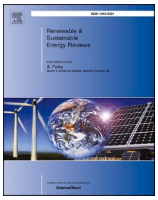
Renewable and Sustainable Energy Reviews 170 (2022) 112945

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Uncertainty in life cycle greenhouse gas emissions of sustainable aviation fuels from vegetable oils

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ARTICLE INFO

Keywords:
Sustainable aviation fuel
Life cycle assessment
Greenhouse gas emissions reductions
Land use change
Biofuels
Vegetable oils

ABSTRACT

Sustainable aviation fuel (SAF) is one of the most promising short-to medium-term term options to mitigate greenhouse gas (GHG) emissions from aviation. Life cycle assessment (LCA) is commonly used to estimate GHG emissions from SAF in comparison to fossil kerosene. While there are several studies reporting the GHG emissions from SAF, uncertainty in the results is not always addressed in a comprehensive way.

In this work, GHG emissions of hydroprocessed esters and fatty acids (HEFA) fuels derived from jatropha (*Jatropha curcas*), pennycress (*Thlaspi arvense*), castor (*Ricinus communis*), energy tobacco (*Nicotiana tabacum, Solaris*) and Salicornia (*Salicornia* bigelovii) oils were estimated. A stochastic methodology was employed where parametric uncertainty was propagated using Monte Carlo simulations. Uncertainty due to methodological choices was incorporated through scenario analyses. Emissions from direct land use change (DLUC) and the associated uncertainty were assessed under the IPCC Tier 1 approach by considering alternative land use transitions per feedstock.

Analyzed HEFA pathways provide GHG emissions benefits (34–65%) in comparison to fossil kerosene when DLUC emissions are not considered. Parametric uncertainty yields up to 26% deviation from the median well-to-wake GHG emissions. Changing the allocation choice for the oil extraction step, from the base assumption of energy-based allocation to mass- or market-based, can impact the results by up to 46%. DLUC is a more significant source of uncertainty than both parametric uncertainty and allocation assumptions in the analysis. DLUC emissions negate any GHG savings from HEFA fuels if forests or natural shrublands are lost.

1. Introduction

The aviation industry is a major contributor to the global economy with an economic impact of €3.5 trillion per year (pre-COVID-19) [1]. While the COVID-19 pandemic has led to a significant decrease in aviation activity [2], it is generally expected that the sector will not only rebound, but that traffic will increase beyond pre-COVID-19 levels in the medium-term. With regard to long-term traffic development, COVID-19-adjusted forecasts now predict that aviation traffic will grow between 2.3 and 3.3% per annum between 2019 and 2050 [3].

In 2019 the aviation sector accounted for approximately 2.4% of total anthropogenic CO_2 emissions [4]. When other emissions species, such as different nitrogen oxides (NO_x), particles and water vapor, were included, the total climate impact reached approximately 3.5% of total anthropogenic radiative forcing (RF) [4]. In the absence of any commercially available alternatives to current-technology aircraft, such as solar or electric aircrafts, international aviation is bound to be mostly dependent on liquid hydrocarbons by 2050.

In 2013, International Civil Aviation Organization (ICAO) declared its decarbonization goal, which requires the aviation sector to offset carbon dioxide emissions in excess of the 2020 levels [5]. To achieve this decarbonization goal, ICAO Member States have agreed to develop the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), and the Committee on Aviation Environmental Protection (CAEP) within ICAO has developed specific measures [6]. In October 2021, the International Air Transport Association (IATA) member airlines pledged to achieve net-zero carbon emissions from their operations by 2050 [7]. To achieve this ambitious goal, a combination of measures is necessary. The use of sustainable aviation fuels (SAF) as "drop-in

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https://doi.org/10.1016/j.rser.2022.112945
Received 17 May 2022; Received in revised form 14 August 2022; Accepted 16 September 2022

Abbreviations

ABG	Above-ground biomass
ASTM	American Society for Testing and Materials
BGB	Below-ground biomass
CAEP	Committee on Aviation Environmental Protection
CO_2e	Carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DLUC	Direct land use change
FFA	Free fatty acids
GHG	Greenhouse gas
GMO	Genetically modified organism
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
HEFA	Hydroprocessed esters and fatty acids
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ILUC	Indirect land use change
IPCC	Intergovernmental Panel for Climate Change
JRC	European Commission Joint Research Center
LCA	Life cycle assessment
LCI	Life cycle inventory
LUC	Land use change
RED	Renewable Energy Directive
SAF	Sustainable aviation fuel
SOC	Soil organic carbon
SMR	Steam methane reforming
WTWa	Well-to-wake

fuels" is considered the most promising option to reduce greenhouse gas (GHG) emissions and mitigate climate change. The potential of SAF to provide significant GHG emission reductions has been widely reported in the literature [8,9], and it is the only measure that may deliver large-scale emissions reduction in the medium-term. Research is underway to find more efficient and cost-effective technologies to produce SAF, since there is a large price gap between petroleum-based jet fuel and SAF. Given that fuel costs constitute around 20% of an airline's operating cost [10], there is also a clear need for policy support to make SAF price competitive. Although global production of SAFs is increasing, the current share of SAFs for aviation is still very small (<0.1%) [11].

