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The potential of climate-friendly fuels from natural oils

Image credit: https://www.shentongroup.co.uk

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1. Introduction

This article deals with the global potential of biogenic fuels based on non-edible vegetable oils for blending or as a substitute for corresponding fossil equivalents such as diesel, gasoline and kerosene.

Vegetable oils have been used for many years as so-called biodiesel, either directly or preferably after transesterification as fatty acid methyl ester (FAME).

Some of these vegetable oils are produced under ecologically dubious conditions (e.g. palm oil on a large scale) and also compete with the production of food and feed (keyword: "food or fuel"). This part will **not be considered further here**.

Instead, the focus is on the potential and the technical and economic conditions for a large-scale cultivation of certain oil plants, such as jatropha, without causing conflicts in terms of land use and resource consumption (e.g. water).
The advantages of these vegetable oils are their sustainability, biodegradability and generally a lower carbon footprint compared to fossil fuels.

The fuels produced in this way are fully compatible with their fossil-based equivalents and differ only slightly in their properties. Products produced by hydroprocessing waste fats and cooking oils as well as fatty acid waste are already in commercial use. They are known under the terms HVO (hydroprocessed vegetable oil) and HEFA (hydroprocessed esters and fatty acids). An overview of this can be found in three previous GES publications, among others [1] [2] [3] .

An additional aspect is the permanent binding of CO_2 by the wood of the reforested oil plants, provided that at the end of their useful life they are used, for example, as building material or for the production of biochar as a soil improver and are not burned.

For comparison other compatible non-fossil fuels are based on different raw materials and production processes. E-fuels, for example, are produced in a "power-to-liquid" process from renewable hydrogen and CO_2 using Fischer-Tropsch or methanol synthesis. Their production is significantly more complex.
This also applies to products from biomass-to-liquid processes. These are based on

[1] https://global-energy-solutions.org/wp-content/uploads/2022/11/HVO-Papier_final_HJW_17.9.22_update-3.10.22_18.1.24.pdf

[2] https://global-energy-solutions.org/wp-content/uploads/2024/07/240620_Die-Rolle-von-Kraftstoffen-auf-dem-Weg-zu-klimaneutraler-Mobilitaet_HJW_18062024_bb_update-June-30k.pdf

[3] https://global-energy-solutions.org/wp-content/uploads/2024/04/240410hvo_final.pdf

biomass gasification in combination with Fischer-Tropsch synthesis, biomass pyrolysis or fermentation processes.

An optimistic phase in the 2010s, during which in particular the jatropha plant was used to produce biodiesel, was followed by disillusionment and the end of many projects. The reasons for this were lower than expected yields, a lack of infrastructure for cultivation and processing, and a lack of demand compared to the more readily available palm, rapeseed and soybean oils.

There is little and sometimes contradictory data on the current production of non-edible oils and the future potential for producing fuels from these raw materials.
In a 2018 estimate [4] , achievable jatropha oil production was forecasted at 263 million tonnes by 2050. After deducting processing losses, this would cover approximately half of the 2050 kerosene consumption, highlighting the considerable potential. In addition, progress is being made in the breeding and cultivation of oil plants, especially the jatropha plant.

By avoiding any competition with food and feed production, this opens up new opportunities to extract non-edible oils for fuel production from unused and barren land and use them to meet the growing demand for sustainable diesel, gasoline and aviation fuel.

Despite all efforts to increase the share of electric drives, it can be assumed that conventional while also very durable combustion engines will continue to dominate over the coming decades. However, this share will vary depending on the region and economic prosperity.

Industrialised countries with high fuel demand could finance corresponding cultivation programmes for oil crops and, in return, purchase the vegetable oils to use them in the existing refinery structure to produce biogenic diesel, petrol and kerosene.
The introduction of mandatory blending quotas for biogenic fuels with conventional (fossil) fuels leads directly to an improvement in the CO_2 balance and has the additional effect of cleaner combustion compared to fossil fuels.

However, there are also concerns about the use of waste vegetable oils and fats as well as non-edible oils. For example, there are fears that the certification of oil origin will be abused. It is also assumed that the use of biogenic fuels will cement the use of fossil fuels and as a

[4] G. Gruber et al, "Energy Storage and Balancing Power for 100% Renewable Hybrid Systems: The Potential for Jatropha for Rural Electrification in Hot Semi-Arid Areas", 26th European Biomass Conference, Copenhagen, 14-17 May 2018

result delays the complete switch to other (electric) drive types [5][6] .
In the overall balance the lower CO_2 emissions of HVO 100 compared to fossil diesel are also questioned. [7]

The large-scale cultivation and use of non-edible oil plants as proposed here follow an overarching approach of promoting economic cooperation between industrialised and developing countries (especially in the Global South). For the mutual benefit of both sides the aim is to jointly reduce greenhouse gas emissions through the cultivation, processing and use of energy crops and to avoid expensive and inefficient national programmes. [8][9]

Global consumption of diesel, petrol and kerosene (jet fuel) in 2024 was approximately 1.4 billion tonnes, 1.1 billion tonnes[10] and approximately 370 million tonnes[11] . Projections for future consumption are determined by the respective scenarios for the development of mobility and the types of drive systems involved.
According to IEA forecasts for 2040, for example, diesel fuel consumption will range between 460 and 510 million tonnes[12] , while OPEC forecasts indicate little change at approximately 1.2 to 1.4 billion tonnes[13] .

The addition of biodiesel (FAME) and HVO, which is still small but growing rapidly, amounted to approximately 72 million tonnes in 2023[14] , or about 5% of diesel on a global average.

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[5] Süddeutsche Zeitung, "Zweifelhafte Klimabilanz", 7 August 2025

[6] FAZ, "Wie nützlich ist Frittendiesel", 23 August 2025

[7] H. Fehrenbach et al, "Klimabilnaz von Biodiesel und HVO auf Basis von gebrauchtem Pflanzenöl (UCO)", ifeu – Institute for Energy and Environmental Research, Heidelberg 2025

[8] https://global-energy-solutions.org/wp-content/uploads/2025/07/250729internationale_klimapartnerschaften.pdf

[9] Interview, F.J.Radermacher, https://www.welt.de/wissenschaft/plus256340762/Energiepolitik-Es-muss-Schluss-sein-mit-dem-Klimanationalismus, 21 July 2025

[10] https://www.energyinst.org/statistical-review, “Statistical Review of World Energy 2025, accessed 20 August 2025

[11] https://www.iea.org/energy-system/transport/aviation, accessed 21 August 2025

[12] https://www.iea.org/data-and-statistics/data-product/world-energy-outlook-2024-free-dataset, accessed 21 August 2025

[13] https://publications.opec.org/woo/chapter/142/2640?utm_source=chatgpt.com, accessed 20 August 2025

[14] https://www.ufop.de/files/3017/1767/4441/24_23_W_Biodiesel.pdf

For air transport and thus kerosene demand, a continuation or even increase in demand in the range of 330 million tonnes to 490 million tonnes is predicted [9] [10] [15] [16] .

With its "Refuel EU Aviation" initiative, the European Union wants to ensure that suppliers at EU airports add a minimum proportion of sustainable aviation fuels (SAF) to kerosene, 2% by 2025 and 70% by 2050.

In 2025, 88% of SAF will be based on HEFA, and in the long term, a larger proportion will also be covered by other processes (alcohol-to-jet, Fischer-Tropsch)[17] .

2. <u>Main types and origins of natural non-edible oils</u>

Among the variety of plants that produce natural, non-edible oils for biofuel production, one can principally distinguish between plants suitable for land-based cultivation and algae suitable for marine cultivation.

<u>Oil extraction from plants on land:</u>

Here is a description of the four most important oil plants for the production of non-edible oils:

a) <u>Jatropha</u>

Due to its frugality Jatropha curcas is a tree or shrub belonging to the spurge family, which can be cultivated even on barren and dry soils. The nuts ("purging nut") have an oil content of 30-60%. The oil is particularly well suited for the production of biodiesel.

Jatropha trees take approximately 3 to 5 years to bear their first fruit, depending on climatic conditions, soil quality and cultivation management.

b) <u>Pongamia</u>

This tree belongs to the Millettia genus (papilionaceous plants) or legumes, which is native to India and Southeast Asia.
The tree is extremely resistant to temperatures ranging from below 0°C to around 50°C and grows in almost all soils. The seeds have an oil content of 30-40% (karanja oil).

