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

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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 analyze to what extent the environmental, social, economic, and technical 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. 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: waste cooking oil (UCO/WCO), biodiesel, multi-criteria decision analysis (MCDA), sustainability assessment, biofuel feedstocks, comparative evaluation, life cycle assessment (LCA)

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 impact. 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, 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, et al., 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 the extent to which 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.

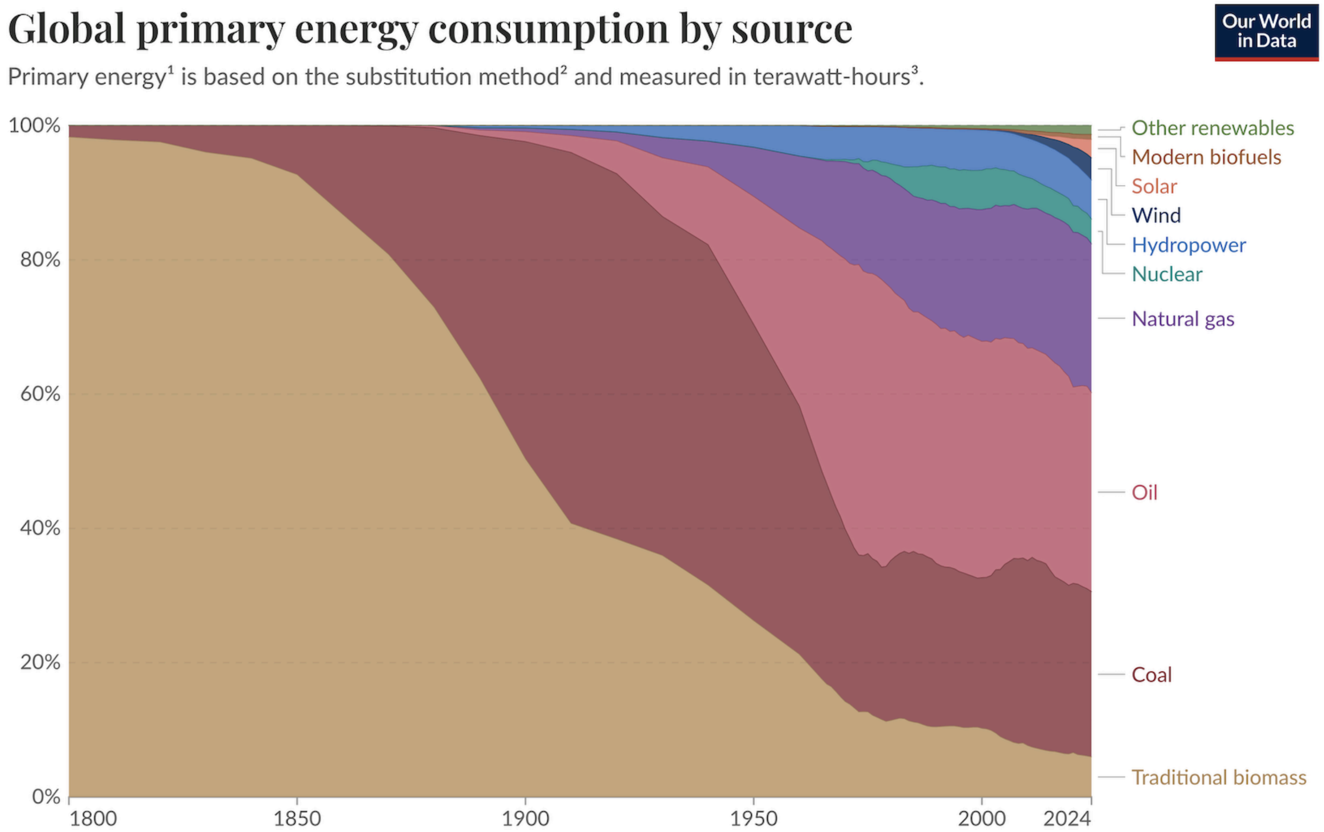

Figure 1: A demonstration of global primary energy consumption by source within the last 2024 years. Sourced from Ritchie et al. (2020).

2. Materials and Methods

2.1. Formulation of Alternatives

Figure 2 illustrates thirteen of the most produced vegetable oils in 2022 (Ritchie, Roser, et al., 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 the 10 remaining oils from Figure 2.