The largest share of commercial SAFs produced today comes from the hydroprocessing of triglyceride fatty acids from lipid feedstocks, also known as *hydroprocessed esters and fatty acids* (HEFA) [12]. The HEFA process produces paraffin-rich hydrocarbon liquids from the triglyceride molecules in the lipid feedstocks such as vegetable oils, waste oils and algal oils. Over the years, successful flight trials have been carried out by major airlines using HEFA fuels from jatropha, camelina, used cooking oil, and others [13]. HEFA fuels are certified by the American Society for Testing and Materials (ASTM) to be blended with petroleum-based jet fuel up to 50% by volume [14]. HEFA fuels may help achieve the goal of net-zero by 2050, since the amount of SAF production is projected to increase from 0.05 million tonnes today to 445 billion tonnes in 2050 [3].

The conversion of biomass or waste products into aviation biofuel requires the use of energy and chemicals, which are often of fossil origin [15,16]. In addition, emissions from agricultural production of biomass due to the on-site emissions from fertilizer application and from fuel combustion in farming operations can reduce the GHG advantages of biofuels over fossil fuels [17–19]. Life cycle assessment (LCA) has been used to estimate the potential environmental benefits from the use of SAF [20–22]. There are two different methodological options for performing an LCA: attributional and consequential LCA [23,24]. Attributional LCA (ALCA) accounts for the energy and material flows throughout the life cycle of a product within precisely defined systems boundaries. This method relies on detailed GHG emission inventories that are useful for benchmarking different feedstocks properties and conversion technologies, and for comparing the emission intensities of biofuels with those of petroleum-based fuels. Additionally, the production cycle of biofuels is affected by external events such as GHG mitigation policies, increase in demand for certain feedstocks, fuel prices, and land use change (LUC). Consequential LCA (CLCA) relies on economic models to estimate the effect of these potential changes on the biofuel production chain, by trying to capture the market-mediated adjustments of the system as a consequence of an increased (decreased) demand for the product [25,26].

The results from a well-to-wake (WTWa) ALCA of GHG emissions from SAF can be compared with fossil kerosene to determine the emissions savings [27–31]. Although studies have been conducted on the environmental performance of SAF, there is heterogeneity in the methods and variability in the results from the literature with regard to the life cycle GHG emissions of the different pathways available [32]. Consequently, efforts have been made recently to estimate life cycle GHG emission values for SAF pathways using a robust methodology, with a particular focus on those conversion technologies that have received ASTM approval. ICAO and other organizations are discussing the best way to standardize the LCA methodology for the accounting of GHG emission savings associated with the most readily available SAFs [8,20].

The technologies that are assessed for SAF production have not yet been fully commercialized. The data is mostly limited and proprietary. As a result, LCA outcomes are subject to *epistemic uncertainty*, which refers to the lack of knowledge of the process being modeled, or the lack of evidence on the accuracy of the models in representing such processes [33,34]. Furthermore, there is *decision uncertainty* or *uncertainty due to choices* derived from the selection and application of a specific methodology [35,36]. While there are a number of LCA studies in the literature about hydroprocessing of oilseed crops [30,37–47], most are deterministic studies. The results from these studies show that GHG emissions are highly impacted by methodological choices such as the selection of co-product use, and allocation method [41–43], as well as uncertainty in the life cycle inventory (LCI) data [41]. The uncertainty due to choices is often tackled through scenario analysis; that is, by defining different scenarios to capture different possibilities of the choices made [48–50]. To assess parametric uncertainty, two approaches are commonly applied: (a) sensitivity analysis, to understand how uncertainty in one or more input parameters leads to uncertainty in the output variables; and (b) uncertainty analysis, to propagate and quantify results uncertainty based on stochastic techniques. For instance, Stratton et al. (2010) tried to capture the variability due to choices by examining multiple scenarios, and conducting local (one-at-a-time) sensitivity analysis by changing selected representative parameters [41]. However, the combined effects of simultaneous changes from the input parameters have been ignored, which could lead to poor reflection of uncertainty in the results. Moreover, changing the parameters by a pre-determined magnitude (for example, ±10%) may not reflect the variability of that parameter, and it might be more advantageous to use probability distributions [51]. Stochastic analysis has previously been shown to be a method for propagating and quantifying results uncertainty for techno-economic analysis (TEA) [52–54]. Monte Carlo simulation has been used in some cases, which makes it possible to obtain a probability distribution of the results by randomly selecting values from previously defined probability distribution for each parameter to conduct a detailed uncertainty assessment for LCA of biofuels [35,51,55,56]. For instance, Mousavi-Avval et al. (2021) estimated the environmental impact of pennycress-based HEFA jet fuel using Monte Carlo simulation to evaluate the uncertainty [39].

