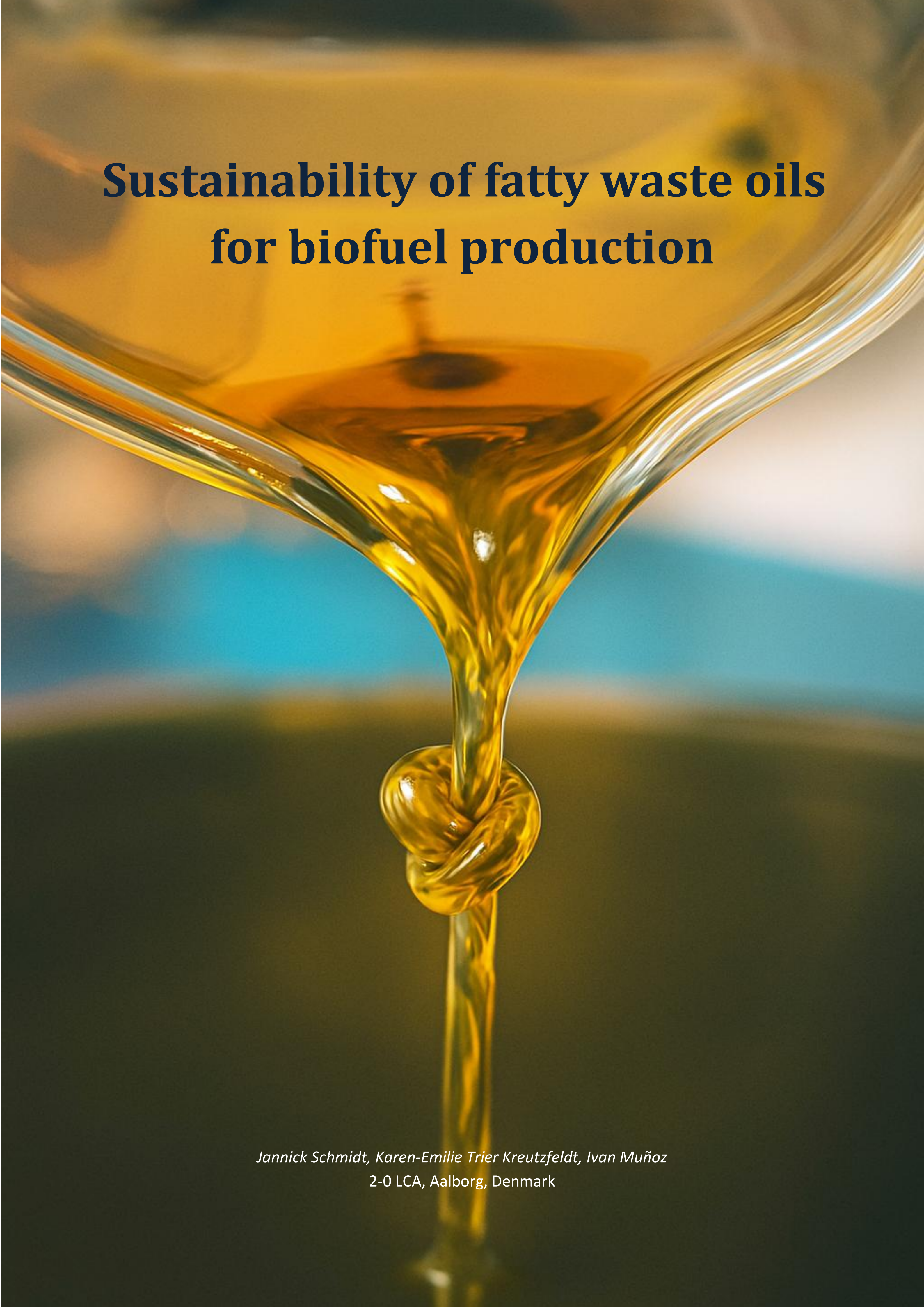

Sustainability of fatty waste oils for biofuel production

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Preface

This report is carried out by 2-0 LCA. The study is carried out in May 2024- April 2025. The intended audience of the report is stakeholders within the biofuel and transport sectors, as well as policymakers and other interested parties within the topic of sustainability of fatty waste oils for biofuel production.

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Contents

Executive Summary

This report evaluates the sustainability of various used for biofuel production. The assessment covers ten different feedstocks, including Used Cooking Oil (UCO), Palm Oil Mill Effluent (POME) oil, Spent Bleach Earth (SBE) oil, soap stock acid oils, animal fats, Fatty Acid Methyl Ester (FAME) bottoms, brown grease, sewage, and food waste. The key aspects analysed for each feedstock include overall sustainability concerns, plausible global volumes, competing industries, potential risks of indirect land use change (iLUC), geographical dependencies, and potential mitigating actions.

The key findings are:

- Used Cooking Oil (UCO): Highly constrained with high demand and limited supply, leading to potential fraud and iLUC risks. Estimated annual global potential is 10 million tonnes.
- Palm Oil Mill Effluent (POME) Oil: Highly constrained supply. Estimated annual global potential is 0.84 million tonnes.
- Spent Bleach Earth (SBE) Oil: Currently mainly landfilled, which leave room for increasing its use for biofuel, i.e. in the shorter term until fully utilised, it can be used with low iLUC risk. But given the very low potential, it is estimated that it will be fully utilised within very short time (few years). Therefore, it is important to ensure that an additional demand for SBE is associated with a corresponding additional recovery/collection of SBE. Estimated annual global potential is 0.037 million tonnes from non-palm vegetable oils and 0.013 million tonnes from palm oil.
- Soap Stock Acid Oils: Constrained with high demand, leading to potential high iLUC risks. Estimated annual global potential is 1.2 million tonnes.
- Animal Fats: Constrained with high demand, leading to potential iLUC risks. Estimated annual global potential is 2.8 million tonnes.
- Fatty Acid Methyl Ester (FAME) Bottoms: Constrained with high demand, leading to potential iLUC risks. Estimated annual global potential is 0.3 million tonnes.
- Brown Grease: Constrained with high demand, leading to potential iLUC risks. Estimated annual global potential is 2.0 million tonnes.
- Sewage: Oil and fat from sewage are currently mainly disposed of as waste, which leave room for increasing its use for biofuel, i.e. in the shorter term until fully utilised, it can be used with low iLUC risk. However, it is important to ensure that an additional demand for sewage oil and fat is associated with a corresponding additional recovery/collection. Estimated global potential is 5.4 million tonnes from sewage sludge and 13 million tonnes from sewage.
- Food Waste: Currently mainly disposed of as waste, which leave room for increasing its use for biofuel, i.e. in the shorter term until fully utilised, it can be used with low iLUC risk. However, it is important to ensure that an additional demand for oil from food waste is associated with a corresponding additional recovery/collection. Estimated global potential is 16.5 million tonnes of lipids.

1 Introduction

Biofuels are increasingly sourced from various fatty waste oils, including Used Cooking Oil (UCO), food waste, FAME bottoms, non-palm Spent Bleach Earth Oil (SBEO), sewage, soap stock acid oils, and brown grease. Understanding the sustainability implications of these feedstocks is important for evaluating risks, making informed decisions, and implementing necessary corrective measures.

This report aims to provide comprehensive information on the following aspects for each of the mentioned feedstocks:

- Overall sustainability concerns related to each feedstock
- Plausible total global volumes available of each feedstock
- Competing industries for each feedstock
- Qualitative potential risk of indirect land use change (iLUC) accompanied by quantitative iLUC values
- Geographical dependency of the identified sustainability issues
- Potential mitigating actions to achieve a sustainable use of the feedstocks

The above aspects are investigated for the following ten biofuel feedstocks:

1. Used cooking oil (UCO)
2. Palm oil mill effluent (POME) oil
3. Spent bleaching earth (SBE) oil
   3a) Palm oil based
   3b) Non-palm oil based
4. Soap stock acid oils
5. Animal fats (categorized and uncategorized)
6. Fatty acid methyl ester (FAME) bottoms
7. Brown grease
8. Sewage
9. Food waste

2 Methods and data

This section describes how each sustainability aspect is assessed.

2.1 Overall sustainability concerns related to each feedstock

This topic is covered qualitatively by a brief review of published studies and a general assessment on whether or not the feedstock is constrained, meaning that supply is limited and not responsive to an increase in demand. The latter is investigated further quantitatively under sections 2.2 and 2.3.