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[15] https://www.dnv.com/publications/transport-in-transition-242808, accessed 21.8.25

[16] Chemie-Technik, 2 August 2023, Forecast by the Air Transport Action Group (ATAG)

[17] https://www3.weforum.org/docs/WEF_Scaling_Sustainable_Aviation_Fuel_Supply_2024.pdf, accessed 28 August 2025

Fig. 1: Jatropha/purging nut [18]

Fig. 2 Pongamia seed [19]

c) <u>Castor bean</u>

Castor also belongs to the spurge family. Ricinus communis originates from north-east Africa, but is now widespread in almost all tropical and subtropical areas. The (poisonous) seeds contain 40-50% (non-poisonous) castor oil, also known as ricinus oil.

[18] Taken from: http://www.westafricanplants.senckenberg.de/

[19] Taken from: https://www.indiamart.com/proddetail/dry-pongamia-oil-seed

Fig. 3 Castor seeds [20]

d) Neem tree

The neem tree (Azadirachta indica) belongs to the mahogany family and is mainly found in tropical and subtropical regions. It is particularly resistant to drought and can cope with most soil types, preferably sandy soils. The seeds contain 30-50% oil.

Fig. 4 Seeds of the neem tree [21]

Other examples include oils from the seeds of the rubber tree and safflower, from the nuts of the soapberry tree and the fruits of the Indian butter tree and the particularly undemanding Chinese tallow tree.

[20] Taken from https://www.dreamstime.com/seed-ricinus-communis-castor-bean

[21] Taken from: https://hortica.de/neemoel

Algae:

Another source of oil that presently is commercially exploited only to a limited extent is microalgae such as Chlorella, Nannochloropsis and Botryococcus braunii. Some of these have an oil content of over 50% of their dry matter.

The area-related annual yields are significantly higher than those of rapeseed (1.2–2 m^3/ha) and soya (0.4–0.6 m^3/ha), for example, with open ponds yielding 10–20 m^3 of oil per hectare.
However, large-scale production of algae-based biofuels is still uneconomical due to the high energy consumption involved in drying and extracting the oil, as well as the low yields in relation to the volume of the culture medium. It has only been implemented in a few pilot and demonstration plants and has often been abandoned.

At this time oil extraction from algae is therefore limited to special products in the food industry (food supplements, omega-3 fatty acids), animal feed additives and applications in the cosmetics industry.

For economic reasons, algae oils are not currently used as a raw material for the production of biogenic fuels and are not discussed further in this article [22] [23] .

Yields of oil plants:

Depending on the region, soil conditions and climate, the four oil plants mentioned generate the following oil yields, with considerable potential for future increases through better varieties, optimised cultivation methods and the use of fertilisers:

Jatropha oil: 0.6 – 2.0 to/year and hectare [24]

Pongamia/karanja oil: 1.0–2.4 tonnes/year per hectare [25]

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[22] L.M.Casanova et al, “Development of Microalgae Biodiesel: Current Status and Perspectives”, Microorganisms 11(1), 34 (2023)

[23] Shinqiu Zhang et al, “A review on biodiesel production from microalgae: Influencing parameters and recent advanced technologies” Front. Microbiol., Vol 13 (2022)

[24] Yanbing Liu et al, “Life cycle assessment and life cycle cost analysis of Jatropha biodiesel production in China”, Biomass Conversion and Biorefinery 14, p. 28635–28660 (2024)

[25] F. Dalemans et al, “Tempering expectations on a novel biofuel tree: Seed and oil yield assessment of pongamia (Millettia pinnata) shows low productivity and high variability”, Industrial Crops and Products Vol 178, p.114384 (2022)

Castor oil: 0.75–1.5 tonnes/year per hectare [26]

Neem oil: 0.4 – 1.5 tonnes/year per hectare [27]

For comparison
Rapeseed oil 1.1–1.8 tonnes/year per hectare (Germany) [28]

The annual production volumes of these oils are difficult to determine, as larger projects, especially those involving jatropha, have been abandoned due to insufficient yields and a lack of economic viability.

Although new jatropha varieties achieve up to four times higher yields than the wild types originally used in trial cultivation, this is highly dependent on soil quality and climatic conditions.[29] [30] [31]
Today Jatropha oil is a niche product with an estimated annual production of 100,000 tonnes.

Similarly production volumes in the order of 50,000 tonnes per year are reported for karanja oil and neem oil.

More detailed data is available for castor oil, which has a wide range of established applications. In 2023, 950,000 tonnes were produced [32] , mainly as a base for lubricants, paints, cosmetics and pharmaceutical products.
The main component of castor oil is ricinoleic acid ester, which is converted to 11-amino undecanoic acid to manufacture nylon-11.

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[26] S. Jindal et al, "Variability and association for seed yield, oil content and tree morphological traits in neem (Azadiracta indica A.Juss)", Journal of Tropical Forest Science, Vol 11, p. 320 (1999)

[27] V. Cafaro et al., "Castor: A Renewed Oil Crop for the Mediterranean Environment", Agronomy 15(6), 1402 (2025)

[28] https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Feldfruechte-Gruenland/Tabellen/liste January 2025, accessed 5 August 2025

[29] Chenxin Xi et al, "A New Jatropha Curcas Variety (JO S2) with Improved Seed Productivity", Sustainability 2014,6, 4355-4368

[30] Xue Bai et al, "Fusion of transgene and interspecies hybridisation enhances seed yield and root rot disease resistance in Jatropha curcas", Physiologia Plantarum Vol 177 (2), 70183 (2025)

[31] Mbako Jona et al, "Variation of Jatropha curcas seed oil content and fatty acid composition with fruit maturity stage", Heliyon. 2020, Vol 6(1), 03285 (2020)

[32] https://www.chemanalyst.com/industry-report/castor-oil-market, accessed 5 August 2025

3. Extraction and further processing

The process technology for extracting oil from plant fruits and seeds is similar in all cases and consists of the steps shown in Fig. 4[33] .

(When the oil is used for food and feed purposes, additional refining steps such as degumming, bleaching and deodorisation are added.)

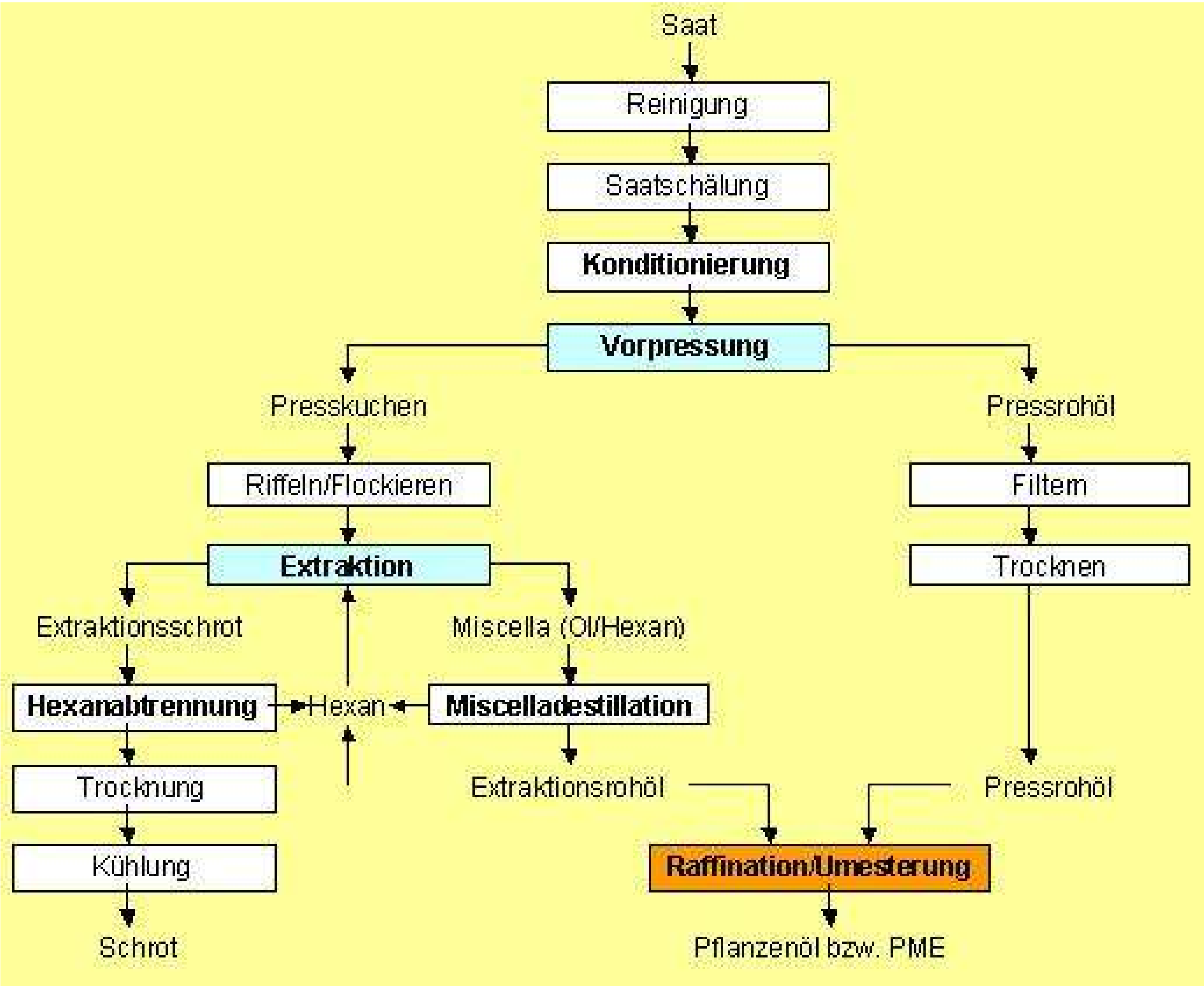

Fig. 4 Basic steps in the processing of oilseeds into vegetable oil [33]