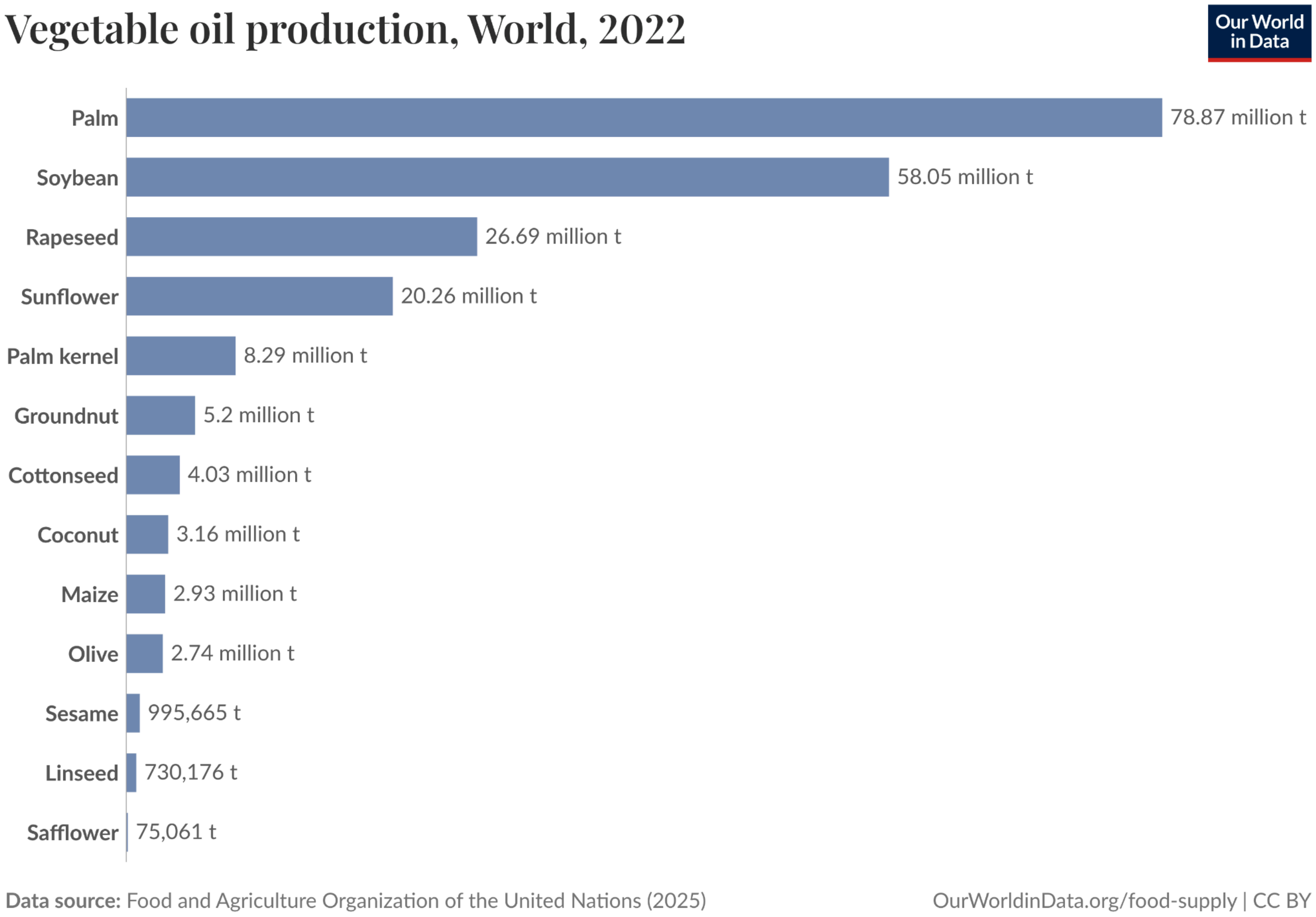

Figure 2: A bar chart showing global vegetable oil production, broken down by oil type. Sourced from Ritchie, Roser, et al. (2024).

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 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.

2.1.2. 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 criterion, 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

Table 1: Grading criteria for oil evaluation

Aspect	Criteria	Grading scale
Economic	Cooking oil prices	1 = above average; 2 = approx. average; 3 = below average
Economic	Oil yield	1 = above average; 2 = approx. average; 3 = below average
Environmental	Chemical usage	1 = highest rates; 2 = middle rates; 3 = lowest rates
Environmental	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
Social	Smoke point	1 = < 400; 2 = 400–450; 3 = > 450
Social	UFA value	1 = < 30% or > 50%; 2 = 30–35% or 45–50%; 3 = 35–45%
Technical	UCO acid value (mg KOH/g)	1 = > 0.5; 2 = 0.45–0.5; 3 = < 0.45
Technical	UCO water content	1 = > 0.15%; 2 = 0.1%–0.15%; 3 = < 0.1%
Technical	Biodiesel flash point	1 = < 120°C; 2 = 120–170°C; 3 = > 170°C
Technical	Kinematic viscosity (mm²/s)	1 = < 1.9 or > 6.0; 2 = 1.9–3.5 or 5.0–6.0; 3 = 3.5–5.0

