maize and rapeseed cooking oils, additional investigation is needed. Therefore, this research uses available data for fresh oils with the understanding that values for UCOs would be lower than current (Černoch et al., 2010; Yusof et al., 2021).

Table 4: Flash Point Comparison of Biodiesel from Various Feedstocks relative to the 120°C Heating Oil Standard

Biodiesel Feedstock	Flash Point (°C)	Reference
Safe Range (> 120 °C):		
Rapeseed (Fresh)	195	(Černoch et al., 2010)
Soybean (Waste)	182	(Lin et al., 2021)
Sunflower (Waste)	179	(K et al., 2024)
Maize (Refined)	170	(Yusof et al., 2021)
Cottonseed (Waste)	128	(Sinha & Murugavelh, 2016)
Palm Oil (Used)	127	(Yogeeswara et al., 2020)
Olive Oil (Waste)	>120	(Paschou et al., 2025)
At Risk Range (< 120 °C):		
Coconut Oil (Waste)	110	(K et al., 2024)
Palm Kernel Oil (Fresh)	90	(Olatundun et al., 2024)
Peanut (5:5 Kerosene blend)	<63	(Soni et al., 2022)

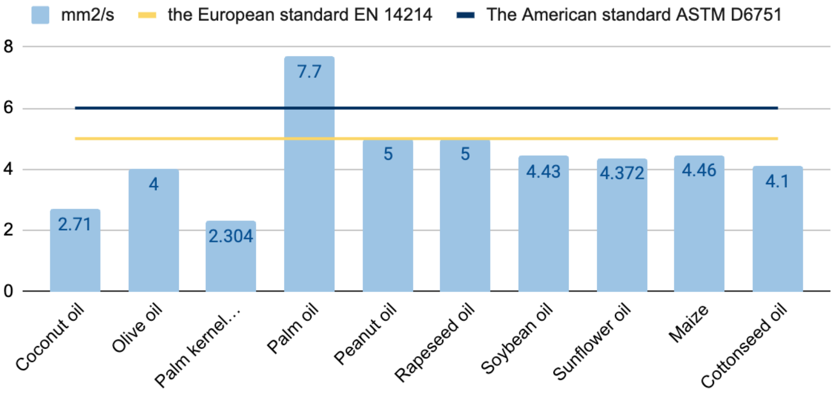

Figure 12: A given bar chart depicts the kinematic viscosity of biodiesels in mm2/s from 10 UCOs, comparing values with the American standard ASTM D6751 and the European standard EN 14214. Data taken from:(Cordero-Ravelo & Schallenberg-Rodríguez, 2018; Dabai et al., 2018; Ejeromedoghene, 2021; Khalighi et al., 2025; Köse et al., 2020; Saeed et al., 2019; Tilinti et al., 2024; Ubabuike et al., 2024).

3.4.4 Biodiesel kinematic viscosity

Viscosity is the measure of a fluid's resistance to flow and is inversely proportional to the flow velocity. High viscosity level is assumed to be the main reason for sedimentation in equipment. Moreover, difficulties in evaporation and automatization also arise due to high viscosity (e Silva et al., 2023; Pham et al., 2018). The American standard ASTM D6751 and the European standard EN 14214 for the biodiesel kinematic viscosity at 40°C are 1.9–6.0 mm2/s and 3.5–5.0 mm2/s, respectively (Knothe & Steidley, 2007).

No vital difference was found in engine performance during engine tests between the biodiesel from fresh oils and UCOs. Therefore, this study believes that it is reasonable to substitute kinematic viscosity values for UCO biodiesel with values from fresh oil biodiesel, when no data about the first type was available (Adhikesavan et al., 2022). This approach was implemented for palm kernel and cottonseed oil biodiesel (Ejeromedoghene, 2021; Tilinti et al., 2024).

On the contrary, waste peanut and rapeseed oil kinematic viscosities were considered acceptable for biodiesel production. Therefore they were pointed as 5 mm2/s on the graph - the greatest European standard boundary (Khalighi et al., 2025). During multi-criteria comparison in this study, both were graded as 2 out of 3. Since no accurate details were found, the field needs additional investigation. In addition, waste olive oil biodiesel was reported to have a value around 4 mm2/s, without a precise number. It was graded as 2 out of 3 (Cordero-Ravelo & Schallenberg-Rodríguez, 2018).

Figure 12 shows collected data (Cordero-Ravelo & Schallenberg-Rodríguez, 2018; Dabai et al., 2018; Ejeromedoghene, 2021; Khalighi et al., 2025; Köse et al., 2020; Saeed et al., 2019; Tilinti et al., 2024; Ubabuike et al., 2024) correlation with the American standard ASTM D6751 and the European standard EN 14214 for biodiesel kinematic viscosity values at 40 °C.

4 Results

Table 5 summarizes the comparison and grading phase of this study using the MCDA method. The total points range from 16 to 25, demonstrating a significant difference in the impacts of UCOs as biodiesel feedstocks.