2.2 Plausible total global volumes available for each feedstock

The global plausible volumes are estimated based on publicly available data. IEA (2023a,b) provide figures for the use of main feedstocks for transport fuels in 2021 and estimates for 2027/2030. Data for biofuels for 2021 and 2027 are obtained from IEA (2023a), while data for oil, gas, and electricity for 2021 and 2030 are obtained from IEA (2023b). However, since only UCO and animal fats are included in these studies, the remaining fuels in scope in this study are estimated based on other data. Since most of the evaluated feedstocks are by-products of other production, the production volumes can in most cases be estimated as the production volumes of the main product, for which statistical data are available, multiplied with a by-product to main product ratio.

When assessing the global volumes available of each feedstock, this is compared to the total volumes of transport fuels, as well as their expected change from 2021 to 2027/30.

Table 2.1. Quantities of transport fuels consumed in 2021 and expected quantities in 2027 (biofuels) and 2030 (oil, gas and electricity) (EIA 2023a,b).

Transport fuels	2021 [EJ]	2027/30 [EJ]	Share in 2021	Share in 2027/30	Change 2021-2027/30
Oil	103	81	90%	82%	-21%
Natural gas	5.3	4.0	4.7%	4.1%	-25%
Electricity	1.6	8.0	1.4%	8.1%	399%
Biofuels, 1st generation	**3.9**	**4.6**	**3.4%**	**4.7%**	**20%**
Maize	1.5	1.6	1.3%	1.6%	6%
Sugars	0.86	1.0	0.8%	1.0%	11%
Soy oil	0.45	0.71	0.4%	0.7%	60%
Rapeseed oil	0.24	0.32	0.2%	0.3%	34%
Palm oil	0.60	0.69	0.5%	0.7%	15%
Other crops	0.27	0.40	0.2%	0.4%	48%
Biofuels, 2nd generation	**0.5**	**0.8**	**0.4%**	**0.9%**	**74%**
Used cooking oil (UCO)	0.27	0.45	0.2%	0.5%	64%
Animal fats	0.18	0.34	0.2%	0.3%	94%
Other wastes and residues	0.04	0.05	0.0%	0.1%	45%
Total	**114**	**99**	**100%**	**100%**	

2.3 Competing industries for each feedstock

While section 2.2 has focused on the supply-side for each feedstock, this section instead focuses on the use-side, namely on competition for the feedstocks. Competition for feedstocks is relevant when the supply is constrained. As previously mentioned, by constrained, it refer to a situation where a demand for a feedstock will not trigger increased supply. This limited supply leads to competition by different users of the feedstock. The topic of competition is introduced by listing the current users for each feedstock. This is followed by attempting to identify which of the uses is the marginal. Here 'marginal' refers to the user of the feedstock that is most likely affected (to give up the use) caused by a change in demand and considering that the overall supply is constrained. This is illustrated in Figure 2.1.

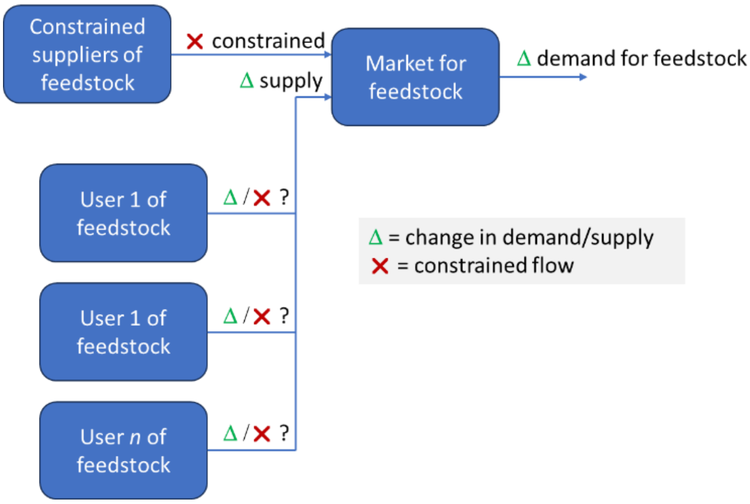

Figure 2.1. Competing users (1, 2, … *n*) of feedstock. The user(s) which are most likely to give up their use of the feedstock are called marginal users.

2.4 Qualitative potential risk of iLUC accompanied by quantitative iLUC values

The risk of iLUC appears when a change in demand for the feedstock has a spillover effect on "first generation" feedstocks that require land for their production, e.g. palm oil would require land for the cultivation of oil palm fruits. The risk of iLUC is deemed high if:

1. The supply of a particular feedstock is constrained, and
2. If the marginal user of the feedstock is likely to shift to an alternative product that requires land for its production.

2.5 Geographical dependency of the identified sustainability issues

The geographical dependency of the identified sustainability issues is assessed based on the geographical extent of the markets for the considered feedstocks, their derived fuels as well as their alternatives identified in section 2.3.

2.6 Potential mitigating actions to achieve a sustainable use of the feedstocks

Mitigation actions include those that can prevent or reduce the identified undesirable impacts and risks. The feedstocks investigated in the current report are wastes, i.e. a change in demand for the feedstock will not increase it's production because this is determined by the demand for the determining product. However, even though the production of the feedstock is constrained, it could be that a change in demand could be met by diverting the feedstock from one use/treatment, e.g. landfill, to biofuel feedstock. Such a shift in the users/treatment of the feedstock are not always automatically caused by a change in demand. Therefore, mitigation actions can also include actions to ensure that the 'claimed suppliers' are actually changing their production volume equivalent to the change in demand for feedstocks. This would in some cases require to pay an additional price to ensure that the production volume of the supplier can be expanded. If this is not feasible, an alternative mitigation option is off-setting, although it can be questioned if this can be called mitigation. The latter is not dealt with in this report.

3 Sustainability assessment of selected fatty waste oils

3.1 Used cooking oil (UCO)

UCO is oils and fats that have been used for e.g. food purposes (cooking or frying). This can be in food processing industry, restaurants, and in households (EUBIA 2024). UCO is listed as a biofuel feedstock in the EC Renewable Energy Directive (EC 2023, annex IX), i.e. RED III. The corresponding annex of the RED II describes the option that UCO based biofuels can count twice in a member state's obligation to meeting the required renewable shares in transport fuels as set out in the directive. However, this option has been removed with RED III.

According to van Grinsven et al. (2020), the production process for converting UCO into biodiesel is similar to conventional FAME production capacity, and therefore it is relatively mature and cheap. The production prices of biodiesel based on UCO are relatively low compared to other second-generation biodiesel feedstocks, which may explain why this is popular. However, despite the low production price, the prices of traded UCO are high: according to van Grinsven et al. (2020, p 46) UCO methyl ester was 41-64% higher than FAME in 2019-2020, and in 2023/2024 it was 6-21% higher (Vesper 2024). The price of UCO methyl ester has remained higher than FAME even after the double counting option of the RED II has been removed. This is probably because UCO can be claimed to be a second-generation biodiesel, whereas FAME cannot. van Grinsven (2020, p 50) even reports higher prices of UCO than virgin cooking oil. This both indicates that UCO is highly constrained (demand is higher than supply) as well as an opportunity for fraud, e.g. by repurposed virgin palm oil for UCO (van Grinsven 2020; Transport and Environment 2023). van Grinsven (2020) points at the risk of iLUC because a change in demand for UCO may spill over to virgin oils.

Plausible total global volumes available of UCO

It appears from Table 2.1 that UCO accounted for 0.2% of global transport fuels in 2021, and that it is projected to increase by 64% in quantities towards 2027. According to FAOSTAT (2024a), the global production of vegetable oils is 215 million tonnes, of which palm, soy, rape and sunflower account for >90%. The use of vegetable oils for food purposes is 87 million tonnes. Other uses include 35 million tonnes for transport fuels (IEA 2023a), 1 million tonne for feed (FAOSTAT 2024b), and a residual of 92 million tonne, which refer to use in the surfactants industry and for other non-transport fuel. The potential for reusing cooking oil for fuel purposes can be estimated as the 87 million tonne minus what is actually consumed as food. No data on the share of the 87 million tonne of vegetable oils used for food purposes that is ingested by humans have been identified.

van Grinsven (2023, p 37) refer to estimates of the EU potential for UCO at 1.7-2 million tonne in 2016. Comparing with consumption of vegetable oils for food in the EU at 15 kg/capita in 2016 (FAOSTAT 2024b), this indicates that as 11-13% of the consumption for food can be potentially reused as UCO. Another estimate is provided by EUBIA (2024), which reports a potential for UCO in the EU at 8 litres/capita/year. Comparing with consumption of vegetable oils for food in the EU at 17 kg/capita in 2021 (FAOSTAT 2024b), this indicates that as much as almost half of the vegetable oil consumption for food can be reused as UCO. This seems unrealistic and too optimistic from a biofuel potential perspective. Hence, based on these two identified sources of data, a best estimate of UCO potential is regarded as 12% of the vegetable oil that is used for food.