[33] Graph taken from: http://www.mobil-ohne-fossil.de, accessed 5 August 2025

For all oils generated in this way, there are two main further processing paths:

- To produce biodiesel the transesterification of triglycerides with methanol (product: FAME), occasionally also ethanol (product: FAEE)
- To target for HVO (biodiesel) or HEFA-SPK (biokerosene) by hydroprocessing and isomerisation to paraffin-like hydrocarbons

HEFA-SPK is one of several options for producing climate-friendly aviation fuel, which is collectively referred to as SAF (sustainable aviation fuels).

Transesterification:

In the classic biodiesel/FAME route, vegetable oil is transesterified with (ideally renewable) methanol to form fatty acid methyl ester and glycerine as a by-product, Fig. 5 [34]

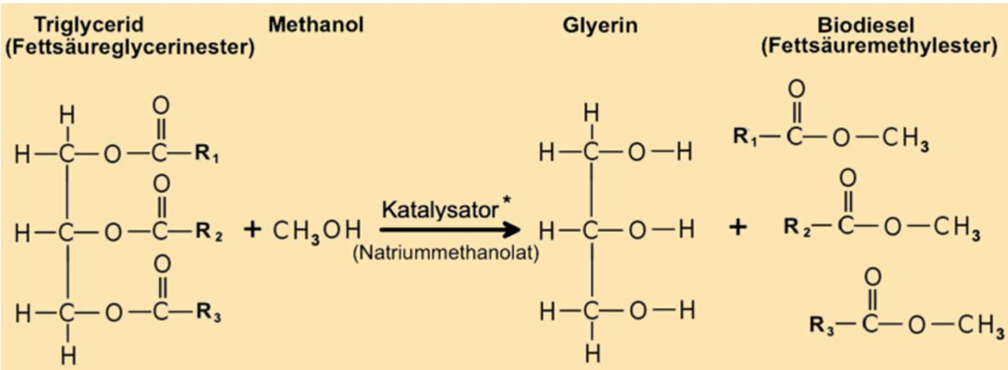

Fig. 5 Transesterification of vegetable oil with methanol to produce biodiesel (FAME) [34]

The transesterification has been established on an industrial scale for many years and is necessary to reduce viscosity, stabilise the oil, improve ignition (cetane number) in the engine and achieve cleaner combustion.
After transesterification, the oils can replace the commonly used raw materials for biodiesel, such as rapeseed, soybean and palm oil, without restriction and do not compete with food and feed production

Typical properties of methyl esters from non-edible oils are shown in Table 1 for the examples jatropha, pongamia, castor and azadirachta (neem tree) and in comparison with fossil diesel and the biodiesel standards ASTM D6751 and EN 14214.   .

[34] Graph taken from https://grafs-bio-seiten.de/biodiesel-aus-raps, accessed 5 August 2025

Origin of biodiesel	Density at 15°C	Kinematic viscosity	Flash point	Total sulphur	Ash	Water content	Cetane number
	kg/m^3	40°, CSt	°C	ppm wt	ppm wt	ppm wt	
Jatropha	880	4.3	135	n.a.	120	250	55.4
Pongamia	890	4.3	174	100	10	50	57.6
Azadirachta	898	5.8	175	300	-	-	56.8
Castor oil plant	924	14.5	273	340	n.a.	27	50
Conv. diesel	840	3.0	70.5	14	80	30	49.7
EN 590 Diesel, EU	820-845	2.0-4.5	n.a.	Max 10	Max 100	Max. 200	Min 51 Winter: 49
ASTM D6751 Biodiesel	880	1.9-6.0	Min 130	Max 500	Max 200	Max 500	Min 47
EN 14214 Biodiesel, EU	860-900	3.5-5.0	Min 120	Max	Max 200	Max 500	Min 51

Tab 1 Properties of biodiesel (FAME) from non-edible oils compared to the EU standard for (conventional) diesel and the EU and ASTM standards for biodiesel[35]

Hydroprocessing and Isomerisation:

In order to produce not only biodiesel but also jet fuel from vegetable oils, the oil must undergo a hydroprocessing step.. A process flow diagram is shown in Fig. 6[36] .
In the so-called HVO or HEFA route (HEFA = Hydroprocessed Esters and Fatty Acids), the triglycerides in the oil are converted by catalytic hydrogenation and isomerisation into hydrocarbons with a structure and chain length similar to fossil kerosene or diesel.

[35] Extract from Table 3 in B. Thangaraj et al, "Scope of Biodiesel from Oils of Woody Plants: a Review", Clean Energy Vol. 4, p. 89-106 (2020) and EU standard EU 590

[36] Flow chart of the HEFA process by Anne Rödl, taken from "Process Engineering for the Bioeconomy, Chapter 9 Bio-based Aviation Fuels" Hamburg Open Online University, https://learn.hoou.de/mod/book, accessed 5 August 2025