Table 5: Final Comprehensive Analysis Table for ten evaluated UCOs

Oil\Criteria	Price	Oil yield	Nitrogen fert.	Land empl.	Calor. value	Smoke point	UFA value	UCO acid value	Flash point	Kin. viscosity	Tot.
Palm oil	3	3	2	3	3	2	2	1	2	1	22
Coconut oil	2	1	3	2	2	1	1	1	1	2	16
Olive oil	1	1	3	1	3	1	1	1	2	3	17
Palm kernel oil	3	3	1	3	1	2	1	1	1	2	18
Peanut oil	1	1	3	1	1	2	1	3	1	3	17
Rapeseed oil	1	2	1	3	3	3	1	1	2	3	20
Soybean oil	2	1	3	2	3	3	1	2	3	3	23
Sunflower oil	2	2	2	3	3	3	1	3	3	3	25
Maize	3	1	1	2	3	3	1	1	2	3	20
Cottonseed oil	3	1	1	1	3	2	1	1	2	3	18

The maximum potential grade is 30, while the minimum is 10. Sunflower oil behaved the best out of all materials, resulting in the closest result to the maximum of 25 total points. Soybean oil received 23 points in total, proving to be the second-best option for sustainable UCO biodiesel production, considering the criteria used in this paper. Palm oil is the third best choice out of ten evaluated oils, with improvements needed in its acid values and the biodiesel's kinematic viscosity. Maize and rapeseed oil scored 20 out of 30, signaling improvements needed for sustainable biodiesel production.

In contrast, coconut oil scored one point more than half of the maximum, demonstrating the necessity of strong interventions to produce satisfactory quality biodiesel from it. It received 3 only once for low usage of nitrogen fertilizers, showing potential for its sustainable usage as a biodiesel feedstock. Olive and peanut oils are second worst options with 17 total points each. Oil yield, price, land employment, UFA value were criteria where both scored 1 out of 3, raising the need for severe enhancements. Cottonseed and palm kernel oils were given 18 points each, highlighting the requirement for at least lowering nitrogen fertilization, improving UFA and UCO values to create more sustainable biofuel.

UCO Source	**Total Score**	**Final Rank**
Sunflower	25	1
Soybean	23	2
Palm	22	3
Maize, rapeseed	20	4
Palm kernel, cottonseed	18	5
Peanut, olive	17	6
Coconut	16	7

Table 6: Final ranking of oil types based on aggregate scoring.

Table 6 represents the final rate of UCOs, starting with sunflower that has the highest score and ending with coconut that received 16 points in total.

Table 7 presents all criteria in descending order, commencing from those exhibiting the highest summed values across all oil grades. In general, the lowest grades were given for oil's unsaturated fatty acid value, UCO's acid value, and oil yield. These fields require more thorough investigation in general, as great scientific intervention is needed to boost UCO biodiesel's quality and sustainability. On the other hand, values for biodiesel's kinematic viscosity appeared to be no-

Criteria	**Total Score**	**Rank**
Kinematic viscosity	26	1
Calorific value	25	2
Smoke point	22	3
Price	21	4
Land employment	21	4
Nitrogen fertilizers	20	5
Flash point	19	6
Oil yield	16	7
UCO acid value	15	8
UFA point	11	9

Table 7: Ranking of criteria based on cumulative evaluation scores.

tably high, with only 3 oils scoring less than the maximum of 3. The same situation was observed for calorific value. Conversely, the overall smoke point score was lower, totaling 22 points, which is 3 points less than the calorific value.

5 Discussion

The multi-criteria evaluation results in a clear hierarchy; however, the choice for stakeholders is rarely one-dimensional. Thus, in this section, two main scenarios are proposed to stakeholders to ensure that the most suitable biodiesel types are highlighted.

Firstly, as sustainability is one of the main pillars in modern engineering, the most environmentally safe oils must be highlighted. Palm, sunflower, coconut, and soybean oils scored the highest for land employment and nitrogen fertilizer usage criteria. Nevertheless, coconut oil was considered an underperformer during general grading. This shows that while its choice can seem to be sustainable, significant resources would be needed to enhance the technical properties of the oil. Thus, if one wants to maximize the sustainability of their production without great resource losses, this study advises choosing from palm, soybean, and sunflower oils.

If we add the economic aspect to the environmental scenario, palm oil scored the highest in both economic and environmental sectors. Slightly lower but still leading scores were obtained by palm kernel and sunflower oils. These three leaders are recommended to be considered if a stakeholder wants to decrease environmental consequences without a significant increase in production costs. To enhance sustainability and cost aspects, other oils require additional development of crop harvesting technologies.

Secondly, as biodiesel is used in the transport sector, one might find the product's quality the most important parameter for feedstock choice. This will result in additional safety and convenience for consumers of the final good. For this aim, one is suggested to narrow the selection to sunflower and soybean oils. Both showed the greatest scores on technical criteria, with sunflower scoring one point higher. These candidates demand less investment in biodiesel performance innovation, thus saving resources. This also results in speeding up the process of final product development.