According to EUBIA (2024), around 10% of the UCO in EU originates from animal fat. The use of animal oils and fat for food includes butter and category 3 fat. Butter is not a relevant feedstock at the EU level. Also, its relatively high price makes it an unattractive feedstock in this context (Haas et al. 2010). According to Aveno (2020), the consumption of category 3 fat for food purposes in the EU in 2019 is 0.19 million tonnes, equalling 0.43 kg/capita, which is significantly smaller compared to the potential for UCO from vegetable oils. Hence the animal-based UCO is regarded as small (<10%) compared to UCO based on vegetable fats.

Combining the global consumption of vegetable oils for food at 87 million tonnes and a realistic potential of 12% of this to be recycled as UCO, the potential is estimated as 10 million tonnes, which is equal to 0.37 EJ. This corresponds to 0.33% of the energy used for transport fuels in 2021. This is summarised in Table 3.1 below.

Recycling rates may be driven higher than the estimated potential of 12%, but this will probably require higher collection costs. This is because a large share of the increased collection needs to come from households with many collection points with small quantities, whereas today's supply is dominated by collection from the professional sector with few collection points with large quantities (van Grinsven 2023).

Table 3.1. The annual potential of UCO.

Parameter	Unit	Value	Data sources/comments
Input parameters			
Oils and fats used for food purposes (a)	Million tonne	87	(FAOSTAT 2024b)
Share of oils and fats for food that can be reused (b)	%	12%	See text in this section
Calorific value (c)	MJ/kg	37	(Mehta and Krishnasamy 2009)
Calculated values			
Global UCO potential (d)	**million tonnes**	**10**	**Calculated: (a)*(b)**
Global UCO potential (e)	**EJ**	**0.018**	**Calculated: (d)*(c)/1000**
Global UCO potential relative to transport fuels	**%**	**0.33%**	**Calculated: (e) / 114 (from Table 2.1)**

The current and potential increase in UCO supply is very small compared to the total energy for transport. Further, the supply of UCO will be fully proportional and determined by the general demand for food produced using cooking oil, except if the recovery efficiency of UCO changes. In this respect, higher collection rates would come with an additional cost on top of an already high cost. Therefore, the supply of UCO is regarded as constrained in terms of its likelihood to react to changes in demand.

Competing industries for UCO

As described in the previous section, the supply of UCO is highly constrained, i.e. changes in demand will not lead to corresponding changes in supply. UCO is by far mainly being used as feedstock for biofuels, however other uses are: (GF Commodities 2019; Neste 2024; DAR PRO Solutions 2021)

- ingredient for animal and petfood
- feedstock for soap
- feedstock for bio-polymers
- feedstock for cosmetics

No literature has been found specifying quantities of UCO going to each of the above uses, while biofuel is the only large-scale purpose described in the available literature. Therefore, this is regarded as the main use, as well as the marginal use. Hence, a change in demand for UCO is most likely to affect the availability of UCO for fuel purposes to other users. The resulting effect of changing the demand for UCO is that another user must shift from UCO to another alternative. This is likely to be palm oil, which is the cheapest source of vegetable oil, or fossil fuels. Palm oil is regarded as more likely to be affected than fossil fuels since the users who use UCO are probably already committed to using biofuels, hence they can be expected to search for alternatives within this market.

Qualitative potential risk of iLUC accompanied by quantitative iLUC values

As explained above, there is a high risk that a change in demand for UCO will have a spillover effect in demand for virgin vegetable oils. Virgin vegetable oils are related to iLUC effects.

On top of the general high risk described above, there is an additional risk of fraud, which will also lead to iLUC: In particular, there are cases where UCO is more expensive than virgin cooking oil (van Grinsven 2020, p 50). This means there is a high risk that professional kitchens increase their output of UCO by increasing the input of virgin cooking oil and replacing the cooking oil more often. When UCO has a higher price than virgin cooking oil, there is an incentive for the kitchens to do so.

If virgin oil is affected as a consequence of a change in demand for UCO, it is most likely that the affected oil will be palm oil, since this is oil is the fastest growing (in terms of global production volume), and since this oil is the cheapest source of virgin oil (Schmidt 2015; Schmidt and De Rosa 2020). The GHG emissions related to the production of palm oil and use for biofuel are 135 g CO_2e/MJ (Schmidt and De Rosa 2020). Hereof 13 g CO_2e/MJ are caused by iLUC.

Geographical dependency of the identified sustainability issues

Transport and the Environment (2023, p 9) show that EU is sourcing approx. 20% of their biodiesel from imports. Further, Transport and the Environment (2023, p 19) show that >60% of the UCO used in the EU is imported. Therefore, both the UCO as well as UCO-based biodiesel are commodities which are largely traded on global markets, where the largest suppliers to the EU are China, Malaysia, and Indonesia.

Given the high magnitude of global trade of UCO and UCO-based biodiesel, there seems to be no geographical dependencies in the identified sustainability issues (spillover effect from UCO to vegetable oils, chiefly palm oil). Only the issues of fraud can be regarded as geographically dependent. Since there is presumably less control over the supply chains of UCO from some countries than from others, probably there are differences in the level of fraud depending on the supplying country. Transport and the Environment (2023, p 20-21) mentions China, Indonesia, and United Kingdom as countries where fraud is suspected. However, since there is already a generally high risk that demand for UCO will spill over to virgin vegetable oils and thereby causing iLUC, the risk of fraud does not change the resulting effect.

Potential mitigating actions to achieve a sustainable use of UCO

Since the supply of UCO is generally not regarded as responding to changes in demand, it would be difficult to identify easily applicable mitigation actions to achieve sustainable use of UCO. The only viable way to ensure that a change in demand for UCO does not spill over to virgin vegetable oils would be to ensure that all additionally demanded UCO is obtained from additional UCO collection. By ensuring this additionality, the undesired environmental impacts related to UCO can be avoided. However, this would probably be associated with high costs.

3.2 Palm oil mill effluent oil (POME oil)

Palm oil mill effluent (POME) is a waste-product from palm oil production and emerges at various stages during the oil milling process (Schmidt and De Rosa 2020). POME has a high concentration of oil and grease, typically ranging from 4000 to 8000 mg per litre and with a chemical oxygen demand (COD) content typically >50,000 ppm. This level is significantly higher than the allowable discharge limit. To bring the COD within acceptable limits, palm oil industries have explored various innovative technologies for processing POME. Generally, POME has been handled in open anaerobic ponds, leading to significant methane emissions. To address this issue, POME can also be treated with biogas capture. After treatment, POME is either predominantly applied in the estates as a fertilizer or discharged into rivers (Zulqarnainet al. 2021).

The significant resource from POME to biofuels is the POME oil (or sludge oil), which is separated from the POME before the treatment begins. The POME sludge is collected in a container, where over time, the POME oil separates and forms a distinct layer that can be extracted and subsequently utilized as biodiesel feedstock. The separation of POME oil results in lower COD content in the POME for treatment. However, since the POME sludge is separated as a standard process, a change in demand for POME oil will not affect the collected POME oil, and therefore this effect is not considered in this report.

Plausible total global volumes available of POME

The global production of POME oil is calculated based on typical conversion factors in palm oil mills and the global production of palm oil. Data and results are shown in **Table 3.2**. According to Tang et al. (2023), the POME oil recovery can be increased from current 35-55% to close to 100%, but this would require high additional costs.

Table 3.2. The annual potential of POME oil.

Parameter	Unit	Value	Data sources/comments
Input parameters			
POME per tonne processed FFB (a)	tonne/tonne	0.700	(Schmidt and De Rosa 2020)
Palm oil per tonne processed FFB (b)	tonne/tonne	0.219	
Oil content in POME (c)	%	1%	(Zulqarnainet al. 2021)
Recovery efficiency of POME oil (d)	%	50%	(Tang et al. 2023)
Global palm oil production, 2021 (e)	million tonnes	80.5	(FAOSTAT 2024a)
Calorific value (f)	MJ/kg	37	(Mehta and Krishnasamy 2009)
Calculated values			
POME per tonne palm oil (g)	tonne/tonne	3.20	Calculated: (a)/(b)
Global POME production, 2021 (h)	million tonnes	258	Calculated: (e)*(h)
Global POME oil production, 2021 (i)	**million tonnes**	**0.837**	**Calculated: (c)*(d)*(d)**
Global POME oil production, 2021 (j)	**EJ**	**0.018**	**Calculated: (f)*(i)/1000**
POME oil potential relative to transport fuels	**%**	**0.016%**	**Calculated: (j) / 114 (from Table 2.1)**

The current and potential increase in POME oil supply is very small compared to the total energy for transport. Further, the supply of POME oil will be fully proportional and determined by the general demand for palm oil, except if the recovery efficiency of POME oil changes. In this respect, it should be mentioned that increasing the recovery rate comes with potentially high additional costs. The supply of POME oil is regarded as constrained in terms of its likelihood to react to changes in demand.