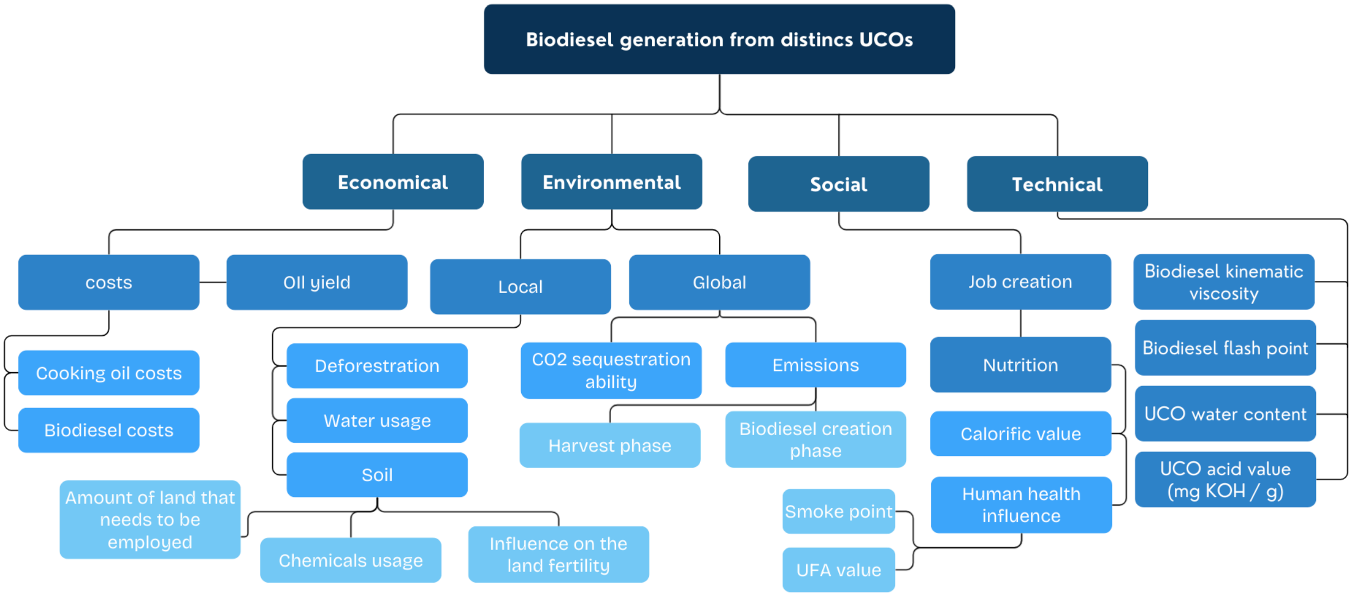

Figure 3: A criteria tree.

Figure 3 presents a criterion 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 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.

3. Literature Review and Comparative Analysis Beginning

3.1. MCDA Methods

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 Figure 4.

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 the formula

$$\overline{\alpha} = \frac{\alpha_1+\alpha_2+\alpha_3+\ldots+\alpha_n}{n} \tag{1}$$