Overall, the average rate equals 19.6 points, using Formula 1 mentioned before. Considering that the maximum possible score was 30 and the mean score is approximately 65%, this indicates that deeper research and enhancements are crucial in the field of biodiesel production from UCOs. Moreover, a lack of data for certain UCOs was noticed in the literature, signaling the necessity for additional research for every separate UCO evaluated.

6 Conclusions

The selection of the best UCO is crucial for sustainable biodiesel production. Multi-criteria comparison analysis was employed to create the rate of potential sustainable biodiesel feedstocks for the ten most popular worldwide cooking vegetable oils.

A great range of results for the ten investigated oils demonstrates that there is a significant difference between most of them. Therefore, more comparison and empirical work are needed to consider all influential criteria in standardized circumstances.

This study highlights sunflower, soybean, and palm UCOs as three of the most suitable UCO feedstocks for sustainable and efficient biodiesel. Coconut, peanut, and olive UCOs are three with the lowest rates of all analyzed materials. The present paper suggests that they might be used as a biodiesel feedstock, but stakeholders could need to apply more effort and investments than for UCOs with higher rates.

UFA point, UCO acid value, oil yield, flash point, and nitrogen fertilizers are criteria from which the majority of UCOs scored the lowest. From all the mentioned criteria here, these fields have great potential for innovative approaches and improvement. They are highly recommended for future work and research. Kinematic viscosity, calorific value, smoke point, price, and land employment scored better; however, any criterion has a maximum of 30. This shows that even in the most successful fields, such as kinematic viscosity, there is still some space for development.

Throughout the data demonstrations for some criteria, the limited information on exact UCOs was noticed. This paper suggests that deeper analysis and research are needed for all UCOs evaluated here, as frequently only data on fresh vegetable oils were available.

7 Acknowledgements

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Thank you for your comments and review. This document serves as a response to your suggestions, while the general “Track changes” document includes all changes that were done.

1.All figures were enlarged for better readability.
2. Thank you for your feedback on the abstract – I tried to reconsider all proposed changes. A new version of the abstract:

The growing concerns about the scarcity of fossil fuels and associated greenhouse gas emissions encourage humanity to develop renewable and environmentally safe alternatives. Over the past 20 years, the field of biofuels has sparked significant investigations, especially biodiesel as a substitute for non-renewable sources in the transport sector. Several Life Cycle Assessments and other types of analyses have been conducted to determine the sustainability of various virgin cooking oils and UCOs as biodiesel sources. However, no distinguishability of the different types of UCOs has been mentioned. The purpose of the present work is to analyse to what extent the environmental, social, economic, and technical impacts of biodiesel from diverse Used Cooking Oils (UCOs) differ when evaluated using a standardised, multi-criteria comparison that covers the entire life-cycle of every investigated oil. The results show that there is a need to distinguish between different kinds of UCOs. Based on a literature review of the most common UCOs and a multi-criteria comparison approach, 10 UCOs were compared by 10 criteria from different sectors. A list of the most efficient and sustainable UCOs is also proposed, highlighting sunflower, soybean, and palm UCOs as the leaders and peanut, olive, and coconut UCOs as the underperformers. This analysis reveals that the unsaturated fatty acids profile, the acid value of the UCOs, the oil yield, the flash point, and nitrogen fertilizers are the criteria by which the majority of UCOs scored the lowest. This suggests that these fields have great potential for improvement. Almost all UCOs demonstrated appropriate kinematic viscosity and calorific values, meaning that the focus might be switched from them towards more undeveloped criteria. The insights are provided for stakeholders in the biodiesel industry with the aim of supporting the transition to less polluting energy generation.

3. Now, the work includes the results section that goes before the discussion section. The results section presents tables and numbers, while the discussion section provides evaluation of two scenarios, as was proposed.

Lines	Before	Comments	After
		The claim that the study provides a guideline for stakeholders is somewhat strong. This could be appropriate, but it should be more explicitly supported in the discussion. For example, under what conditions should biofuels choose one UCO over another?	Now this question is described in the discussion section.
11	used cooking oils(UCOs)	Formatting: add a space between used cooking oils and the abbreviation (UCOs).	Used Cooking Oils (UCOs)
31		The period should appear after	