Competing industries for POME oil

According to Tang et al. (2023) is POME oil typically used either for:

- Biodiesel,
- burner fuel,
- sustainable aviation fuel (SAF), and
- phytonutrients.

The use of this waste product as feedstock for biodiesel production is currently growing, with an assumption that it will become the primary treatment of POME oil in the future. According to Transport and the Environment (2023, p 24) the use of POME oil in EU doubled from 2020 to 2022, reaching 13% of all palm biofuels. However, Tang et al. (2023) finds it necessary to implement improvements to POME-based biodiesel regarding efficiency and cost-effectiveness.

Secondly, POME oil can be directly utilized as a fuel in a burner without the need for any refining process. The viscosity of residual oil from POME is 15 times higher than conventional diesel resulting in decreased emissions of carbon monoxide (CO) and nitrogen oxides (NO_x) by 34% and 90%, respectively (Tang et al. 2023).

Thirdly, SAF with hydrotreated vegetable oil (HVO) technology is also a possible use of POME-oil. This is an alternative to the current use of fossil fuels in the aviation industry (Tang et al. 2023).

Fourthly, the phytonutrients are compounds which exhibit positive antioxidant and anti-inflammatory effects on human health. This makes POME oil a valuable addition to cosmetics, colouring agents, and nutritional supplements in the pharmaceutical and food sectors (Tang et al. 2023).

At an overall level, POME oil is mostly used as feedstock for biodiesel. Therefore, this is regarded as the marginal use. Hence, a change in demand for POME oil is most likely to affect the availability of POME oil as biodiesel feedstock to other users. The resulting effect of changing the demand for POME oil is that another user must shift from POME oil to another alternative. This is likely to be palm oil, which is the cheapest source of vegetable oil, or fossil fuels. Palm oil is regarded more likely to be affected than fossil fuels since the users who use POME oil are probably already committed to use biofuels, hence they can be expected to search for alternatives within this market.

Qualitative potential risk of iLUC accompanied by quantitative iLUC values

As previously described, changes in POME oil demand may affect virgin vegetable oil demand, particularly palm oil, which is associated with iLUC. As described in the section on UCO (section 3.1), the GHG emissions related to the production of palm oil and use for biofuel are 135 g CO_2e/MJ (Schmidt and De Rosa 2020). Hereof 13 g CO_2e/MJ are caused by iLUC.

Geographical dependency of the identified sustainability issues

As POME is mostly used for biofuel purposes it is assumed that there are no geographical dependencies for the identified sustainability issues (spillover effect from UCO to vegetable oils, chiefly palm oil). As in the case of UCO, only the fraud issue can be regarded as geographically dependent. Since there is presumably less control over the supply chains of POME oil from some countries than from others, probably there are differences in the level of fraud depending on the supplying country. Transport and the Environment (2023, p 20-21) mentions among others Indonesia, where fraud is suspected. Since Indonesia is the marginal supplier of palm oil this can affect sustainability issues. However, since there is already a general high risk that demand for POME oil will spill over to virgin vegetables oils and thereby cause iLUC, the risk of fraud does not change the resulting effect.

Potential mitigating actions to achieve a sustainable use of POME oil

As in the case of UCO, the supply of POME oil is generally not regarded to respond to changes in demand. For that reason, it would be difficult to identify easily applicable mitigation actions to achieve sustainable use. Like in UCO, the only viable way to ensure that a change in demand for POME oil does not increase virgin vegetable oil production would be to ensure that all additionally demanded POME oil is obtained from additional POME oil collection. By ensuring this additionality, the undesired environmental impacts related to POME oil can be avoided. However, this would probably be associated with high costs.

3.3 Spent Bleach Earth (SBE) Oil

This section discusses the potential for spent bleach earth oil (SBE) obtained from refining palm oil and other vegetable oils. The processes leading to the production of SBE are very similar for all vegetable oils, which is why they are described in the same section. The calculated potentials are shown in **Table 3.3**.

Crude oil refining consists of several stages: filtration to remove insoluble impurities, degumming to eliminate water-swelling phosphatides, neutralization to address free fatty acids, bleaching with an adsorptive clay for discoloration, hydrogenation for hardening if needed, and ultimately deodorization. The bleaching step involves using a natural absorbent like bentonite clay, also called bleaching earth (BE). BE has a significant ability to adsorb and remove undesirable components in the oil like heavy metals and colour. This removal produces spent bleaching earth (SBE) with a content of 20%-40% oil (Abdelbasir et al. 2023).

According to Abdelbasir et al. (2023) SBE is mainly landfilled resulting in environmental issues as SBE contains undesirable components, and the oil may self-ignite. In poorly managed landfills, the oil may seep into the soil and contaminate water sources. For these reasons, alternative uses of SBE can be attractive, such as using it as feedstock for biodiesel production.

Plausible total global volumes available of SBE oil

The potential production volume of SBE oil is estimated based on the global production of refined vegetable oils, the oil content (20%-40%) in SBE and an oil recovery rate, the latter being 30% of the total oil weight according to Abdelbasir et al. (2023). This results in 9% of the oil initially present in SBE being potentially recoverable.

Table 3.3. The annual potential of SBE oil from vegetable oils.

Parameter	Unit	SBE oil from other veg. oil	SBE oil from palm oil	Data sources/comments
Input parameters				
Non-palm vegetable oil, globally (a)	Million tonnes	65.0	22.2	(FAOSTAT 2024a)
SBE output from refinery (b)	tonne/tonne refined oil	0.0064		(Abdelbasir et al. 2023)
Oil content in SBE (average) (c)	%	30%		
Recovery rate of SBE oil (d)	%	30%		
Calorific value (e)	MJ/kg	37		(Mehta and Krishnasamy 2009)
Calculated values				
Global SBE oil production (f)	**Million tonnes**	**0.0374**	**0.0128**	**Calculated: (a)*(b)*(c)*(d)**
Global SBE oil production (g)	**EJ**	**0.001**	**0.0005**	**Calculated: (e)*(f)/1000**
SBE oil potential relative to transport fuels	**%**	**0.001%**	**0.0004%**	**Calculated: (g) / 114 (from Table 2.1)**

Competing industries for SBE oil

Generally, there are no competition issues associated with SBE oil since the current marginal treatment is landfilling, as previously mentioned. Given that SBE oil can be considered constrained, a demand for SBE oil will not result in increased SBE oil production, but in avoided landfilling, which can be seen as leading to positive environmental effects.

According to Abdelbasir et al. (2023), SBE oils is also used for:

- Wastewater treatment,
- Biofertilizer,
- Fuel briquettes and,
- Non-fired wall tiles to reduce the waste during edible oil refining industry.

In the long term, it is assumed that biodiesel production will become the primary treatment of SBE oil. In this situation, a demand for SBE oil will result in an availability reduction to other SBE oil users, who will in turn resort to an alternative oil source, most likely palm oil, to cover their demand.

Qualitative potential risk of iLUC accompanied by quantitative iLUC values

Using SBE oil does not involve iLUC effect risks, since landfilling is the primary disposal method. However, if in the future biodiesel production becomes the marginal treatment of SBE oil, the counterfactual effect will be an increase in virgin vegetable oil production, particularly palm oil, which is associated with iLUC. Given the small potential (see Table 3.3), it can be expected that SBE oil will be fully utilized within very short time (few years). As described in the section on UCO (section 3.1), the GHG emissions related to the production of palm oil and use for biofuel are 135 g CO_2e/MJ (Schmidt and De Rosa 2020). Hereof 13 g CO_2e/MJ are caused by iLUC.

Geographical dependency of the identified sustainability issues

Disposal of waste, including landfilling of SBE, is managed at a local level. Therefore, the environmental effects of diverting SBE oil from disposal will be different from one place to another. As an example, diverting SBE oil from a location where waste is taken to an unmanaged landfill is preferable to diverting the waste from a sanitary landfill, since the latter has lower environmental impact. In all cases, though, diversion from landfill can be seen as advantageous.

Potential mitigating actions to achieve a sustainable use of SBE oil

Generally, diverting SBE oil from landfilling can be seen as advantageous. However, in a hypothetical situation where SBE oil is instead mainly used for biodiesel production, the same mitigation actions as for UCO and POME oil apply. To avoid the spillover effect on virgin vegetable oils it is necessary to ensure that all additionally demanded SBE oil is obtained from additional SBE collection. However, this approach is likely to incur in higher costs.