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

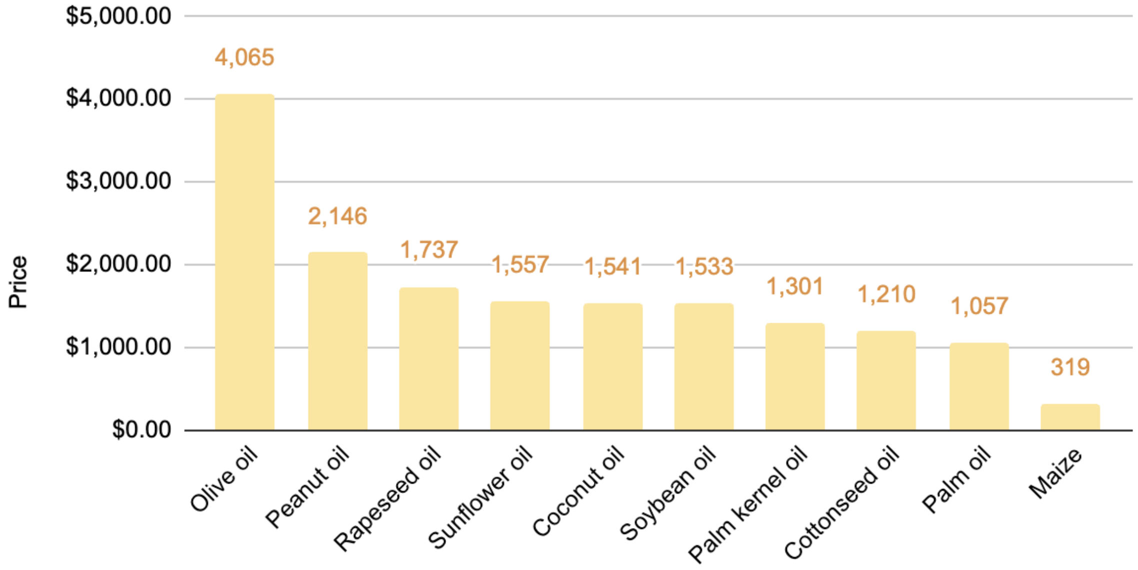

Figure 4: A bar chart demonstrates historical price data of 10 edible oils in July 2022. Price in US Dollars per Metric Ton. Data taken from Ozbun (2025), Shanbhag (2022), and Tridge (2026).

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 were available in direct values (Ritchie, Rosado, et al., 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 (2):

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

where:

- Yoil — oil yield (t/ha);
- Ycrop — 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.

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 the properties of goods, such as temperatures of growing, quality, and size. 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 2004, for information to remain accurate nowadays. Figure 6 visualizes data from Table 2.

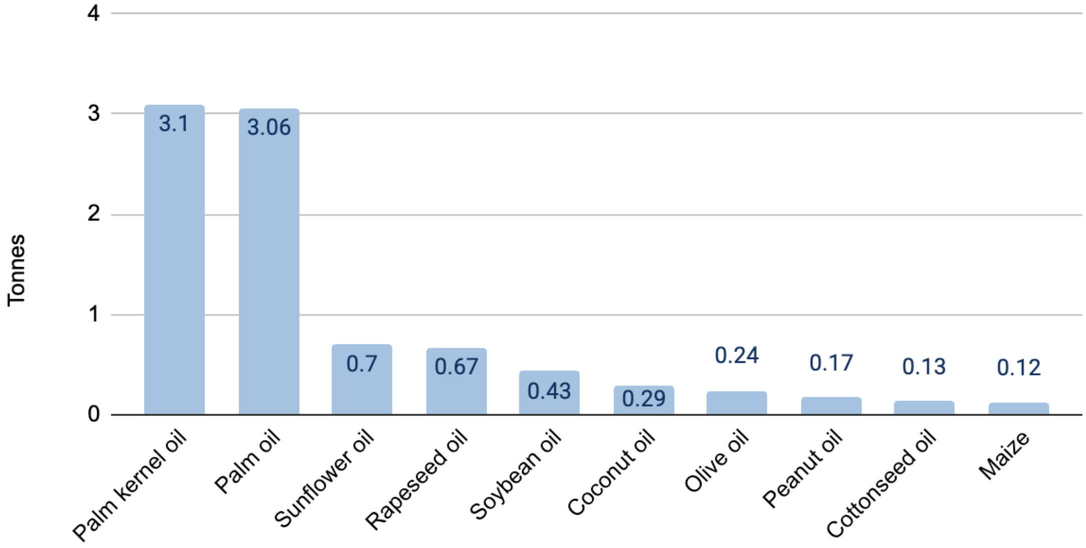

Figure 5: A bar chart depicting global oil yields in tonnes per hectare of land by crop type, evaluating data from Alshafea et al. (2025); Ritchie, Rosado, et al. (2024); and Singh et al. (2014).

Table 2: Standard nitrogen application rates for various oil crops.

Oil crop	Nitrogen rate (kg/ha)	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	N/A	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

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 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 (S. P. da Silva & Costa, 2025). The 218 million tonnes divided separately by the mentioned numbers result in 436 and 726 million hectares, respectively. 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.