34 41 56 59		the in-text citation, not before. Please check the rest of the manuscript since this is a consistent issue.	
42 48	(1)by attracting used cooking oils(UCOs) (2)The reason lies in the of used cooking oil (UCO), which society is currently confronting because of the influence on the environment.	Please review this sentence. It appears that a word may be missing, and the meaning is currently unclear. When first defining the UCO abbreviation, please capitalize Used Cooking Oils.	(1) by attracting Used Cooking Oils (UCOs) (2) The reason lies in the opportunity to address the UCO disposal issue, which society is currently confronting because of the negative environmental influence.
51	(1)No space between text and citation (2)In some literature the term Waste Cooking Oil(WCO) is used when referring to the same feedstock of biodiesel as UCO. In this work only the term UCO, a synonym for WCO, is used to avoid misunderstandings.	Please review citation spacing; there are several instances where a space is missing between the text and the citation. Also add a space between Waste Cooking Oil and (WCO). Instead of “in some literature,” consider a more precise phrasing such as: In the literature, the terms Waste Cooking Oil (WCO) and Used Cooking Oil (UCO) are often used interchangeably to refer to the same biodiesel feedstock. For consistency and clarity, this study uses the term UCO throughout.	(1) All spaces were added where needed (2) In the literature, the terms Waste Cooking Oil (WCO) and Used Cooking Oil (UCO) are often used interchangeably to refer to the same biodiesel feedstock. For consistency and clarity, this study uses the term UCO only.
54	In 2020, the main UCO disposal route was sewage, resulting in sanitary sewer overflows, property flooding, contamination of water bodies with sewage, water, and soil pollution.	The statement about UCO disposal routes in 2020 is interesting and important. Please clarify the geographic context (country or region) of this statistic.	In 2020, the main UCO disposal route in Greece was sewage, resulting in sanitary sewer overflows, property flooding, contamination of water bodies with sewage, water, and soil pollution.
57	As cooking oil consumption and the population of the planet rise every year and oils make up 10% of global caloric consumption	This sentence currently contains too many ideas at once. Consider splitting it into two sentences so each point is clearer and easier to process.	Currently, oils make up 10\% of global caloric consumption \cite{Beghetto2025}. As the global population grows every year, the demand for cooking oil rises accordingly. Consequently, the

	(Beghetto, 2025), the issue of UCOs utilization becomes increasingly topical.		issue of UCO utilization becomes increasingly topical.
63	The rise of UCO supplies from current 3.7 billion gallons to between five and ten billion gallons in 2030 is expected.	The sentence structure is somewhat inverted and difficult to follow. Consider rewriting in a more direct subject–verb–object form. Also, please add a citation supporting the projected values.	The UCO supplies are expected to rise from current 3.7 billion gallons to between five and ten billion gallons in 2030. P.S. The citation was added as well.
66	Additionally, the global consumption of vegetable oils has almost tripled from 2000 (83 million tons) to 2023 (217 million tons) with 167 million tons utilized in the biodiesel industry, signaling a high number of potential new production feedstock (Beghetto, 2025).	You are presenting very strong supporting statistics, but the current wording makes them harder to follow. Suggested revision: Additionally, global vegetable oil consumption has nearly tripled, increasing from 83 million tons in 2000 to 217 million tons in 2023. Of this total, approximately 167 million tons are used in the biodiesel industry, indicating substantial potential for new feedstock production.	Additionally, global vegetable oil consumption has almost tripled from 83 million tons in 2000 to 217 million tons in 2023. Of this total, 167 million tons are utilized in the biodiesel industry, indicating a substantial potential for new feedstock production (Beghetto, 2025).
	Life cycle assessment	Please capitalize Life Cycle Assessment (LCA).	Life Cycle Assessment
Figure 1 and Figure 2	Adapted from	Remember the distinction between “sourced from” and “adapted from.”	Sourced from
Figure 3		Because it contains a lot of information, consider: o switching to a horizontal layout o increasing font size for readability	(1) Font size was increased. (2) The picture size was maximized.

Figure 4, Figure 7	A line chart	This appears to be a bar chart, not a line chart. Please enlarge the figure and consider sorting bars from highest to lowest for readability.	(1)A bar chart (2) Bars are sorted now (3) Figure is enlarged
Section 3.2.1	Nitrogen fertilizers contribute significantly to the overall GHG emission, several investigations recorded that increasing N fertilizer rates leads to greater than proportional N2O emissions. With this said, this research focuses on analysis of the urea usage during harvesting, which is considered the cheapest and richest(46\% of N) primary global nitrogenous fertilizer. For all Oil crops values were taken no later than in 2004: (list of values).	However, the paragraph currently jumps between ideas, which makes the main message harder to follow. Consider: o improving logical flow o checking spacing around inline numbers (e.g., richest(46% of N)) o possibly adding a table for nitrogenous fertilizers (might be easier to present data this way)	(Table 2 was added to Section 3.2.1. to visualize data on the number of Nitrogen used during crop harvesting.) Nitrogen (N) fertilizers are the ones that contribute significantly to overall GHG emissions. Several investigations recorded that increasing N fertilizers rates leads to greater than proportional N2O emissions. With this said, this research focuses on analysis of the urea usage during harvesting, which is considered the cheapest and richest (46\% of N) primary global nitrogenous fertilizer \cite. The average nitrogen employment rates are presented in Table 2 for the harvest of each oil crop. All compared values were taken from sources published no earlier than from 2004 for information to remain accurate nowadays. Figure 6 visualizes data from Table 2.
Figure 5, 7		Figure 5: Please standardize text color across the bars (currently mixed). Also increase figure size and DPI for clarity. This recommendation also applies to Figure 7.	The color was standardised across the bars for both Figure 5 and Figure 7. All Figures were enlarged.
	A staked area chart shows UFA content percentage in every oil\cite{Benexia2022,RedmondOilsGuide,Frančáková2015Composition,Abrante-Pascual2024Vegetable}.	The citation is somewhat unclear, are you citing the data source? Also consider whether an area chart is appropriate only if values vary over time.	A staked area chart shows UFA content percentage in every oil. Based on the data from\cite{Benexia2022,RedmondOilsGuide,Frančáková2015Composition,Abrante-Pascual2024Vegetable}.
	Considering all perspectives, materials with too low or extremely high UFA levels were	Section 3.3.3 (UFA values): You present two contrasting interpretations (good for health vs. less	To balance these opposing criteria, a compromise grading system was employed. Materials with either too low or extremely