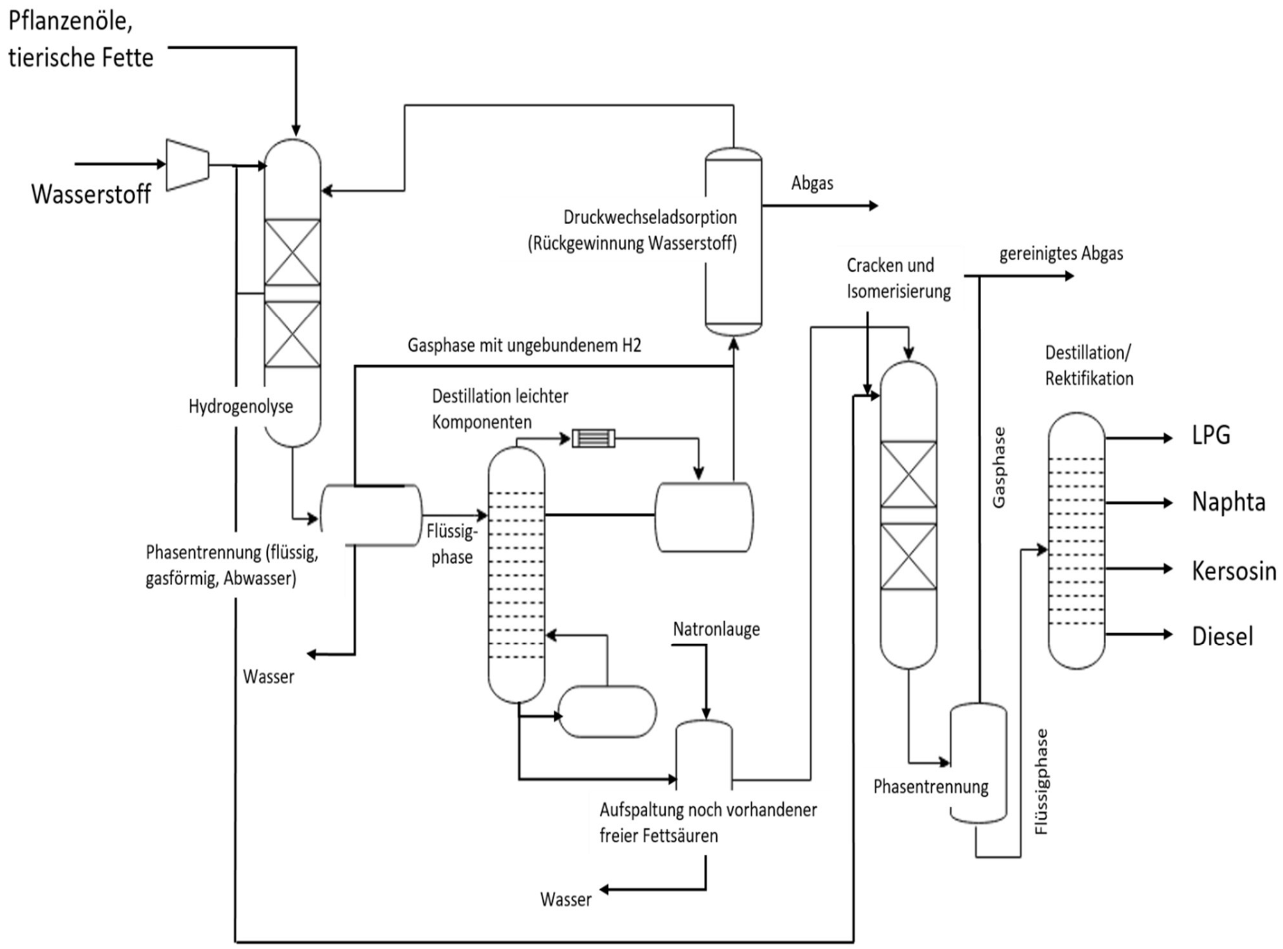

Fig 6 HVO/HEFA process flow diagram for diesel, kerosene and naphtha (raw gasoline) [36]

Depending on the process design and conditions , the main products are HVO (diesel) and/or HEFA Jetfuel A1 (kerosene) [37] with the by-products naphtha (raw naphtha) and LPG (liquid petroleum gas), which consists mainly of propane as a hydrogenation product of the glycerine part of the triglyceride.

A typical product distribution is shown in Fig. 7 (jatropha and, for comparison, camelina, pennycress and castor oil, as well as waste fat) [38] .

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[37] H.J.Wernicke, "Potenzial von hydrierten Pflanzenölen und pflanzlichen Altölen als „grüner“ Treibstoff“, GES publication, 18 January 2024

[38] Ling Tao et al, "Techno-Economic and Resource Analysis of Hydroprocessed Renewable Jet Fuel," Biotechnology for Biofuels Vol 10, 261 (2017)

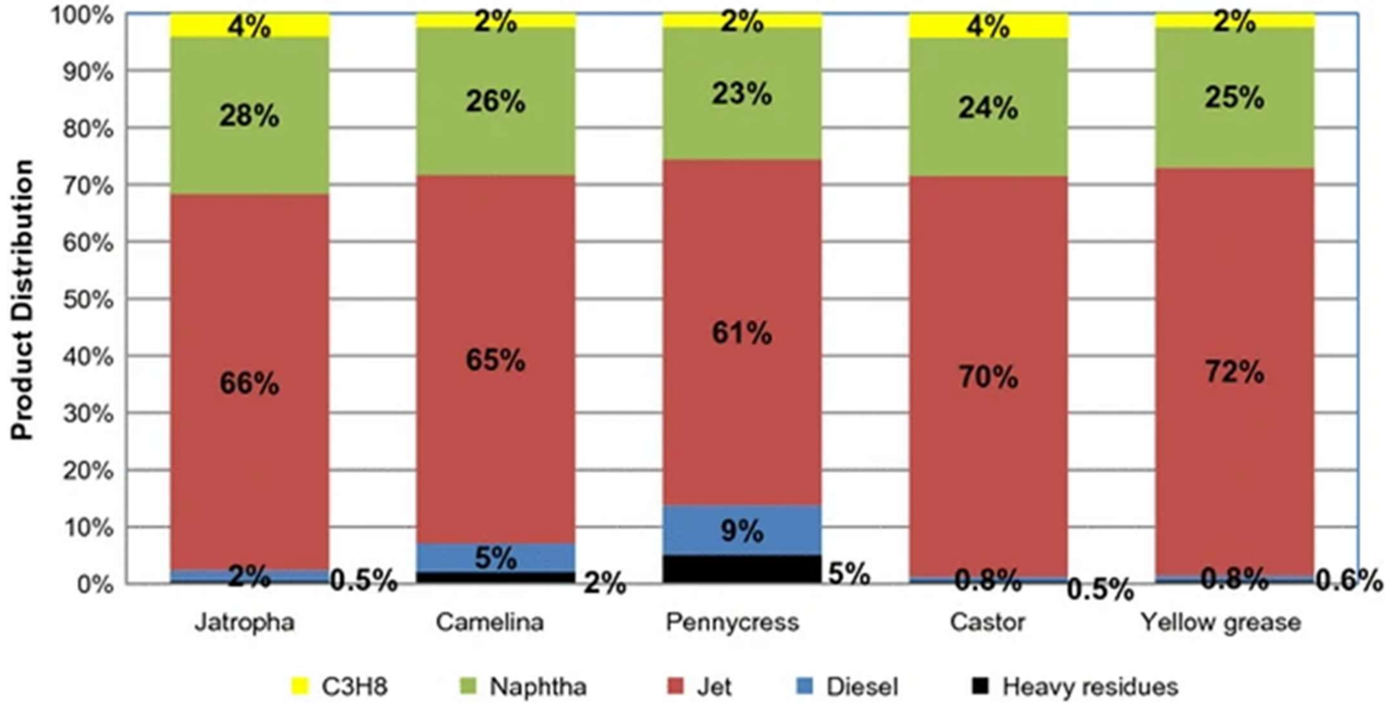

Fig. 7 Product distribution in the HEFA route for processing various oils [38]

The processes are established on an industrial scale and are applied or licensed by various licensors such as Neste (NextBTL™), ENI (Ecofining ™), TotalEnergies and Haldor-Topsoe (HydroFlex ™). With a few adjustments, they are suitable for all vegetable oils described here.

Another option is the so called coprocessing, i.e. the joint processing of biogenic oils in conventional petroleum refineries. This is already being used successfully for years in a number of EU countries.
Since 2017, co-processing has also been permitted in Germany for the production of biogenic components in fuels, albeit with restrictions. To this end, regulations on the use of biofuels were amended and the Renewable Energy Sources Act (EEG) adapted.
Due to the higher oxygen content of bio-oils, coprocessing requires adjustments to the conditions of the hydroprocessing stages in the refinery [39] [40] .

[39] K. Magrini et al, "Co-Processing Bio-Oils in Refineries", SDI Project Peer Review 22 March 2021, NREL/PR-5100-79348, https://docs.nrel.gov/docs/fy21osti/79348.pdf, accessed 7 August 2025

[40] A.K.Vuppaladadiyam et al, “Coprocessing of bio-oils and petroleum fuel blends for clean transportation fuels” chapter 12, Advances in Hydrotreating for Integrated Biofuel Production, Elsevier, Pages 327-344 (2024)

HVO diesel:

The properties of the HVO diesel fuel obtained in this way are largely identical to those of conventional diesel. Table 2 shows some important key figures.

		HVO, EN 15940 A [41] [42]	Diesel EN 590 [43]
Cetane number		Min 70	Min 51
Density 15°	kg/m^3	765-800	820-845
Total sulphur	ppm wt	Max 5	Max 10
Flash point	°C	> 55	> 55
Ash content	ppm wt	Max 100	Max 100
Water content	ppm wt	Max 200	Max 200
Viscosity at 40°C	mm^2 /sec	2.0-4.5	2.5-4.5
Total aromatics	Weight %	Max 1.1	Max
FAME content	% by weight	Max 7	Max 7

Table 2 Properties of HVO 100 – diesel according to EN 15940 A, comparison with conventional diesel according to standard EN 590

HVO 100 (i.e. pure HVO diesel) has been approved in Europe for several years and, since 2024, also in Germany, where it is available at many fuelling stations, especially independent ones.

Leaders in the use of HVO 100 are Sweden (up to 35% of diesel consists of HVO) and Norway (up to 40% HVO blending into standard diesel). The largest production capacity within the EU is in the Netherlands.

[41] EN 15940 Class A (with high cetane number)

[42] T. Willner, A. Sievers, “CO_2- Einsparpotential für die Bauindustrie bei Umstellung auf HVO 100 in Deutschland”, May 2024, https://www.bauindustrie-nord.de/fileadmin/bauindustrie-nord.de/Dateien/Stiftung/HVO-Studie_Bauind_HAW_Hamburg_final_rev3.pdf, accessed 15 September 2025

[43] EN 590

HVO 100 has excellent combustion properties and compared to fossil diesel reduces CO_2 emissions by up to 90%. It is approved by the manufacturers without restriction for use in almost all newer diesel vehicles and can also be used alternately with normal diesel without any problems.