3.4 Soap stock acid oils

Soap stock acid oils are byproducts formed during the refining of vegetable oils to neutralize the taste of the edible oils (Fazli et al, 2013). In the process, known as alkali neutralization or saponification, some of the oil's fatty acids react with alkalis to produce soap. This soap is separated through washing, yielding a mixture called soap stock. To obtain soap stock acid oils, the soap stock undergoes acidulation, where acid is added to liberate remaining fatty acids. These fatty acids, now in the form of free fatty acids (FFA), are then separated from the aqueous phase, constituting the soap stock acid oils. (Fazli et al, 2013)

In the refining process of vegetable oils, excluding palm oil, chemical refining is typically employed. This process results in the formation of free fatty acids (FFA) as a byproduct. In the case of palm oil, the refining process can vary between chemical and physical methods (Fazli et al, 2013). In chemical refining, the byproduct is palm acid oil (PAO), while in physical refining, it becomes palm fatty acid distillate (PFAD) (Top, 2010). FFA is the broad term of soap stock acid oils, where PAO and PFAD are the specific names in the palm oil industry.

Plausible total global volumes available of soap stock acid oils

By finding the global production of vegetable oils for food purposes in FAOSTAT (2024a) it is possible to calculate the production of soap stock acid oils. See section 3.1 (UCO) for further description on the data from FAOSTAT (2024a). Palm oil, palm kernel oil and olive oil are shown individually, as their content in PAO/PFAD is different from other vegetable oils (Metrohm 2024). The FFA content found in other vegetable oils originates from rapeseed and sunflower oil. It is possible to extract up to 95% of the PAO, PFAD and FFA. Data are further detailed in **Table 3.4**, along with the global production of vegetable oils in 2021.

Table 3.4. The annual potential of soap stock acid oil.

Parameter	Unit	Value	Data sources/comments
Input parameters			
Refined vegetable oil in 2021 (other than palm oil, palm kernel oil and olive oil) (a)	Millon tonnes	61.7	(FAOSTAT 2024a)
Refined palm oil and palm kernel oil in 2021 (b)	Millon tonnes	22.2	
Refined olive oil in 2021 (c)	Millon tonnes	3.32	
FFA in crude oil (rapeseed and sunflower oil) (d)	%	0.07%	Metrohm (2024)
PAO/PFAD in crude palm oil (e)	%	5.30%	
FFA in crude oil (olive oil) (f)	%	2.10%	
Recovery efficiency of FFA, PAO and PFAD from the vegetable oils (g)	%	95%	(Hammond 2003)
Calorific value (f)	MJ/kg	37	(Mehta and Krishnasamy 2009)
Calculated values			
Total FFA in crude oil (rapeseed and sunflower oil)	Millon tonnes	0.0381	Calculated: (a)*(d)*(g)
Total PAO/PFAD in crude palm oil	Millon tonnes	1.12	Calculated: (b)*(e)*(g)
Total FFA in crude oil (olive oil)	Millon tonnes	0.0663	Calculated: (c)*(f)*(g)
Global soap stock acid oil (h)	**Million tonnes**	**1.22**	**Calculated (sum of outputs)**
Global soap stock acid oil (i)	**EJ**	**0.045**	**Calculated: (h)*(f)/1000**
Soap stock acid oils potential relative to transport fuels	**%**	**0.040%**	**Calculated: (i) / 114 (from Table 2.1)**

Competing industries for soap stock acid oils

FFAs are typically utilized either for biodiesel production or as feed. The former is currently on the rise due to the potential of utilizing this waste product as feedstock (Transport and Environment 2023). It is assumed that biodiesel production will become the primary treatment of FFAs in the future. Nevertheless, a significant amount of FFAs is being added to the feeding industry (FEDIOL 2016), suggesting that this sector is still competitive.

Constituting a byproduct, soap stock acid oils can be considered constrained, whereby a change in demand will not result in increased supply. If the marginal treatment of FFA becomes biofuel production, an increased demand for these soap stock acid oils will lead to less availability to other users, who will in turn resort to alternative feedstock, chiefly palm oil.

Qualitative potential risk of iLUC accompanied by quantitative iLUC values

As explained above, there is a high risk that a change in demand for soap stock acid oils will have a spillover effect in the demand for virgin vegetable oils, particularly palm oil, which is associated with iLUC. As described in the section on UCO (section 3.1), the GHG emissions related to the production of palm oil and use for biofuel are 135 g CO_2e/MJ (Schmidt and De Rosa 2020). Hereof 13 g CO_2e/MJ are caused by iLUC.

Geographical dependency of the identified sustainability issues

The full utilization of soap stock acid oils for biodiesel raises similar sustainability concerns and associated geographical dependencies as with UCO.

Potential mitigating actions to achieve a sustainable us of soap stock acid oil

The same arguments appear for the mitigating actions as above regarding the geographical dependency of the identified sustainability issues.

3.5 Animal fats

Animal fats can be divided into three categories: Category 1 represents the highest risk material, Category 2 denotes intermediate risk material, and Category 3 indicates material with a low risk (EC 2024). As mentioned in **Chapter 1,** category 3 is used for feed and petfood purposes, and it is not mentioned by the Renewable Energy Directive as feedstock for sustainable biofuels. For this reason, it is excluded from our analysis, which focuses instead on category 1 and 2 fat availability. It must be highlighted, though, that category 3 fats are increasingly used and marketed as biofuel feedstock, entering a competition with the pet food and the feed industry (FeedNavigator 2023).

Plausible total global volumes available of animal fats

According to Malins (2023), Europe produced 3 million tonnes of animal fats in 2021, with 2 million tonnes falling into category 3, and the remaining 570 thousand tonnes categorized as category 1 and 2 combined[1]. This distribution is applied to estimate the relative proportion of fat categories 1, 2 and 3.

The total amount of uncategorized cattle and pig fat are drawn from FAOSTAT (2024a). In 2022, the global production of these fats was 3.39 and 11.13 million tonnes respectively. These amounts are multiplied with the share of category 1 and 2 based on Malins (2023) to estimate the availability of animal fat feedstock. The result is included in the following table.

Table 3.5. The annual potential of animal fats (cattle and pig).

Parameter	Unit	Value	Data sources/comments
Input parameters			
Cattle fat (a)	Million tonnes	3.39	(FAOSTAT 2024)
Pig fat (b)	Million tonnes	11.13	
Share of category 3 (c)	%	80%	(Malins 2023)
Share of category 1+2 (d)	%	19%	
Share of other/waste (e)	%	1%	
Calorific value (f)	MJ/kg	37	(Mehta and Krishnasamy 2009)
Calculated value			
Global animal fats (cat. 1+2) (g)	**Million tonnes**	**2.76**	**Calculated: ((a)+(b)) * (d)**
Global animal fats (cat. 1+2) (h)	**EJ**	**0.102**	**Calculated: (f)*(g)/1000**
Animal fats potential relative to transport fuels	**%**	**0.09%**	**Calculated: (h) / 114 (from Table 2.1)**

Competing industries for animal fats

According to Malins (2023) categories 1 and 2 in Europe are almost fully utilized for biodiesel production already. Another study from 2016 (Chudziak and Haye 2016), also indicates that animal fats are fully utilised, as a change in demand for biofuels will have substitution effects on especially palm oil. This means that the current demand for animal fats will be covered by palm oil as a counterfactual effect if there is an increased demand for animal fat as feedstock. The reason is that the supply of animal fat is constrained, as its supply is linked to food demand. Thus, a change in demand for animal fat will lead to less availability to other users, who will in turn resort to alternative feedstock, chiefly palm oil.

Qualitative potential risk of iLUC accompanied by quantitative iLUC values

As explained above, there is a high risk that a change in demand for animal fats will have a spillover effect in demand for virgin vegetable oils, particularly palm oil, which is associated with iLUC. This risk is also pointed out in Chudziak and Haye (2016). As described in the section on UCO (section 3.1), the GHG emissions related to the

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[1] Data are further provided by EFPRA.eu (2024) who presented 2021 data on byproducts from the rendering industry at EFPRA congress (Malins 2023).

production of palm oil and use for biofuel are 135 g CO_2e/MJ (Schmidt and De Rosa 2020). Hereof 13 g CO_2e/MJ are caused by iLUC.

Geographical dependency of the identified sustainability issues

The full utilization of animal fats for biodiesel raises similar sustainability concerns and associated geographical dependencies as with UCO.

Potential mitigating actions to achieve a sustainable use of animal fat

The same arguments appear for the mitigating actions as above regarding the geographical dependency of the identified sustainability issues.