	graded for 1 point, whereas oils with UFA around 40 percent were rated for 3 points. Figure 9 illustrates percentage of UFA in every oil.	ideal for biodiesel). Please clarify the overall takeaway. What does grading imply for biodiesel performance?	high UFA levels were graded 1 point, whereas oils with a UFA content around 40 % were rated 3 points. Figure 9 illustrates the percentage of UFA in each oil.
Figure 12	A line chart	This is a bar chart with line indicators for U.S. and European standards not a line chart	A bar chart
Figure 11	A line chart	This is a bar chart but is labeled as a line chart. Please enlarge for readability and ensure decimal precision is consistent across bars.	A bar chart
		you want to mention figures more than once, if possible, to make sure they are actually serving a purpose in your manuscript. Also, when you make a graph it’s important you mention how it was made. In the caption as well as in the paper the reader knows how to interpret what they are seeing.	

Thank you for your comments and review. This document serves as a response to your suggestions, while the general “Track changes” document includes all changes that were done.

	Line	Before	Comments	After
1.	Title	A multi-criteria comparison	(First Suggestion: To be consistent with writing the title with proper title capitalization, “Multi-Criteria Comparison” should be capitalized as well.	A Multi-Criteria Comparison
2.	Figure 3		While I can read all the text in the Criteria Tree, I had to zoom in a bit, and wonder if it is possible to enlarge the text a little bit, especially for the lower boxes. It is okay for this figure to take up a little more space, and for clarity and accessibility purposes, making this figure larger would be helpful.	(1) Font size was increased. (2) The picture size was maximized.
3.	Figure 5	The accidentally different colour across the bars caused lack of clarity.	Figure 5: What is the meaning, if any, of the faint blue values denoting oil yields of olive oil, peanut oil, maize, and cottonseed oil? Or are the black bold values for the others simply indicating that they are top six oil yield crops?	The color was standardised across the bars for both Figure 5 and Figure 7.
4.	Figure 8		Figure 8: There is quite a bit of wasted space on the y-axis, especially since none of the UCOs have calorific values lower than about 35,000 kJ/kg. I would suggest perhaps starting the y-axis with this value to better highlight differences. Also, the numbers are nearly impossible to read – please consider changing the font color to black.	(1) Changes across the y-axis. (2) The number coloring was changed to a darker one.
5.	Table 2		Table 2: Only three UCOs	Table 2 (currently

	(before) Table 3 (now)		have the requirements for sufficiently low moisture content. Is there a better way to highlight this in the table?	Table 3) was modified to bold the specific values that meet the recommended moisture criteria, and an explanatory footnote was added.
6.	Line 19	A list of the most efficient and sustainable UCOs to use is also proposed, highlighting sunflower UCO as a leader and coconut UCO as an outsider.	Why does soybean oil not appear in the abstract? After all, it ranks overall as the second leading candidate of a UCO for use as a biofuel, but a reader would not know that if only the abstract was consulted.	A list of the most efficient and sustainable UCOs is also proposed, highlighting sunflower, soybean, and palm UCOs as the leaders and peanut, olive, and coconut UCOs as the underperformers.
7.	Line 16	distinguishing	I would suggest using “distinguishability” here instead of “distinguishing.”	distinguishability
8.	31 34 41 56 59		When a citation is included in parentheses, the period follows after the second parenthesis, not before the first of the pair of parentheses.	Throughout the text the punctuation near citations was changed as required.
9.	48	The reason lies in the of used cooking oil (UCO), which society is currently confronting because of the influence on the environment.	The sentence: “The reason lies in the of used cooking oil ...” appears to have a missing word and is unclear. Did the author intend to include “type of” prior to “used cooking oil?”	The reason lies in the opportunity to address the UCO disposal issue, which society is currently confronting because of the negative environmental influence.
10.	51		There appears to be an extra period not needed (before the parenthesis).	

11.	101	While the sesame oil	“the” is not needed before “sesame”.	While sesame oil
12.	102	In the present time,	Lines 95-96: Verbose – change “In the present time” to “Presently,”	Presently
13.	103, 117		missing article – add “a” before “luxury oil.” Missing article – add “a” before “criteria tree”	Added
14.	167	In charge of	Suggest changing “is in charge of” to “is responsible for”	Is responsible for
15.	165	Nitrogen (N) fertilizers are the ones that contribute significantly to the overall GHG emission.	Change “to the overall GHG emission” to “to overall GHG emissions”	Nitrogen (N) fertilizers are the ones that contribute significantly to overall GHG emissions.
16.	175	All compared values were taken from sources published no later than from 2004 for information to remain accurate nowadays.	Add a comma after “values”; also, change “no later” to “no earlier.”	All compared values were taken from sources published no earlier than from 2004 for information to remain accurate nowadays.
17.	181	global average yield of 3.5 tons of oil	This is an incomplete sentence as written. Change the portion of line 177, which now reads as “global average yield of 3.5 tons of oil” to “global average yields 3.5 tons of oil ...”	For palm oil and palm kernel oil together, the researchers argue that the global average yields 3.5 tons of oil per hectare
18.	196	Process	The sentence, currently beginning with “Process”, should begin with “The.”	The process
19.	236	mg KOH / g Additionally,	There is a missing period after “g.”	mg KOH / g. Additionally,
20.	240-241	Additionally,	There’s a missing article	Additionally, the