The production and use of HVO are described in detail in several GES publications [44] [45] [46] .

HEFA kerosene

The main routes for the production of synthetic aviation fuels are the HEFA route (HEFA-SPK), based on hydrocracking and isomerisation, and the sugar and starch-based "alcohol-to-jet (AtJ-SPK)" route.

		Norm	Min.-Wert	Max.-Wert	Neste MY HEFA-SPK
Flash Point	°C	IP 170	38		41
Density 15°C	kg/m^3	ASTM D4052	730	772	771
Freezing Point	°C	IP 529		-40	-51
FAME-Content	mg/kg	IP 585		< 5	< 4,5
Thermal Stability: Filter Pressure Drop	mm Hg	ASTM D3241		25	< 1
Thermal Stability Visual Tube Rating				< 3	<1
Thermal Stability *)				85	< 85
Cycloparaffins	wt%	ASTM D2425		15	4
Aromatics	wt %	ASTM D 2425		0,5	0,1
Water	mg/kg	ASTM D6304		75	33
Nitrogen	mg/kg	ASTM D4629		2	< 0,3
Sulfur	mg/kg	ASTM D5453		15	< 1

*) Interferometric Tube Rater Deposit thickness over area of 2.5 mm2

Table 3 Selected properties of HEFA-SPK according to ASTM D7566 Annex 2 and from a Neste Corp data sheet [48]

[44] https://global-energy-solutions.org/wp-content/uploads/2024/07/240620_Die-Rolle-von-Kraftstoffen-auf-dem-Weg-zu-klimaneutraler-Mobilitaet_HJW_18062024_bb_update-June-30k.pdf

[45] https://global-energy-solutions.org/wp-content/uploads/2024/04/240410hvo_final.pdf

[46] https://global-energy-solutions.org/wp-content/uploads/2022/11/HVO-Papier_final_HJW_17.9.22_update-3.10.22_18.1.24.pdf

The IATA currently allows a maximum blending ratio of 50% of these fuels such as HEFA-SPK. For the origin IATA mentions specific examples of vegetable oils which include palm oil, camelina oil and jatropha oil, as well as used vegetable oils [47] .

The specification of HEFA-SPK for use as aviation fuel is defined in ASTM D7566, Annex 2. Selected properties of HEFA-SPK taking Neste MY as an example are listed in Table 3 [48] .

The limitation of the addition of HEFA-SPK in aviation kerosene to a maximum of 50% is due to the required low temperature properties of the fuel, which is achieved by the aromatic content of the fossil component and further by additives.

4. Potential for producing diesel and aviation fuel from non-edible oils

The following consideration is based on the assumption that the relevant oil plants are grown exclusively on degraded land ("marginal lands", see Fig. 8). These lands are not or no longer used for the production of food and feed, so there exists no conflict.

The literature data on degraded land worldwide varies greatly and is influenced by different scales and methods used to assess the cossresponding soil quality.

For example, various figures taken from literature range from 1 billion hectares (= 10 million km^2 to 6 billion hectares (= 60 million km^2) [49] .

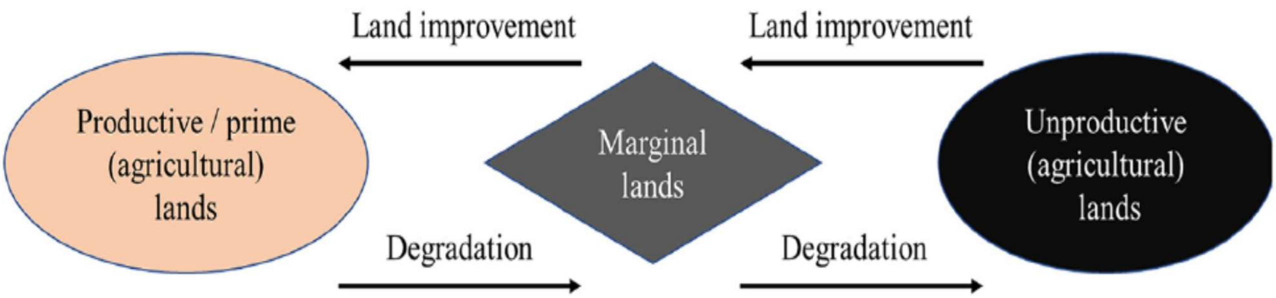

Fig. 8 "Marginal lands" [50]

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[47] https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-technical-certifications.pdf, accessed 6 August 2025

[48] https://www.neste.com/files/pdf/02b1d78d1996136630fa8bc31c3de5ea-productdatasheet_neste_my_saf.pdf, accessed 6 August 2025

[49] H.k.Gibbs et al, “Mapping the World’s Degraded Lands”, Appl. Geography Vol 57, 12-21, Feb., 2015

[50] Graphic taken from: N. Csikos et al, "Concepts of Agricultural Marginal Lands and their Utilisation: a Review", Agricultural Systems 204, 103560 (2023)

A certain consistency in the figures can be found in a study by the Heinrich Böll Foundation[51] (18.1 million km^2) and by the UNCCD [52] (15 million km^2 plus an increase of 1 million km^2 per year).
The former study distinguishes between 62% of damaged soil as a result of unsustainable use and 38% of damaged arable land due to overgrazing.

Another study focusing on the cultivation of jatropha plants[53] names an area of approximately 15.9 million km^2 divided up into approximately 7.8 million km^2 in Africa, 4.6 million km^2 in South America and 2.4 million km^2 in Asia.

The criteria for the usability of such land, e.g. for reforestation (and the formation of a CO_2-sink) or – as in this case – the cultivation of suitable and appropriately undemanding oil plants (to aim at a reduction of CO_2-emissions by replacing the use of fossil fuels) are, of course, fluid. Those criteria are strongly influenced by economic and infrastructural constraints[54] .

Detailed life cycle analyses for the cultivation and use of plants for the production of biodiesel based on non-edible oils can be found in Yanbing Liu [61] , Ruatpuia et al[55] , K.Patel et al[56] and G.Perez[57] , among others. LCAs for the production of HEFA kerosene from similar oils are described by P. Kurzawska[58] and K. Oehmichen et al[59] , among others.

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53 M. Hao et al, "Global Marginal Land Availability of Jatropha Curcas Based Biodiesel Development", Journal of Cleaner Production Vol 364, 132655, Sept. 2022

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59 K.Oehmichen et al, Comprehensive LCA of Biobased Sustainable Aviation Fuels and Jet A1 Multiblend, Appl. Sci. 12, 3372 (2022)

Potential Quantities (estimate based on Jatropha):

Following an arbitrary assumption, 20% of a potentially suitable total area of 15 million km^2 (300 million hectares) is used for the cultivation of jatropha.

Further assumptions are an annual yield of 1.5 tonnes of oil per hectare, an oil yield of 90% based on solvent extraction, a 5% loss during transesterification to biodiesel and a 15% loss during hydroprocessing to HVO or kerosene.

Mathemally, this could result in a production of approximately 420–440 million tonnes of biodiesel or 360–380 million tonnes of HVO or HEFA annually.

Based on the 2024 demand HVO as a diesel substitute could contribute approximately 25% of the total diesel demand. HEFA (as a kerosene substitute) could even cover 100% of the total kerosene demand.
Depending on the 2040 consumption forecasts, HVO could cover 25% to over 80% of total diesel demand. In the case of HEFA, it would be 75% to 100% of total kerosene demand.

Reduction in CO_2 -Emissions (estimate based on Jatropha):

The use of fossil diesel produces approximately 3.2 tonnes CO_2 per tonne of fuel. Replacing it with jatropha HVO would improve the CO_2 balance by more than 1 gigatonne per year. Referring to the current global anthropogenic CO_2 emissions of approximately 40 gigatonnes per annum [60] , or approximately 4.5 gigatonnes by the use of currently 1.4 billion tonnes of fossil diesel [10] this would be a significant and comparatively fast contribution to reducing emissions.

The emission of fossil kerosene also amounts to approximately 3.2 tonnes of CO_2 per tonne of kerosene. Complete replacement with HEFA-SPK would lead to a reduction of CO_2 -emissions of approximately 980 million tonnes, whereby production-related CO_2 -emissions of approximately 0.5 tonnes CO_2 per tonne of HEFA-SPK are included in this calculation.

However, only a 50% admixture is currently permitted [47], meaning that any available quantity exceeding this would initially be used as HVO.

With regard to the overall CO_2 balance, this does not yet take into account that reforestation with jatropha or other non-edible oil plants at the same time leads to a significant CO_2 fixation from atmosphere. (see Chapter 5).