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

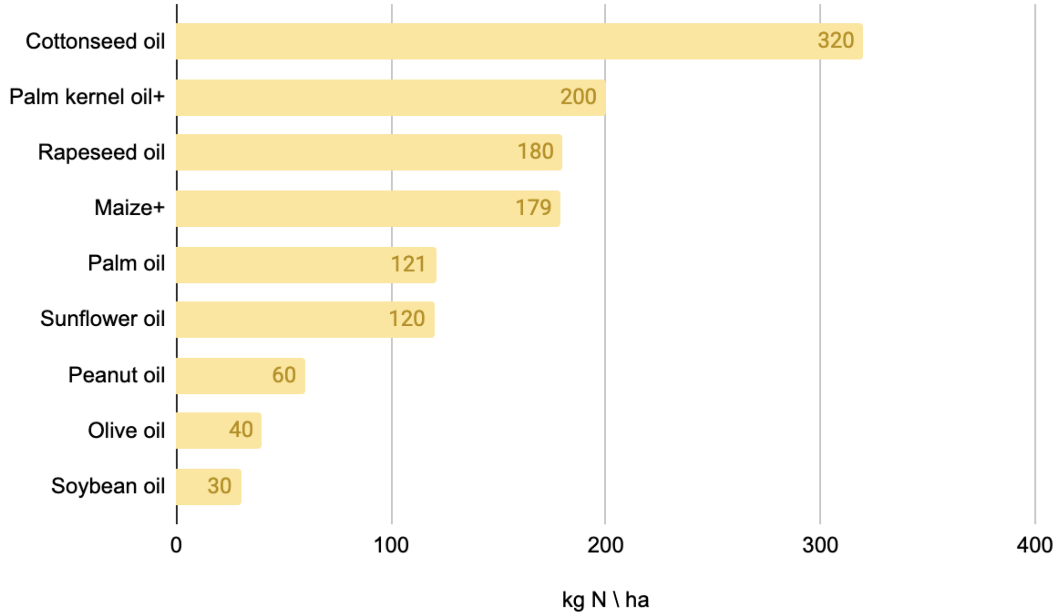

Figure 6: A bar chart compares the average amount of Nitrogen required for the harvest of each oil within the last 20 years.

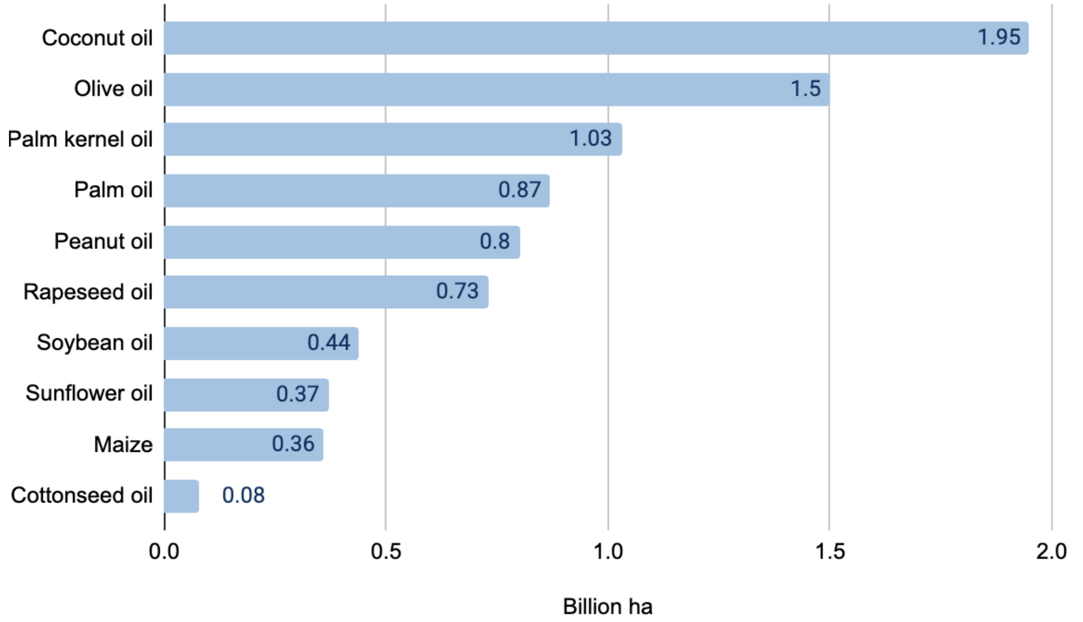

Figure 7: A bar chart demonstrates the area of land in billions needed to satisfy global vegetable oil demand using only 1 oil in 2022