		value for maize from the236 graph is worth highlighting, as it represents a combined average number	before “value” (should add “the” before “value”).	value of maize on the graph is worth highlighting, as it represents a combined average number
21.	242	data were provided for heavily used maize oil and simply used	I do not understand what “simply used” refers to here.	data were provided for heavily and moderately used maize oils
22.	243	For the rest exact UCOs acid numbers where found	Add a comma after “rest”. Also, I believe that “where” should be “were.”	For the rest, exact UCOs acid numbers were found
23.	247	number	change “excess number of water” to “excess amount of water”	amount
24.	253	This criteria shows that deeper and more organized research is needed regarding the correlation between UCOs water content and fried in it products	The phrase “water content and fried in it products” is awkward and needs to be rewritten	This criteria shows that deeper and more organized research is needed regarding the correlation between the moisture content of UCOs and the food products previously fried in the oil.
25.	253 267 277 285	High the required High viscosity These approach	Missing “a” before “high.” Add “the” before “required”. Begin the sentence with “A” Change “These approach” to “This approach”	A High The required A high viscosity This approach
26.	314	On the contrary	Change “On the contrary” to “In contrast”	In contrast

27.	357	that the maximum possible number to score was 30	Clunky sentence: Change “that the maximum possible number to score was 30” to “that the maximum possible score was 30”	that the maximum possible score was 30
28.	323	Deeper	Change “the deeper research” to “additional research”	additional
29.	329	Than maximum of 3	add “the” before “maximum.”	than the maximum of 3
30.	329	The same situation was observed329 for calorific value, with smoke point reaching 3 points less	add “the” before smoke point”. However, I do not understand what this sentence means ... e.g. starting with “The same situation ...” Please consider a complete overhaul of this sentence	The same situation was observed for calorific value. Conversely, the overall smoke point score was lower, totaling 22 points, which is 3 points less than the calorific value.
31.	335	a rapid difference	“rapid” is not an appropriate word here; change to “large” or something else.	a significant difference

Lines	Before	After
Title	A multi-criteria comparison	A Multi-Criteria Comparison
11	used cooking oils(UCOs)	used cooking oils (UCOs)
16	distinguishing	distinguishability
The whole abstract structure + clarifications Comment: The results are now more clearly presented in the abstract. Also the current structure allows the reader to easily follow the narrative. (1) The parts are market red if nothing was changed in words (or minor changes) but the order of sentences was changed (2) The parts are marked blue if they overcame significant changes or were added. (3) Deleted sentences are marked yellow.	The growing concerns about the scarcity of fossil fuels and associated greenhouse gas emissions encourage humanity to develop renewable and environmentally safe alternatives. Over the past 20 years, the field of biofuels has sparked significant investigations, especially biodiesel as a substitute for non-renewable sources in the transport sector. The purpose of the present work is to analyse to what extent the life-cycle environmental impacts of biodiesel from diverse used cooking oils(UCOs) differ when evaluated using a standardized, multi-criteria comparison that covers the entire life-cycle of every investigated oil. This article provides guidelines on which cooking oil to choose if one wants to maximize the sustainability of biodiesel production. Several life cycle assessments and other types of analyses have been conducted to determine the sustainability of various virgin cooking oils and UCOs as biodiesel sources. However, no distinguishing of the different types of UCOs has been mentioned. This paper tries to shed light on this aspect and proves that there is a need to distinguish between different kinds of UCOs. A list of the most efficient and sustainable UCOs to use is also proposed, highlighting sunflower UCO as	The growing concerns about the scarcity of fossil fuels and associated greenhouse gas emissions encourage humanity to develop renewable and environmentally safe alternatives. Over the past 20 years, the field of biofuels has sparked significant investigations, especially biodiesel as a substitute for non-renewable sources in the transport sector. Several Life Cycle Assessments and other types of analyses have been conducted to determine the sustainability of various virgin cooking oils and UCOs as biodiesel sources. However, no distinguishability of the different types of UCOs has been mentioned. The purpose of the present work is to analyse to what extent the environmental, social, economic, and technical impacts of biodiesel from diverse Used Cooking Oils (UCOs) differ when evaluated using a standardised, multi-criteria comparison that covers the entire life-cycle of every investigated oil. The results show that there is a need to distinguish between different kinds of UCOs. Based on a literature review of the most common UCOs and a multi-criteria comparison approach, 10 UCOs were compared by 10 criteria from different sectors. A list of the most efficient and sustainable UCOs is also proposed, highlighting sunflower, soybean, and palm UCOs as the leaders