3.6 Fatty acid methyl ester (FAME) bottoms

Fatty acid methyl ester (FAME) is the generic chemical term for biodiesel, which is obtained via the transesterification of oils and fats. During transesterification, the oil/fat feedstock is reacted with an alcohol (typically methanol) in the presence of an alkaline catalyst (potassium hydroxide or caustic soda) to form FAME and glycerol as a byproduct. In the reactor, glycerol accumulates at the bottom layer, which needs to be separated from the FAME. Crude glycerol contains remaining unconverted triglycerides, unreacted methanol, some dissolved biodiesel, fatty acids, alkali hydroxides, different semi-saponified triglycerides, alkali salts of fatty acids, water, pigments and some other remains (Herseczki et al. 2013). Daka (2023) reports a fat and oil content in crude glycerol of 8-12% by weight, while Mythili et al. (2014) report a FFA content of 4.9% only, but also a content in soap of 10.6%, from which free fatty acids (FFA) can be extracted by acidification. Management of crude glycerol varies according to the size of the biodiesel facility. While small plants treat crude glycerol as waste, big plants have the economies of scale to install a glycerol purification process, where the purified product is sold for a wide variety of applications in the food, beverages, pharmaceutical, and chemical industries (Pagliaro and Rossi 2008). Treatment of crude glycerol starts with acidification to a pH equal to approximately 3, to hydrolyse soaps and neutralize the catalyst. This releases FFA which can be separated by decantation or centrifugation. This is what is called FAME bottoms. Crude glycerol then follows additional steps to recover methanol and remove water and other contaminants (Maquirriain et al. 2022).

Plausible total global volumes available of FAME bottoms

An estimate of the potential availability of fatty acids from crude glycerol can be made based on several data and assumptions, namely the global volume of biodiesel produced, the ratio of crude glycerol to biodiesel, the recoverable FFA content in crude glycerol, the yield of biodiesel from FFA and the calorific value of biodiesel. The estimated potential for FFA from this source is calculated in the following table.

Table 3.6. The annual potential of fatty acids from crude glycerol.

	Unit	Value	Data sources/comments
Input parameters			
Biodiesel production (a)	Million m^3	38.6	OECD (2018)
Biodiesel density (b)	tonne/m^3	0.88	USDE (2024)
Crude glycerol to biodiesel ratio (c)	Tonne glycerol/tonne biodiesel	0.11	Binhayeeding et al. (2017)
FFA recovery rate (d)	Tonne FFA/tonne glycerol	0.08	Assumed, based on Daka (2023) and Mythili et al. (2014)
Biodiesel yield from FFA (e)	Tonne biodiesel/tonne FFA	0.98	Assumed
Biodiesel net calorific value (f)	GJ/tonne	37	Mehta and Krishnasamy (2009)
Calculated values			
Recoverable FFA potential (g)	**Million tonnes**	**0.3**	**Calculated: a*b*c*d**
Biodiesel potential (h)	**EJ**	**0.011**	**Calculated: (g*e*f)/1E-09**
Biodiesel potential relative to transport fuels	**%**	**0.01%**	**Calculated: h / 114 (from Table 2.1)**

Our estimate results in a potential availability of 0.3 million tonnes of biodiesel produced from FFA recovered from crude glycerol, or 0.011 EJ, a negligible amount when put in context of the global use of transport fuels as displayed in **Table 2.1**.

Competing industries for FAME bottoms

FAME bottoms are a by-product from the processing of crude glycerine in biodiesel plants. This means this feedstock is constrained, i.e. a demand for FAME bottoms will not lead to increased supply, since the amount of FAME bottoms available is dictated by how much biodiesel is produced. Instead, a demand for FFA will affect the most likely unconstrained supply source. FFA are mainly produced by vegetable oil refineries, but in this case they also constitute a by-product, and therefore such refineries are not expected to be affected. The marginal use, i.e. the user that will give up their use when changing the demand for FFA, can be defined as the one with the lowest value added. It is expected that this is either for energy use (biodiesel production) or fodder fat (animal use). In this way, it can be established that a demand for FFA from FAME bottoms will eventually lead to a reduced supply of biodiesel from FFA or fodder fat; this gap in the biodiesel feedstock or animal fodder fat market will most likely be fulfilled by an increase in supply of an unconstrained source of fat, namely palm oil.

The market effects described above assume that FFA from FAME bottoms are currently extracted from crude glycerol and used for feed or biofuel purposes. Even though the literature clearly describes how FFA are extracted from crude glycerol, the fate of the recovered material is usually not described. In spite of this, given that FFA have a substantial economic value, close to that of crude palm oil (MPOB 2023), it can be safe to assume that FFA from FAME bottoms is currently not treated as a waste, but as a valuable by-product.

Qualitative potential risk of iLUC accompanied by quantitative iLUC values

As explained above, there is a high risk that a change in demand for FAME bottoms will have a spillover effect in demand for virgin vegetable oils, particularly palm oil, which is associated with iLUC. As described in the section on UCO (section 3.1), the GHG emissions related to the production of palm oil and use for biofuel are 135 g CO_2e/MJ (Schmidt and De Rosa 2020). Hereof 13 g CO_2e/MJ are caused by iLUC.

Geographical dependency of the identified sustainability issues

The utilization of FFA from FAME bottoms raises similar sustainability concerns and associated geographical dependencies as with UCO.

Potential mitigating actions to achieve a sustainable use of FAME bottoms

The same arguments appear for the mitigating actions as above regarding the geographical dependency of the identified sustainability issues.

3.7 Brown grease

Brown grease can refer to that collected from wastewater treatment plants (WWTPs) and that obtained from grease traps installed in restaurants, event halls, etc. In this section only the latter is discussed, while grease from wastewater is discussed in section 3.8.

Brown grease is a mix of oils and fats which is not usually considered a suitable feedstock for biodiesel production, because of high water and free fatty acid content (Spiller et al. 2020). Several authors report that currently, brown grease is either landfilled or combusted (Kolet et al., 2020), however there is increasing interest on this material as biodiesel feedstock.

The extent of the presence of grease traps around the world is uncertain, especially in developing countries. This must be taken into account in the calculations for global availability of brown grease.

Plausible total global volumes available of brown grease

Data for brown grease is mainly available from US. Kolet et al. (2020) states that 1.7 million tonnes of brown grease are collected yearly, whereas Spiller et al. (2020) states instead around 1.5 million tonnes. Milbrandt et al. (2018) estimated brown grease availability in the US by means of population in 2010 and a generation factor of 6 kg/capita-year. This factor is from a survey in 30 metropolitan areas in the US, done in 1998. From the brown grease it is the fat, oil, and grease (FOG) content, which is possible to convert into biodiesel (Bashir et al. 2020).

Table 3.7 shows an estimate of produced brown grease on a global scale based on US data. By dividing the 6 kg brown grease/capita-year with the consumed vegetable oils per capita in this country, namely 40.3 kg (OECD-FAO 2024), the share of recoverable brown grease can be calculated. The share of FOG is 60% (Bashir et al. 2020). Furthermore, the share of vegetable oils used in the food service industry is estimated. By multiplying these with the global consumption of vegetable oils in 2021 a potential amount of brown grease is found. Data and calculations in **Table 3.7**.

Table 3.7. Potential brown grease availability from grease traps in the food service industry.

	Unit	Value	Data sources/comments
Input parameters			
Brown grease recovered per person in US (a)	kg/person	6.00	(Milbrandt et al. 2018)
Vegetable oil consumption per person in US (b)	kg/person	40.3	(OECD-FAO 2024)
Vegetable oil production, global (c)	Million tonnes	87.2	(FAOSTAT 2024a)
Recovery rate of FOG from brown grease (d)	%	60%	(Bashir et al. 2020)
Vegetable oil consumption in food service sector in US (e)	%	25%	Estimated
Calorific value (f)	MJ/kg	37	(Mehta and Krishnasamy 2009)
Calculated values			
Brown grease recovered per person in US (g)	%	15%	Calculated: (a) / (b)
Global brown grease production (h)	**Million tonnes**	**1.95**	**Calculated: (c)*(d)*(e)*(g)**
Global brown grease (i)	**EJ**	**0.072**	**Calculated: (h)*(f)/1000**
Brown grease potential relative to transport fuels	**%**	**0.06%**	**Calculated: (i) / 114 (from Table 2.1)**

The calculation above is highly uncertain, given that it is based on data from the US, which might not be a good representation of reality for the rest of the world, especially in developing countries. In any case, the result shows that the potential for brown grease as biodiesel feedstock is very small compared to the total energy demand for transport.

Competing industries for brown grease

The literature reports that collected brown grease is treated as waste (Kolet et al. 2020). However, there is an increasing demand for brown grease as feedstock for biodiesel from multiple sectors, thus it is assumed that in the long term this could become the marginal use. The counterfactual effect of increased demand for brown grease in the long term would be an increase in palm oil supply. The reason is that the supply of brown grease is constrained, as its supply is linked to food demand. Thus, a change in demand for brown grease will lead to less availability to other users, who will in turn resort to alternative feedstock, chiefly palm oil.