[60] https://ourworldindata.org/co2-emissions: "Anthropogenic CO2 emissions from fossil energy and land use change", accessed 22 August 2025

Cost Estimates (based on Jatropha):

As jatropha oil is currently only produced with limited capacities, derivatives such as HVO diesel or HEFA kerosene are not yet competitive. Favourable local factors and, above all, economies of scale by a broad cultivation are required to promote commercial use.

Estimates have been made in studies and project developments for various geographical areas, particularly China and sub-Saharan Africa. The production costs for jatropha oil in these studies range from US$0.52 to US$0.68 per litre [61] [62] .

FAME biodiesel from jatropha:

Typical production costs for FAME biodiesel based on jatropha are reported to be US$0.78–1.05 per litre [56] [63] [64] .

Despite the very uncertain data basis, biodiesel from jatropha currently appears to be more expensive than traditional products made from palm oil (US$ 0.57–0.82/litre) or soybean oil (US$ 0.70–0.95/litre).

This is due to the economies of scale that have yet to be achieved with jatropha, as well as the higher yields of established oil crops (palm oil: approx. 4 tonnes per hectare) and their partially mechanised cultivation.

In contrast, the cultivation and management of jatropha is largely manual. Even with large-scale cultivation, jatropha would require five times more labour than palm oil [59], which is more costly but also an important argument in developing countries to provide job opportunities.

Exporting jatropha diesel from Africa to Europe ("free Rotterdam") would increase costs by 0.10-0.19 US dollars to 0.88-1.19 US dollars/litre.

With a crude oil price (Brent) of US$75-85/bbl, fossil diesel costs "only" US$0.52-0.72/l in comparison.

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[61] Yanbing Liu et al, "Life Cycle Assessment and Life Cycle Cost Analysis of Jatropha Biodiesel Production in China, Biomass Conversion and Biorefinery 14, 28635-28660 (2024)

[62] D. Mitchell, "Biofuels in Africa, Opportunities, Prospects, and Challenges", The World Bank (2021)

[63] N.N. Yusuf et al, “Techno-economic Analysis of Biodiesel Production from Jatropha Curcas via a Supercritical Methanol Process”, Energy Conversion and Management 75, 710-717 (2013)

[64] T.F.Ianda et al., “Optimising the Cooperated Multi-Countries Biodiesel Production and Consumption in Sub-Saharan Africa”, Energies 13 (18), p. 4717 (2020)

Overall, biogenic diesel is more expensive than fossil diesel in all cases.
(Even palm oil diesel ex Rotterdam would be significantly cheaper than jatropha diesel at US$0.68–0.99/litre, but palm oil diesel is no longer counted towards the greenhouse gas quota.)

However, the cost disadvantage of FAME biodiesel could be offset by CO_2-based taxation of fossil diesel in order to achieve price equality for users.

In Germany, the cost disadvantage is not decisive for diesel manufacturers or suppliers due to the GHG Quota Act, as they have no choice but to use advanced biofuels due to the blending quota.
This effects a surcharge at the fuelling station, meaning that motorists and lorry drivers ultimately bear the additional costs.

HEFA-SPK kerosene from Jatropha:

The costs for HEFA-SPK based on jatropha are higher than for FAME due to the more complex hydroprocessing rquirements. The production costs for jatropha-based HEFA-SPK are estimated at US$1.25-1.50/l [65] [66] [67].

The reference price for fossil kerosene (before taxes and duties) is also significantly lower at around US$0.60/l [68] .

A study for production in China [38] based on an annual capacity of 150,000 tonnes of HEFA-SPK from jatropha (and other oil plants) shown in Table 4 and Figure 8 contains the yield structure and an estimate of HEFA costs.
In this study the assumed starting price for jatropha oil of US$0.40/kg appears very low.
This results in a correspondingly low "minimum price" of US$3.82/gallon = US$1.02/litre.
Despite the low jatropha oil price, this estimate results in a jet fuel price which is still significantly higher than the reference price for fossil kerosene.

The mandatory blending quotas for alternative aviation fuels results in significantly higher costs compared to the use of fossil kerosene alone.

[65] Jagtap, S. S.; Childs, P. R. N.; Stettler, M. E. Data in Brief: Comparative Life Cycle Evaluation of Alternative Fuels for a Futuristic Subsonic Long-Range Aircraft. Preprints 2025, https://doi.org/10.20944/preprints202504.1222.v1, accessed 2.9.2025

[66] J. Aburto et al, “Is Sustainable Aviation Fuel Production Through Hydroprocessing of Esters and Fatty Acids (HEFA) and Alcohol-to-Jet (ATJ) Technologies Feasible” Sustainability 17(4), 1584 (2025)

[67] F.Müller-Langer et al, “PTG-HEFA Hybrid Refinery as Example of a SynBioPTx Concept—Results of a Feasibility Analysis”, Appl. Sci. 9(19), 4047 (2019)

[68] “Jet Fuel and Diesel Prices as of July 2025”, https://www.linkedin.com/posts/global-oil-and-gas-trading_global-oil-and-gas-trading-activity, accessed 2.9.2025

	Jatropha	Camelina	Pennycress	Castor	Yellow grease
Oil price ($/kg)	$0.40	$1.75	$0.81	$1.70	$0.61
Jet fuel production (MMgal/year)	44.0	57.7	40.3	50.8	50.4
Propane fuel yield (gal/dry ton oil)	18.3	1.0	2.1	1.8	1.6
Gasoline fuel yield (gal/dry ton oil)	94.2	100.0	74.3	94.9	93.7
Jet fuel yield (gal/dry ton oil)	170.0	184.3	155.5	196.2	194.7
Diesel yield (gal/dry ton oil)	3.1	4.7	36.9	0.5	0.8

Table 4 Product distribution for a 150,000 t/a HEFA-SPK cost study [37]

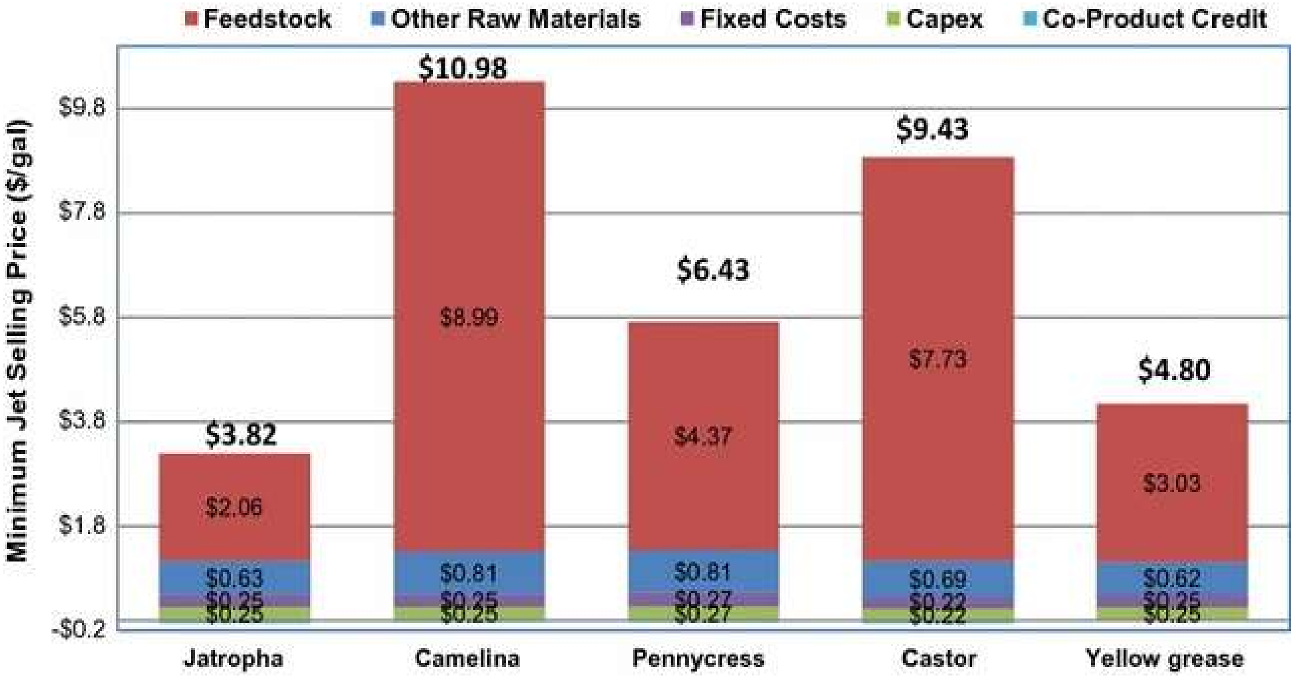

Fig. 8 "Minimum selling price" for HEFA-SPK from jatropha and other oils based on a cost price of US$ 0.40/kg for jatropha oil and an annual capacity of 150,000 tonnes of HEFA-SPK (see Table 4) [38]

Within the EU, an increase of blending quotas for biogenic components in kerosene applies, e.g. 6% in 2030. These quotas do not apply outside the EU, leading to competitive and cost disadvantages and refuelling outside the EU wherever possible .