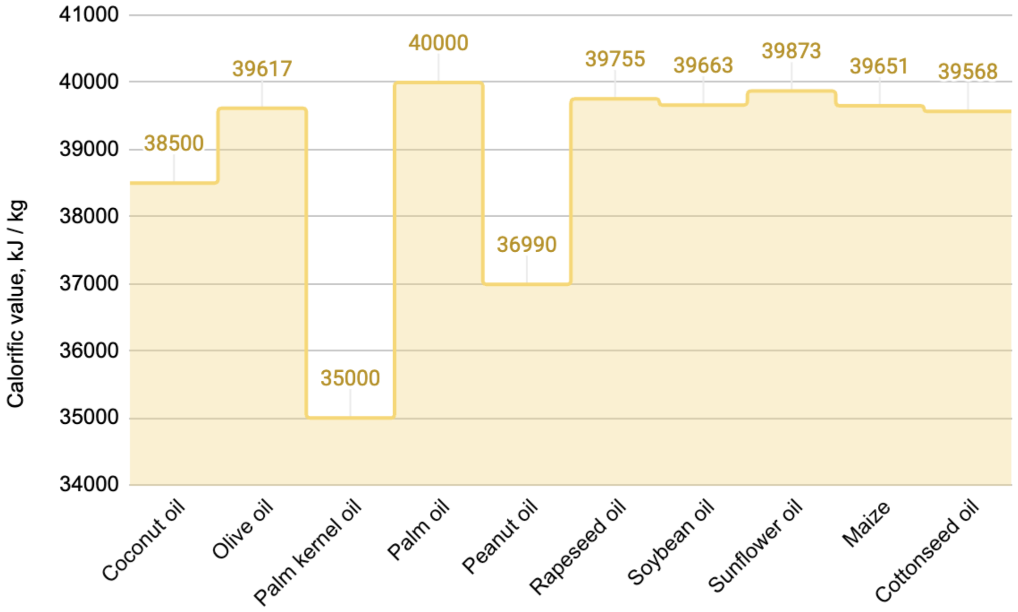

Figure 8: A stepped area chart compares energy values of evaluated oils in kJ per kg

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:

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

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

$$Q\ =\ nC_p \triangle T \tag{4}$$

Where Q is heat produced, n is no. of moles of fuel, CP 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 the 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) and 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 consumers (Ng & Choo, 2017). Figure 8 compares smoke points of 10 vegetable oils, taking data from Benexia (2022) and Redmond (2024).

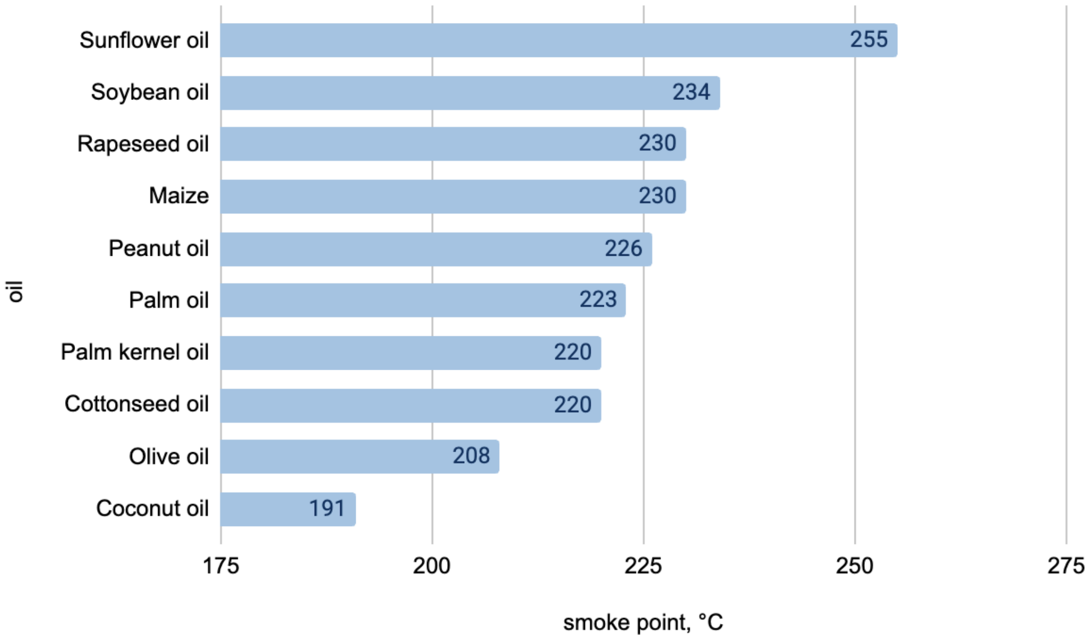

Figure 9: A bar chart presents smoke points of 10 examined oils (Benexia, 2022; Redmond, 2024).

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 cardiovascular 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 acids, 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 levels 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).