Qualitative potential risk of iLUC accompanied by quantitative iLUC values

As explained above, there is a high risk that a change in demand for animal fats will have a spillover effect in demand for virgin vegetable oils, particularly palm oil, which is associated with iLUC. As described in the section on UCO (section 3.1), the GHG emissions related to the production of palm oil and use for biofuel are 135 g CO_2e/MJ (Schmidt and De Rosa 2020). Hereof 13 g CO_2e/MJ are caused by iLUC.

Geographical dependency of the identified sustainability issues

The utilization of brown grease for biodiesel production raises similar sustainability concerns and associated geographical dependencies as with UCO.

Potential mitigating actions to achieve a sustainable use of brown grease

Generally, diverting brown grease from waste disposal can be seen as advantageous. However, in a hypothetical situation where brown grease is instead mainly used for biodiesel production, the same mitigation actions as for UCO and POME oil apply. To avoid the spillover effect on virgin vegetable oils it is necessary to ensure that all additionally demanded brown grease is obtained from additional brown grease collection. However, this approach is likely to incur in higher costs.

3.8 Sewage

In this report the potential availability of biodiesel feedstock from sewage is calculated from two sources. The first one considers the content of lipids in sewage sludge, the main solid residue obtained in wastewater treatment plants. The second one considers oil and grease directly recovered from wastewater during the water pre-treatment. The material from both sources is interesting for this analysis, as in both cases it consists of organic matter containing fats, oils, waxes, and related substances, which can be used for bio-fuel production (Bashir et al. 2020; Supaporn et al. 2019).

Plausible total global volumes available of oil and grease from sewage

According to Supaporn et al. (2019), 14.5% of the dry mass of sewage sludge consists of lipids, of which 82% (11.9% of the sludge mass) can be extracted and processed into biodiesel. The global production of raw sewage sludge from municipal wastewater treatment plants (WWTP) was in 2023 45 million tonne expressed as dry mass (Ferrentino et al, 2023). The potential of sewage sludge as feedstock for biofuels is shown in **Table 3.8**.

Table 3.8. Potential availability of oil and fat in sewage sludge.

Parameters	Unit	Value	Data sources/comments
Input parameters			
Global sewage sludge production from WWTP (a)	Million tonne DM	45.0	(Ferrentino et al. 2023)
Recovery efficiency of lipid from raw sewage sludge (b)	%	11.9	(Supaporn et al. 2019)
Calorific value of lipids (c)	MJ/kg	37	(Mehta and Krishnasamy 2009)
Calculated values			
Global oil and fat available from sewage sludge (e)	**Million tonne DM**	**5.36**	**Calculated: (a)*(b)**
Global oil and fat available from sewage sludge (f)	**EJ**	**0.20**	**Calculated: (c)*(e)/1000**
Sewage lipids potential relative to transport fuels	**%**	**0.17%**	**Calculated: (f) / 114 (from Table 2.1)**

As previously mentioned, besides sewage sludge, untreated sewage is also a source of oil and fat. This material is typically collected in WWTP during the pre-treatment stage. According to FAOSTAT (2024a) 213 billion m^3 wastewater (WW) were treated globally in 2020. The content in oil and fat in municipal wastewater ranges from 50 to 150 mg/L wastewater (Metcalf & Eddy et al. 2013). An average value of 100 mg/L is considered in our calculations, shown in **Table 3.9**.

Table 3.9. Potential availability of oil and fat from sewage.

Parameters	Unit	Value	Data sources/comments
Inputs: parameters			
Global production of sewage (a)	Giga tonne	213	(FAOSTAT 2024a)
Oil and fat content in sewage (b)	kg / kg WW	0.0001	(Metcalf & Eddy et al., 2013)
Recovery efficiency of oil and fat (c)	%	60%	(Bashir et al. 2020)
Calorific value of oil and fat (d)	MJ/kg	37	(Mehta and Krishnasamy 2009)
Calculated values			
Global oil and fat available from sewage (e)	**Million tonnes**	**12.8**	**Calculated: (a)*(b)*(c)*1000**
Global oil and fat available from sewage (f)	**EJ**	**0.47**	**Calculated: (d)*(e)/1000**
Brown grease from WW potential relative to transport fuels	**%**	**0.41%**	**Calculated: (f) / 114 (from Table 2.1)**

Our estimate results in a potential availability of 0.20 EJ and 0.47 EJ biodiesel produced from oil and fats from sewage sludge and sewage respectively shows a negligible amount compared to the global use of transport fuels as displayed in **Table 2.1**.

Competing industries for sewage

Sewage sludge can be dewatered and sent for disposal, although in developed countries it is common to apply anaerobic digestion to stabilize the material and recover energy in the form of biogas. It is assumed that, in plants applying anaerobic digestion, oils and fats would be extracted before this process, as otherwise such oils and fats would be substantially lost during digestion. Under these circumstances, extraction of oils and fats would come at the cost of a reduction in biogas energy production, making the feedstock less attractive from an environmental perspective.

Regarding final disposal in the absence of anaerobic digestion, according to Haghighat et al. (2020) sewage sludge is mainly disposed of in three ways: incineration, landfilling and agricultural use. Incineration of sewage sludge releases dioxins, NO_x, SO_2, and heavy metals into the air, contributing to various air pollutants. Furthermore, the ash must be disposed of, and the incineration process requires high amounts of energy (Kowalski et al. 2024). Landfilling of sludge from municipal wastewater is decreasing in the EU due to more stringent legislation but is still widely applied in other regions of the world. Regarding the agricultural sector, Kowalski et al. (2024) argues that 23% of the sewage sludge produced in the EU in 2014-15 was used in this sector. The sludge has significant levels of nitrogen, phosphorus, and organic matter, which improve soil quality. Because of these advantages, some countries in the EU like Ireland and Bulgaria use sewage sludge as fertilizer, although in other countries this use is banned due to concerns related to the presence of pollutants in sludge, such as heavy metals.

Regarding oil and fat recovered directly from sewage, this is a waste stream typically sent to disposal. Globally, landfilling is likely to be the most prevalent option, although incineration with energy recovery might be more relevant in certain developed countries. Therefore, diverting this material as a feedstock for biofuels can be seen as advantageous especially when landfilling is concerned. In the long-term, if all oil and fat is recovered from sewage sludge, this supply can be constrained, and the effect of changing the demand of it will spillover into virgin vegetable oils.

Qualitative potential risk of iLUC accompanied by quantitative iLUC values

Oil and fat obtained from either sewage or sewage sludge is disposed of as waste and therefore there are no immediate iLUC risks associated with the use of these materials as feedstocks. However, waste disposal can be associated with some beneficial aspects, namely the recovery of energy (in some controlled landfills, in incineration plants) and nutrients (when sludge is used as fertilizer), which are no longer possible if the feedstock is diverted to biodiesel production.

Even though that the immediate risks of iLUC are assessed a low above, there still is a risk for triggering iLUC. There might be situations, where the suppliers of oils and fats from sewage sludge do not adjust their production volume when demand for oils and fats from the sludge changes. This is if there are more competitive treatment of the sludge. In this case a change in demand for the sludge oil could be achieved by another user shifting to another feedstock with iLUC.

Geographical dependency of the identified sustainability issues

The environmental effects of diverting oils and fats from sewage and/or from sewage sludge are related to the fact that these waste streams can be disposed of differently in different parts of the world. In general, though, the diversion of these materials from landfills, incineration plants, etc., can be seen as advantageous.

Potential mitigating actions to achieve a sustainable use of sewage

Given that sewage and waste streams thereof are sent for disposal, their diversion for use as biodiesel feedstock can be seen in general as advantageous for the environment and no particular mitigation actions are needed.

However, as mentioned in the section describing the risk of iLUC, there could be situations, where suppliers of sewage sludge oils do not adjust their production volumes when there are changes in demand. Therefore, it is advisable to check with the suppliers that they can and will increase their production volume both in the short term (capacity utilization) as well as, and more importantly, in the long term (installing new capacity).

3.9 Food waste

Roughly one third of food produced for human consumption has been estimated to be lost or wasted globally (FAO 2011). This refers to losses or wastage throughout the entire supply chain, from initial agricultural production down to final household consumption. In the literature, a distinction is made between ‘food losses’ and ‘food waste’ (Parfitt et al. 2010), where the former include losses during agricultural production, postharvest and processing stages in the food supply chain, while losses occurring at the end of the food chain, namely at retail, food service and households, are referred to as food waste. This report focuses on food waste only, as losses of fat-containing materials in other parts of the supply chain are covered in previous sections.