	a leader and coconut UCO as an outsider. Based on a review of literature for the most common UCOs and a multi-criteria comparison approach, the insights are provided for stakeholders in the biodiesel industry with the aim of supporting the transition to less polluting energy generation.	and peanut, olive, and coconut UCOs as the underperformers. This analysis reveals that the unsaturated fatty acids profile, the acid value of the UCOs, the oil yield, the flash point, and nitrogen fertilizers are the criteria by which the majority of UCOs scored the lowest. This suggests that these fields have great potential for improvement. Almost all UCOs demonstrated appropriate kinematic viscosity and calorific values, meaning that the focus might be switched from them towards more undeveloped criteria. The insights are provided for stakeholders in the biodiesel industry with the aim of supporting the transition to less polluting energy generation.
Throughout the whole text	Incorrect citation formatting	Accurate formatting of all citations
48	The reason lies in the of used cooking oil (UCO), which society is currently confronting because of the influence on the environment.	The reason lies in the opportunity to address the UCO disposal issue, which society is currently confronting because of the negative environmental influence.
51	In some literature the term Waste Cooking Oil(WCO) is used when referring to the same feedstock of biodiesel as UCO. In this work only the term UCO, a synonym for WCO, is used to avoid misunderstandings.	In the literature, the terms Waste Cooking Oil (WCO) and Used Cooking Oil (UCO) are often used interchangeably to refer to the same biodiesel feedstock. For consistency and clarity, this study uses the term UCO only.
54	In 2020, the main UCO disposal route was sewage, resulting in sanitary sewer overflows, property flooding,	In 2020, the main UCO disposal route in Greece was sewage, resulting in sanitary sewer overflows, property flooding,

	contamination of water bodies with sewage, water, and soil pollution.	contamination of water bodies with sewage, water, and soil pollution.
57	As cooking oil consumption and the population of the planet rise every year and oils make up 10% of global caloric consumption, the issue of UCOs utilization becomes increasingly topical.	Currently, oils make up 10\% of global caloric consumption. As the global population grows every year, the demand for cooking oil rises accordingly. Consequently, the issue of UCO utilization becomes increasingly topical
63	The rise of UCO supplies from current 3.7 billion gallons to between five and ten billion gallons in 2030 is expected.	The UCO supplies are expected to rise from current 3.7 billion gallons to between five and ten billion gallons in 2030. P.S. The citation was added as well.
66	Additionally, the global consumption of vegetable oils has almost tripled from 2000 (83 million tons) to 2023 (217 million tons) with 167 million tons utilized in the biodiesel industry, signaling a high number of potential new production feedstock (Beghetto, 2025).	Additionally, global vegetable oil consumption has almost tripled from 83 million tons in 2000 to 217 million tons in 2023. Of this total, 167 million tons are utilized in the biodiesel industry, indicating a substantial potential for new feedstock production (Beghetto, 2025).
69	Life cycle assessment	Life Cycle Assessment
79	Economical	Economic
82	In the discussion section, all findings are assessed and the ranking of oils is presented, starting from the most suitable and ending with the least appropriate, for UCO biodiesel creation.	In the results section, all findings are assessed and the ranking of oils is presented, starting from the most suitable and ending with the least appropriate, for UCO biodiesel creation. The discussion section offers recommendations on the most appropriate UCOs, taking into account the primary focuses of stakeholders.
101	While the sesame oil	While sesame oil
102	In the present time	Presently

124	unsatisfied	unsatisfactory
124-125	Standing for the optimal	As optimal
167	In charge of	Is responsible for
175	All compared values were taken from sources published no later than from 2004 for information to remain accurate nowadays.	All compared values were taken from sources published no earlier than from 2004 for information to remain accurate nowadays.
181	global average yield of 3.5 tons of oil	For palm oil and palm kernel oil together, the researchers argue that the global average yields 3.5 tons of oil per hectare
225	FFA rates	FFA levels
232	potassium hydroxide in milligrams	milligrams of potassium hydroxide
240-241	Additionally, value for maize from the graph is worth highlighting, as it represents a combined average number	Additionally, the value of maize on the graph is worth highlighting, as it represents a combined average number
242	data were provided for heavily used maize oil and simply used	data were provided for heavily and moderately used maize oils
243	For the rest exact UCOs acid numbers where found	For the rest, exact UCOs acid numbers were found
247	number	amount
253	This criteria shows that deeper and more organized research is needed regarding the correlation between UCOs water content and fried in it products	This criterion shows that deeper and more organized research is needed regarding the correlation between the moisture content of UCOs and the food products previously fried in the oil.
253 267 277 285	High the required High viscosity These approach	A High The required A high viscosity This approach
314	On the contrary	In contrast
357	that the maximum possible number to score was 30	that the maximum possible score was 30