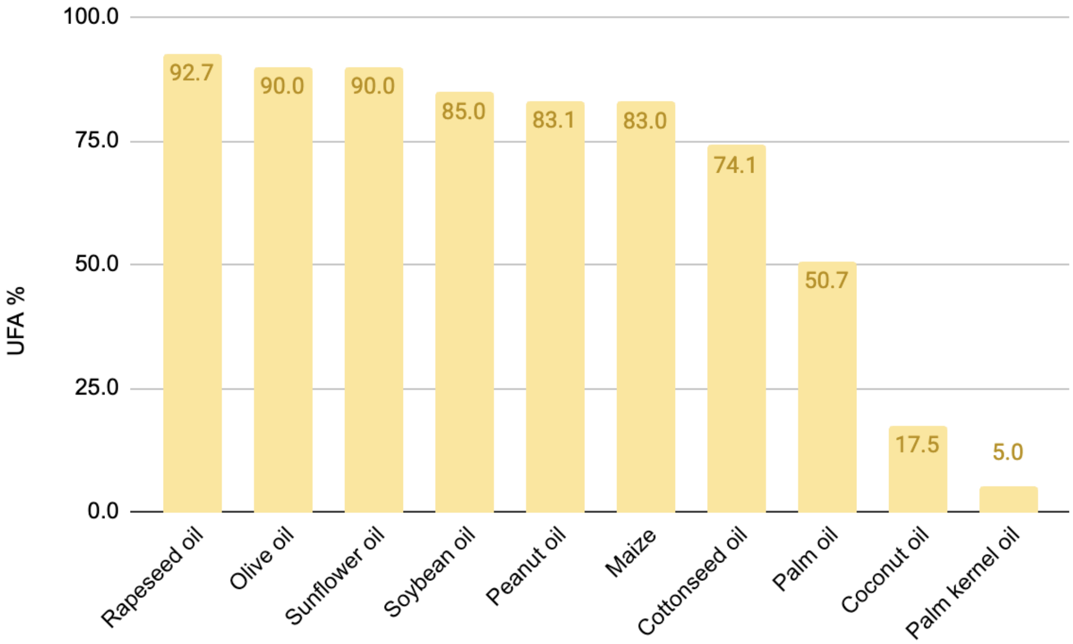

Figure 10: A bar chart shows the UFA content percentage in every oil. Based on the data from Abrante-Pascual et al. (2024), Benexia (2022), Frančáková et al. (2015), and Redmond (2024).

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

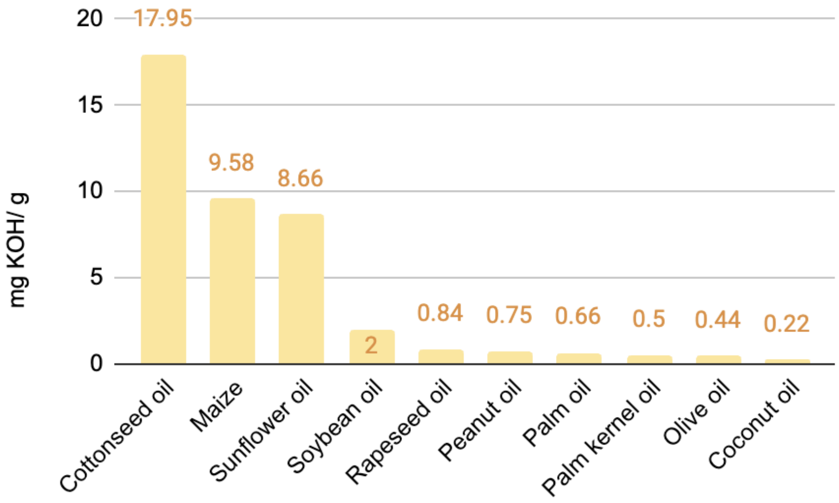

Figure 11: A bar chart provides acid values for 8 UCOs and fresh palm kernel, rapeseed oils in mg KOH / g (Arawandea et al., 2018; Awogbemi et al., 2021; Ling et al., 2016; Mardiana & Santoso, 2020; Marso et al., 2021; Nježić et al., 2023; Paschou et al., 2025).

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 the data are provided in Table 3.

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

Category / Source	Moisture / Water (%)	Reference
Maize seeds	11.00	
Soybean seeds	≈ 11.00	Flores et al., 2025
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
Kernel Palm Oil (refined)	0.44	Novita et al., 2020
Rapeseed Oil (refined)	0.07*	Bąkowska et al., 2021

Note: The asterisk (*) signifies that the moisture/water value meets the recommended requirement of ≤ 0.15% for biodiesel feedstock.