Food waste is constituted, according to UNEP (2021), by the edible and non-edible food parts destined for disposal (landfill, incineration, composting, etc.). While food waste cannot be directly used as a feedstock for biodiesel, it is possible to indirectly use it through production of volatile fatty acids (VFA), which can in turn be converted to lipids, the conventional feedstock for biodiesel production (Park et al. 2014; Vajpeyi and Chandran 2015). Conversion of food waste to VFA (a mixture of, among others, acetic, propionic, butyric and valeric acids) can be carried out via anaerobic digestion (Law et al. 2023; Carvalheira and Duque 2021), while lipid production can be carried out via fermentation utilizing bacteria, yeasts, or microalgae (Park et al. 2014).

Plausible total global volumes available of food waste

Two main studies have attempted to estimate global production of food waste. FAO (2011) published an estimate in 2011, quantifying food losses and food waste at 1.3 billion tonnes per year. This figure, however, includes food losses, which are not in scope for this analysis. Instead, the estimate published by UNEP (2021) in their Food Waste Index Report, quantifying food waste globally at 931 million tonnes per year. 61% of this originates in households, 26% from food service and 13% from retail.

The potential for this feedstock in terms of its conversion to lipids, the relevant feedstock for biodiesel, can be estimated based on the volatile solids (VS) content in food waste, the VFA yield and recovery rate from anaerobic digestion of food waste, and the yields of converting VFA to lipids and lipids to biodiesel. The calculation is shown in the following table.

Table 3.10. The annual potential of food waste.

Parameter	Unit	Value	Data sources/comments
Input parameters			
Global food waste production (a)	Million tonnes	931	UNEP (2021)
Volatile solids in food waste (b)	Tonne VS/tonne wet mass	0.21	Selvam et al. (2021)
Volatile fatty acids yield (c)	Tonne VFA/tonne VS	0.5	Park et al. (2014)
Volatile fatty acids recovery rate (d)	%	90	Atasoy et al. (2018)
Lipid yield (e)	Tonne/tonne VFA	0.19	Fei et al. (2015)
Biodiesel yield from lipids (f)	Tonne biodiesel/tonne lipid	0.98	Assumed
Calorific value of biodiesel (g)	GJ/tonne	37	Mehta and Krishnasamy (2009)
Calculated value			
Global lipid available from food waste (h)	**Million tonnes**	**16.5**	**Calculated: a*b*c*d *e**
Global biodiesel available from food waste (i)	**Million tonnes**	**16.2**	**Calculated: h*f**
Global biodiesel available from food waste (j)	**EJ**	**0.6**	**Calculated: (i*g)/1000**
Biodiesel potential relative to transport fuels	**%**	**0.5%**	**Calculated: j / 114 (from Table 2.1)**

This calculation shows a potential to produce 16.5 million tonnes of lipids per year, equaling 0.6 EJ in biodiesel. This is the same amount of energy as delivered by palm-oil derived biodiesel in 2021 (see Table 2.1). While this is a potentially relevant contribution, it must be borne in mind that it is based on the (highly unrealistic) assumption that all food waste in the world is converted to lipids. While this conversion is based on well-established technologies (anaerobic digestion, fermentation), it seems this lipid production route itself is not applied at a large scale, but rather tested and discussed experimentally in research papers, as those cited in this analysis. Furthermore, it must be borne in mind that waste, by definition, is a constrained feedstock, meaning that an increase in demand will not result in increased supply. The resulting effect will instead be the diversion of food waste from their current disposal methods, which vary from country to country (see next paragraph).

Competing industries for food waste

As mentioned in the previous paragraph, food waste is a constrained feedstock. An increase in demand by any actor in the economy will not result in more food waste being produced. The main food waste production driver is population which, on the one hand, is expected to keep growing globally in the next decades. On the other hand, efforts are currently aimed at reducing as much as possible food waste, as it represents a waste of resources in a world with a growing population. Thus, while more food waste might be available as feedstock in the future, the most likely outcome as a result of increased demand would be its diversion from its current disposal. Food waste disposal typically includes any of the following:

- Landfilling, both controlled and uncontrolled
- Combustion with or without energy recovery
- Sewer disposal
- Anaerobic digestion
- Composting

These constitute the competing uses for food waste. In general, waste disposal is a source of environmental impacts and as such, reducing it by diverting food waste to more valuable uses can lead to environmentally positive effects. The clearest case would be diverting food waste from landfilling, a major source of methane emissions. However, often waste disposal also provides useful secondary products, such as biogas and steam to produce electricity and heat, or soil nutrients as compost. In this way, food waste diversion from these treatments will incur in the loss of these secondary products and in the need to compensate this loss by producing more electricity, heat and nutrients using new resources.

Qualitative potential risk of iLUC accompanied by quantitative iLUC values

The risk of causing iLUC as a result of demanding food waste as feedstock to produce lipids is low. This is the case as the affected competing industries (waste disposal) are not relevant contributors to iLUC.

Even though that the immediate risks of iLUC are assessed a low above, there still is a risk for triggering iLUC. There might be situations, where the suppliers of oils and fats from food waste do not adjust their production volume when demand for oils and fats from the sludge changes. This is if there are more competitive treatment of the waste, and that the suppliers are financed e.g. via subsidies which are not proportional to demand. In this case a change in demand for the food waste oil could be achieved by another user shifting to another feedstock, particularly palm oil, which is associated with iLUC. As described in the section on UCO (section 3.1), the GHG emissions related to the production of palm oil and use for biofuel are 135 g CO_2e/MJ (Schmidt and De Rosa 2020). Hereof 13 g CO_2e/MJ are caused by iLUC.

Geographical dependency of the identified sustainability issues

Disposal of waste, including food waste, is managed at a local level. Therefore, the environmental effects of diverting food waste from disposal will be different from one place to another. As an example, diverting food waste from a location where waste is simply landfilled will have different environmental implications than in a location where food waste is sent for anaerobic digestion or composting. While landfilling is always better avoided, anaerobic digestion still provides some value in the form of energy and nutrients.

Potential mitigating actions to achieve a sustainable use of food waste

While in general diverting food waste from disposal can be seen as the right thing to do, it has been shown in the previous paragraph that it is not the same to e.g. avoid landfilling than to avoid anaerobic digestion. Efforts should be made by the party demanding oil from food waste to promote the diversion of food waste in countries where waste management consists mainly of landfilling, as this will reduce the waste disposal option with the highest environmental impact. Landfilling of food is progressively diminishing in the EU and most developed countries, thanks to more stringent waste legislation, which means the priority to maximize environmental benefits would be to focus on food waste originating in developing countries.

The section describing the risk of iLUC, there could be situations, where suppliers of food waste oils do not adjust their production volumes when there are changes in demand. Therefore, it is advisable to check with the suppliers that they can and will increase their production volume both in the short term (capacity utilization) as well as, and more importantly, in the long term (installing new capacity).

4 Conclusion

The primary objective of this report is to evaluate the sustainability of various fatty waste oils as feedstocks for biofuel production. Ten different feedstocks are investigated, including Used Cooking Oil (UCO), Palm Oil Mill Effluent (POME) oil, Spent Bleach Earth (SBE) oil, soap stock acid oils, animal fats, Fatty Acid Methyl Ester (FAME) bottoms, brown grease, sewage, and food waste. The analysis focuses on several key aspects: overall sustainability concerns, plausible global volumes, competing industries, potential risks of indirect land use change (iLUC), geographical dependencies, and potential mitigating actions.

Special attention has been given to assessing whether the feedstocks are constrained, i.e. if a change in demand for the feedstock will not result in a corresponding additional amount being available on the market. This is highly relevant when evaluating the sustainability of waste-based feedstocks. This is because such feedstocks are categorised as burden-free in many GHG standards, while the actual consequence of demanding a constrained feedstock may cause shifts in markets which result in increased demand for crops and virgin oils and fats, which cause high risks of indirect land use changes.

The results of the assessment indicate that almost all the assessed feedstocks are constrained or are likely to be constrained in the near future. For instance, demand for UCO and POME oil is high, while supply is constrained, leading to shifts in markets resulting in increased demand for crops and virgin oils and fats and high iLUC risks. However, some feedstocks, like sewage and food waste, which are currently disposed of as waste, present opportunities for increased utilization with relatively low iLUC risks in the short term.

Overall, the findings underscore that when demanding fatty waste oils for biofuel production, this is often associated with indirect effects causing potential high iLUC risks and GHG emissions. Therefore, claims on the sustainability of the use of fatty waste oils need to address such indirect effects. To mitigate the indirect effects, it is important to ensure that an additional demand for fatty waste oils is associated with a corresponding additional recovery/collection. By doing so, the environmental benefits of using fatty waste oils for biofuel production can be maximized while minimizing associated risks.

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