This may also be one reason for the limited production capacity within the EU of biogenic SAF (based on HEFA or other alternatives) to date.

Neste is currently the largest supplier, with European sites in Rotterdam and Porvoo. Processing capacities appear to be keeping pace with the increasing intra-European quota obligations, but do not exceed them.

5. Contribution to the Formation of CO_2 - Sinks

Even though the production of the fuels described here is currently not economically viable and can only be initiated through regulation or subsidies.
As there is no competition with the production of food and feed and as no existing natural areas are destroyed by clearing and conversion them into plantations an additional important argument for the cultivation of these plants is the afforestation of barren, unused land and the associated formation of CO_2 sinks.

Extensive studies and project proposals exist on the compatible use of such land areas, including in their function as sustainable CO_2 sinks [69] [70] [71] [72] [73] [74] [75] [76] [77] [78] .

References (selection):

[69] R. Gandhe et al, “Evaluation Trials and Carbon Sequestration Potential of Jatropha curcas and Pongamia pinnata: Technologies and Way Forward”, in Advanced Biodiesel - Technological Advances, Challenges, and Sustainability Considerations, IntechOpen; 2024

[70] P. Bohre et al, "Biomass Production and Carbon Sequestration by Pongamia pinnata in Tropical Environment", Int. J. of Bio-Science and Bio-Technology 6(2), 129-140 (2014)

[71] S. P. Wani et al, “Carbon sequestration and land rehabilitation through Jatropha curcas plantation in degraded lands
Agriculture, Ecosystems and Environment 161, 112 (2012)

[72] L. Pari et al, “Jatropha curcas, L.Oruning Residues for Energy: Characteristics of an Untapped Byproduct”, Energies 11, 1622 (2018)

[73] https://www.eco-business.com/research/a-bean-called-castor-can-cut-carbon-fuel-the-future, 27 May 2013, accessed 21 August 2025

[74] N. Pulpayil et al, “Estimation of carbon sequestration potential of Azadirachta indica from different provenances in South Eastern Rajasthan”, Int. J. of Research in Agronomy, SP-7(1): 196-200 (2024)

[75] A. Ajanai et al, "Comparative Status of Sequestered Carbon Stock of Azadirachta indica and Conocarpus erectus", International Journal of Environment 5(2), 89 (2016)

[76] C.Moreira et al, “Biomass and carbon stock in Jatropha curcas”, Cerne 17(3):353-359 (2011)

[77] N.B.Noor Mohamed et al, “Biomass production and carbon sequestration potential of neem (Azadirachta indica A. Juss) under dryland environment”, Range Mgmt. & Agroforestry 41 (2), 381-385 (2020)

[78] Rohit Soni et al, “Carbon Sequestration Potential of Different Provenance of Pongamia pinnata in Central India,
International Journal of Environment and Climate Change 13 (11), 3057–3064 (2023)

A prerequisite for maintaining the sink is the subsequent permanent use of the wood, for example in buildings or furniture, or in the form of biochar (for soil improvement).

Burning or composting, on the other hand, would release the bound CO_2 - but as long as the felled old plants are replaced by newly planted ones, the one-time carbon sequestration remains intact even if the old wood is burned.

As discussed for potential oil yields, plant varieties, soil conditions and climatic conditions the cultivation density and useful life until clearing are just as crucial.
In relation to the respective cultivation areas and after the end of use as an oil plant the estimated amounts of bound CO2 are significant, but only indicate orders of magnitude.

Jatropha
Jatropha wood is of low quality for construction purposes, but is suitable for biochar. Compared to traditional energy wood species such as eucalyptus, the wood yield per hectare is relatively low at approximately 1–3 tonnes per year (sawn timber) and approximately 25–50 tonnes over a 7–10-year useful life (as air-dried wood).
With a carbon content of 45-50% in the wood, this corresponds to a CO_2 fixation of approximately 45-90 tonnes CO_2 per hectare.

Pongamia
Pongamia is particularly effective in CO_2 sequestration due to its rapid growth, deep root system and ability to fix nitrogen (for fertilizing).
It can be used as construction/furniture wood or for the production of biochar.
The wood yield depends on the planting density (200–500 trees per hectare). The wood yield over a useful life of 15–20 years is approximately 200–400 tonnes per hectare. This corresponds to a CO_2 sequestration of 370–730 tonnes of CO_2 per hectare.

Castor oil

A castor oil plant is not a tree but a fast-growing shrub.
Permanent CO_2 sequestration is therefore low and limited to soil improvement through incorporation and humus formation. Castor beans produce approximately 5 - 20 tonnes of dry matter per hectare per year with a CO_2 sequestration of approximately 1.8 tonnes per tonne of biomass or 9 - 36 tonnes per hectare annually..

Neem tree

Neem trees are medium-sized trees and grow well in dry regions. Their CO_2 sequestration is comparable to other tropical hardwoods, but they grow more slowly than eucalyptus or

teak, for example. The wood is suitable for construction and furniture or for biochar.
With a planting density of 400–1,000 trees per hectare, the wood yield over a useful life of 50 years is 250–275 tonnes per hectare, which corresponds to a CO_2 sequestration of approximately 450–700 tonnes per hectare.

For comparison, beech:

An average beech forest with 350 m3 of wood per hectare and a wood density (dry) of 0.68 tonnes per m3 and a carbon content of 50% binds approx. 430 tonnes per hectare.

The additional effect to generate a natural CO_2 sink through the large-scale cultivation of non-edible oil plants is considerable, especially in the case of pongamia and neem trees, which have a potential of approximately 0.4 - 0.7 gigatonnes of CO_2 per 1 million hectares, based on the respective utilisation or lifespan.

Based on the assumed potential of 300 million hectares of cultivation area (Chapter 5) and taking into account all uncertainties in the data and assumptions this would correspond to forming a sink of 120–210 gigatonnes of CO_2 (comparable to 3 - 5 years of current annual anthropogenic CO_2 emissions.

6. General Considerations

Key arguments in favour of cultivating plants for the production of non-edible oils to be used as substitutes for fossil fuels include the following:

- "Classic" oil plants such as palm, rapeseed or soya cannot be cultivated on the soils and in the climate zones described. This creates a previously untapped or neglected potential.
- In addition to generating climate-friendly energy, large-scale reforestation of unused, semi-arid areas prevents soil erosion, drying out and desertification.
- A major advantage is that it can be implemented quickly: Jatropha trees, for example, produce oil seeds after just three to four years and have a useful life of up to 50 years.
- By using the fuels which are produced by this route, CO_2 - emissions can be reduced immediately and without a principal change of the engine technology or the refinery and fuel supply structure.

- HEFA/SAF enables a high level of demand coverage for aviation fuels – while demand increases for the growing air traffic and given that alternatives will not be available for a long time.
- At the same time international cooperation and crediting mechanisms can form a significant CO_2 sink.
- A largely manual cultivation of oil crops in potential growing areas creates jobs in countries with rapidly growing populations (e.g. sub-Saharan Africa).
- Growth, income from exports and international supply relationships lead to better compliance with basic ethical standards and with the UN's Sustainable Development Goals.
- Global (North-South) cooperation through partnerships in the financing, cultivation and processing of oil crops leads to win-win situations for both - producers in developing countries and the major consumers in industrialised countries.

European Union, Germany:

The GHG Quota Act currently limits the blending of bioethanol and FAME (fatty acid methyl ester), the so-called first-generation biofuels.

However, there is a request for increasing quantities of "advanced biofuels".
These include cellulose-based 2G bioethanol, HVO from waste oils and fats, and fuels based on biomass gasification followed by Fischer-Tropsch synthesis.

Thus the EU regulatory framework through RED II/III and its national implementation creates incentives for installing capacities and use of advanced biofuels, including HVO and HEFA. This adds to the demand for increasing shares of RFNBOs (Renewable Fuels of Non-Biogenic Origin), i.e. synthetic fuels based on CO_2 and renewable hydrogen.

The German GHG quota act already stipulates a CO_2 reduction obligation of 25% in the transport sector by 2030 compared to 2019 levels.