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 satisfy this condition (Paschou et al., 2025).

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
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
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 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 (Pham et al., 2018; D. S. B. e Silva et al., 2023). 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 were 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).

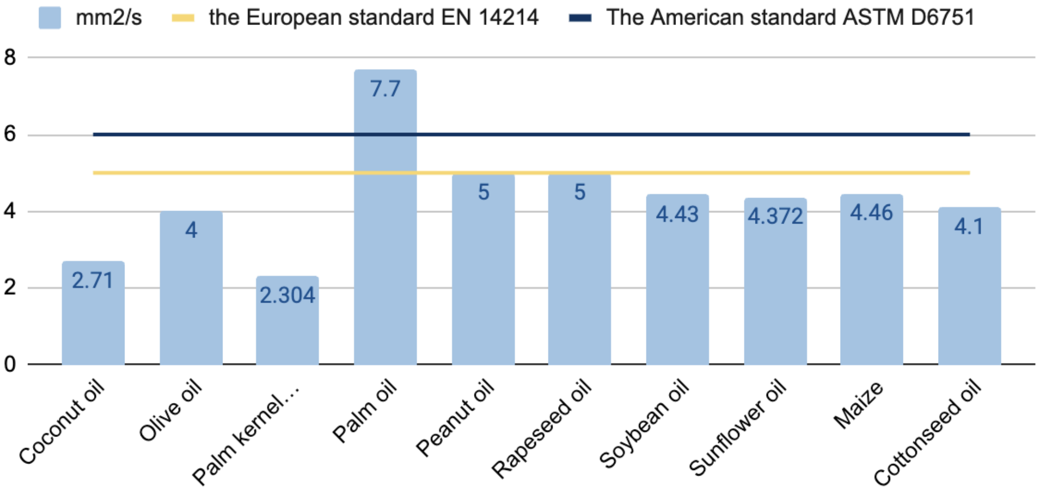

Figure 12: A given bar chart depicts the kinematic viscosity of biodiesel in mm2/s from 10 UCOs, comparing values with the American standard ASTM D6751 and the European standard EN 14214. Data taken fro Cordero-Ravelo & Schallenberg-Rodriguez (2018); Dabai et al. (2018); Ejeromedoghene (2021); Khalighi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

Table 5: Flash Point Comparison of Biodiesel from Various Feedstocks relative to the 120°C Heating Oil Standard

Oil	Price	Oil yield	Nitrogen fert.	Land empl.	Calorific value	Smoke point	UFA value	UCO acid value	Flash point	Kinematic viscosity	Total
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

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.

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 the second-worst options with 17 total points each. Oil yield, price, land employment, and 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 6 represents the final rate of UCOs, starting with the sunflower that has the highest score and ending with the 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 notably 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.

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

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 7: Ranking of criteria based on cumulative evaluation scores.

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

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 environ mentally 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.

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Yuliia Semenyna is a high school student enrolled in the International Baccalaureate (IB) program through a full Technology Leaders of the Future (TLF) scholarship. She demonstrates an interest in mathematics, physics, and computer science. Her research engagement focuses on sustainability, engineering, and mathematics, resulting in a recent independent study investigating the sustainability of prevalent waste cooking oils as a biodiesel feedstock through a multi-criteria comparison. This paper evaluates properties of the ten most popular worldwide vegetable cooking oils and proposes their rate via the considered assessment criteria. Beyond her research, Yuliia has been recognized for her leadership and social impact. She secured grant funding for her school in Ukraine, equipping it with over 10 laptops through a business project. Her academic excellence includes a 2nd-place award in the National Regional Economics Olympiad and participation in international programs, including the Engineering Summer Boarding Courses in Oxford as a scholar. She is also involved in the STEM community, participating in Techaton Teens in AI and Italian national team informatics olympiads, serving in 7th place out of 600 teams. With a passion for enhancing mathematics awareness, she served as a mathematics teaching assistant at the age of 13 and currently contributes to the Peer Math Tutoring Club. By leading an Engineering Club, she unites more than 15 peers in developing practical technical solutions.

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Mr. Marcin Kedziera, currently a CDT scholarship recipient in his fourth year of a PhD in Biomedical Artificial Intelligence at the University of Edinburgh's School of Informatics, acted as a teaching assistant throughout the study. His contribution consisted of a thorough criticism of the research question and further drafts. Comments on the evaluation method decisions for this paper made the analysis process possible using only open sources. Mr. Kedziera provided an editorial overview of the final draft by pointing out places that required enhancement.