323	deeper	additional
329	Than maximum of 3	Than the maximum of 3
329	The same situation was observed for calorific value, with smoke point reaching 3 points less	The same situation was observed for calorific value. Conversely, the overall smoke point score was lower, totaling 22 points, which is 3 points less than the calorific value.
335	a rapid difference	a significant difference
374	mentioned here criteria	the mentioned criteria here
Figure 1 and Figure 2	Adapted from	Sourced from
Figure 3		(1) Font size was increased. (2) The picture size was maximized.
Table 2	Nitrogen fertilizers contribute significantly to the overall GHG emission, several investigations recorded that increasing N fertilizer rates leads to greater than proportional N2O emissions. With this said, this research focuses on analysis of the urea usage during harvesting, which is considered the cheapest and richest(46\% of N) primary global nitrogenous fertilizer. For all Oil crops values were taken no later than in 2004: (list of values).	(Table 2 was added to Section 3.2.1. to visualize data on the number of Nitrogen used during crop harvesting.) Nitrogen (N) fertilizers are the ones that contribute significantly to overall GHG emissions. Several investigations recorded that increasing N fertilizers rates leads to greater than proportional N2O emissions. With this said, this research focuses on analysis of the urea usage during harvesting, which is considered the cheapest and richest (46\% of N) primary global nitrogenous fertilizer. The average nitrogen employment rates are presented in Table 2 for the harvest of each oil crop. All compared values were taken from sources published no earlier than from 2004 for information to remain accurate nowadays. Figure 6 visualizes data from Table 2.
Table 3	The vital information on	Table 2 (currently Table 3) was

	eligibility of only 3 out of 10 oils was not highlighted in the table.	modified to bold the specific values that meet the recommended moisture criteria, and an explanatory footnote was added.
Figure 5, 7	Different text color made it hard to understand main message of the chart	The color was standardised across the bars for both Figure 5 and Figure 7.
Figure 8		(1) Changes across the y-axis to save some space in the graph directly. (2) The number coloring was changed to a darker one.
Figure 10	A staked area chart shows UFA content percentage in every oil\cite{Benexia2022,RedmondOilsGuide,Frančáková2015Composition,Abrante-Pascual2024Vegetable}.	A staked area chart shows UFA content percentage in every oil. Based on the data from\cite{Benexia2022,RedmondOilsGuide,Frančáková2015Composition,Abrante-Pascual2024Vegetable}.

Since it is unusual to put tables and too many numbers in the discussion section, all data from the discussion section was transferred to the results section. The results section is located on lines 303-331, before the discussion section. Only one paragraph was removed from this section and put at the end of the discussion section (currently on lines 356-360). The discussion section now evaluates two main objectives for stakeholders, as was promised in the last sentence of the abstract.

All charts were changed to bar charts, which are commonly used to present data for different candidates.

For the word “criteria” the agreement mistake was fixed throughout the whole text.

Commas and articles were added where required

I have reviewed the revised submission 100143, "Sustainability of Prevalent Waste Cooking Oils as a Biodiesel Feedstock: A multi-criteria comparison." I'm pleased to say the author has successfully addressed the majority of my concerns presented in the initial review. I recommend that we accept the paper for publication with minor edits.

Justification for the decision:

The author has reworked the abstract and successfully included an overall conclusion of the research. The figures have been reorganized, increased in size, and improved in overall quality, along with their corresponding captions. Figures that were previously placed in the discussion and conclusions have now been moved to the appropriate sections in the methods and results. Additionally, new figures were added where too much information had been included in the paragraphs, which helps improve readability.

The discussion and conclusions are now clearly distinguished from one another, whereas before there seemed to be little to no differentiation. The discussion section now has a clearer overall goal. There are still some spacing errors that can be polished during the publication process, such as missing spaces before the end of sentences and in-text citations, but these should be easy to fix during copy editing.

There are also still some wordy and complex sentences that are a bit difficult to follow. However, this reflects original work from the author and demonstrates the effort of a high school student who has successfully completed a research project, even though there is still room for growth in writing clarity.

Second Review of Paper: “Sustainability of Prevalent Waste Cooking Oils as Biodiesel Feedstock: A Multi-Criteria Comparison”

First and foremost, I sincerely appreciate the efforts that the author has taken in addressing each of the concerns expressed in the original review; the table (in the PDF) generated with a point-by-point enumeration was generally quite clear. I especially appreciate the improvement visible in several of the revised figures; in particular, Figure 5 now has been ordered with decreasing yields from left to right and is more logical and accessible. I also prefer the new Figure 6 and the new Table 3, particularly with the explanatory footnote.

In line 12 in the abstract, to be consistent with the rest of the manuscript, I would suggest using “analyze” here instead of “analyse”; either form is grammatically acceptable but usually using the latter is intended for a different geographic audience, and “analyze” as a verb is used with a “z” throughout.

Finally, since the author makes the choice to be consistent throughout the text with Used Cooking Oil(s) (UCO) rather than Waste Oil(s), I wonder if the title should use “Used Cooking Oils” instead? This is a personal choice though and I am not recommending this one way or the other.

Aside from these very minor considerations, I am in favor of accepting this manuscript for publication. Thank you again!