An amendment to the GHG Quota Act presented in July 2025 asks for a 53% GHG reduction by 2040 in order to significantly reduce greenhouse gas emissions further in road transport.[79]

A reduction in GHG emissions in the mobility sector (vehicles, ships, aircraft) can therefore only be achieved by increasing the proportion of biogenic and synthetic fuels (such as methanol in shipping).
"Advanced biofuels" such as HVO and HEFA can play an important role.
The (costly) alternative is a complete change in technology and infrastructure as pursued by an all-electric strategy.

[79] RED III implementation in transport, GES impulse paper, planned for 10/2025

It remains to be seen whether international cooperation will embrace the idea of investing in the cultivation of special oil crops for fuel production as proposed here.

China:

China has introduced strict emission standards comparable to Euro 6 in Europe.

China is pursuing a pragmatic, two-pronged approach concerning technologies for mobility: On the one hand, it is consistently expanding electrification, while on the other, it is further developing advanced combustion engines to ensure security of supply and range, especially in rural areas.
In addition to blending ethanol and methanol into gasoline, HVO, CNG and various hybrid systems are also being used or considered.

In aviation, SAF based on waste, waste oils and even algae lipids is being invetigated.

A growing number of recent publications point to increased activities in growing more efficient and robust plants for non-edible oils for FAME biodiesel and HEFA kerosene.

USA:

The market in the USA remains open in terms of drive types and fuels, including future developments in combustion engines.

A phase-out of combustion engines is only planned on a regional basis. Some states, such as California, have decided to ban new registrations of passenger cars with combustion engines from 2035 onwards. A national ban is not in sight.

Regulations such as the Corporate Average Fuel Economy (CAFE) and the EPA's emissions standards aim at improving efficiency. In the case of biogenic fuels, the focus is on the addition of ethanol (10%, regionally also 15%).

Biodiesel and biogas are heavily subsidised: in 2023, the USA produced 12.6 million tonnes of HVO, which corresponds to around 63% of total biodiesel production (see Fig. 9)[80] . To this end, biogenic oil is increasingly being imported from China.

Large subsidy programmes in the USA are supporting the development of SAF.
The target is to produce 11 million m^3 of SAF by 2030 and 133 million m^3 by 2050 ("SAF Grand Challenge" programme[81] by the DOE and DOT).

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[80] Renewable Carbon News, "Bio-based HVO gains in importance in the US", 24 June 2024 https://renewable-carbon.eu/news/hvo-gains-in-importance-in-the-usa, accessed 2.9.2025

[81] https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge, accessed 2.9.2025

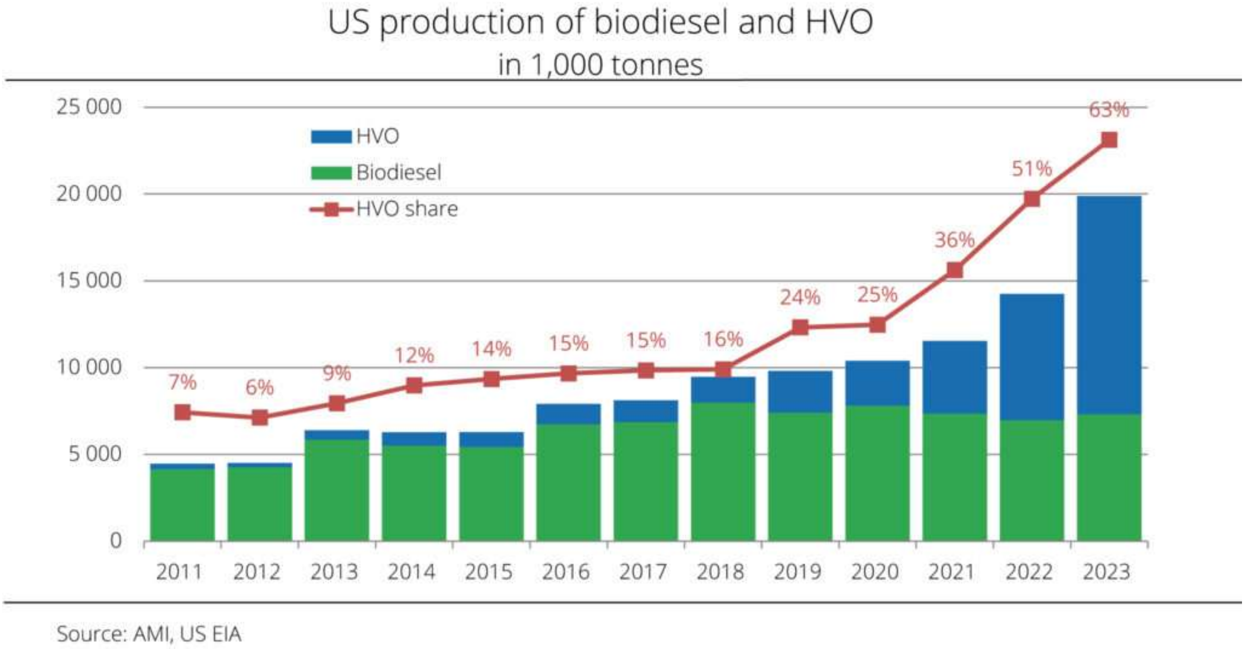

Fig. 9 Biodiesel and HVO production in the USA [77]

There are also tax breaks ("Sustainable Aviation Fuel Credit") for the use of SAF with at least a 50% reduction in greenhouse gas emissions over its life cycle.

Electric mobility is also being promoted through tax breaks under the Inflation Reduction Act.

Conclusions/Summary:

Since extensive electrification of mobility on a global scale is only possible to a limited extent and is unlikely to be economically feasible in many countries in the long term, combustion engines will continue to be used for a long time to come.

In order to reduce CO_2 emissions from vehicles, aeroplanes and ships, a considerable amount of renewable, climate-friendly fuels are therefore required.

In the case of aeroplanes in particular, the current form of propulsion will continue to exist for many years to come, as there are no viable alternatives available or these will require decades of development work. Non-fossil, biogenic or synthetic fuels are in particular demand here.

Besides renewable hydrogen fuel for combustion engines will consist of e-fuels (hydrocarbons from Fischer-Tropsch synthesis or methanol and methanol derivatives), possibly renewable ammonia (for ships) and to a large content of biogenic fuels such as bioethanol, biomethane, biodiesel (FAME), biogenic synthetic diesel (HVO), bio-petrol and biokerosene (HEFA)

The main criticism about biodiesel is the use of raw materials that compete directly with food production or require large-scale deforestation to create plantations.
The focus of criticism is on palm oil plantations in Southeast Asia. (The EU has now banned the use of palm oil for the production of biogenic fuels).
The herewith proposed solution would be to use at least a part of the estimated 15 million square kilometres of land worldwide that is not or no longer suitable for agriculture for growing undemanding oil crops. Their oilseeds are not suitable for food and feed but can be easily processed to biofuels.

If only 20% of this area, i.e. 300 million hectares, were used, future demand for aviation kerosene could be met in full and demand for bio-based diesel could be met to a large extent.

Improvements in plant breeding and cultivation methods would further increase this potential.

The higher prices compared to fossil products could be offset by better efficiencies, economies of scale and subsidies within the framework of CO_2 certificate trading.

An important prerequisite for this is the introduction of internationally tradable CO_2 certificates which are integrated into a cap-and-trade system such as the EU ETS and comprise of an attractive economic value.

In addition, the overall concept would be a building block for beneficial cooperation between industrialised countries and the Global South:

- The cultivation of oil crops and the production of bio-oils in developing and emerging countries would enable their further economic development and at the same time counteract further land degradation.
- The processing and use of the oils by industrialised countries would reduce the use of fossil fuels and the associated CO_2 emissions without having to force a radical technological change (such as "all-electric", which would lead to other unwanted dependencies on raw materials and higher resource consumption and would cause increased CO_2 emissions – a “CO_2 backpack") The existing refinery and supply structure could be maintained, which also seems advisable from a geopolitical and security policy perspective and in terms of security of supply.

In addition, reforestation of currently unused land enables the permanent sequestration of significant amounts of CO_2 from the atmosphere by creating a CO_2 sink (provided that the wood is not burned at the end of its useful life, but is used as a building material or in the form of biochar for soil improvement).
The sink is also preserved if reforestation is repeated after clearing the old plants.

Reforestation covering an assumed total area of 300 million hectares would create a sink of 120 to 210 gigatonnes of CO_2. This corresponds to the absorption of all current anthropogenic CO_2 emissions over a period of three to five years.