Finally, like many other bio-based products, SAFs may generate additional impacts from LUC. This refers to GHG emissions from land conversion and associated carbon losses to grow biofuel feedstock; that is, direct LUC (DLUC) [57,58]. Further market-mediated land transformation can take place due to the increased demand for agricultural products for non-food applications; that is, indirect LUC (ILUC) [59–62]. Estimation of LUC effects entails additional methodological challenges. DLUC accounting is often included within the biofuel's life cycle based on the Intergovernmental Panel on Climate Change (IPCC) guidelines [63], as differences in carbon stocks relative to original land uses, depending on the location of the production site [64–66]. ILUC estimation requires the application of economic modeling under CLCA approaches to be able to predict supply and demand responses across bio-based markets, or across the entire economy, depending on the scope of each model [67–69]. CORSIA provides estimates for ILUC factors of major feedstocks based on two well-regarded global economic equilibrium models [8], to be combined with the so-called core-LCA values [70]. GHG emissions from DLUC must also be quantified when feedstock production causes on-site land conversion after January 1, 2008. DLUC quantification must follow the Tier 1 approach of IPCC [63], but a more specific protocol is still under development. Hence, DLUC remains a source of uncertainty when assessing the GHG savings from SAF production pathways, as DLUC effects are largely influenced by assumptions on feedstock yields, agricultural practices, and land uses to be potentially displaced, which in turn depend on the sourcing region [71–73].

This article quantifies the viability of using HEFA fuels from selected non-edible vegetable oils in terms of lifecycle GHG emissions using a stochastic methodology. A comprehensive uncertainty analysis is carried out to provide a range of GHG emissions considering parametric uncertainty in LCI data and uncertainty in modeling choices. Assumptions on the land uses to be converted for HEFA feedstocks cultivation and underlying carbon stocks are also included. Emissions from DLUC and the associated uncertainty are estimated by including a consistent scenario analysis across different feedstocks. No peer-reviewed LCA studies for GHG emissions from energy tobacco-HEFA jet fuel have been found in the literature, and our work is a first example of this pathway.

2. Methodology

2.1. Goal and scope

In this work, attributional LCA is applied to examine the GHG emission intensity of alternative pathways for aviation biofuel production based on the hydroprocessing of lipids, from cradle-to-grave or WTWa. In addition to the emissions from the SAF production processes, DLUC emissions prior to feedstock cultivation are also included.

The functional unit (FU) used is 1 megajoule (MJ) of SAF produced and combusted and the results are reported as grams of carbon dioxide (CO_2) equivalent of emissions per FU (gCO_2e/MJ jet fuel). CO_2, methane (CH_4) and nitrous oxide (N_2O) emissions from well-to-pump activities are considered using their 100-year global warming potentials (1, 28, 265, respectively), in line with the IPCC reporting guidelines [74].

LCA is fundamentally a comparative tool and fuel from conventional crude is a benchmark for alternative fuels. The choice of baseline is important because it determines the relative benefit of using a particular biofuel product with respect to its fossil counterpart. Within CORSIA, the adopted baseline for WTWa emissions from conventional jet fuel production is 89.0 gCO_2e/MJ jet [20]. This value was agreed on after considering a variety of refinery configurations worldwide for the production of fossil jet fuel, and used for this work.

With regard to scope, the system boundary includes the emissions from the complete fuel cycle of the SAF. This means that all the direct and indirect energy and material inputs from feedstock cultivation and transportation, oil extraction and processing, HEFA conversion, fuel transportation and distribution (T&D), and fuel combustion stages are included. Fig. 1 depicts the system boundary considered for the HEFA fuel production from oilseed feedstocks in detail. At the end of the oil extraction step, oilseed meal is produced as a co-product. This meal can be high in protein content, with potential to be used as animal feed, depending on the feedstock. The HEFA conversion step produces other fuels such as diesel, naphtha, and propane mix, in addition to jet fuel.

The emissions from the initial establishment of infrastructure (construction of the fuel production facility, manufacturing of equipment, etc.) are not included in this analysis since their contribution to overall emissions is found to be negligible [75]. Emissions from DLUC are incorporated, assuming that land conversion takes place after 2008, which requires consideration in line with CORSIA. The CO_2 absorbed during biomass growth is assumed to offset the CO_2 emissions from fuel combustion.

2.2. Feedstock scope

Historically, the large majority of the biofuels produced/used in the European Union (EU) have been produced from biobased feedstocks such as rapeseed, soy, and palm oils [76]. However, these feedstocks are also used for food purposes, fueling the food vs. fuel debate [77]. In addition, production of palm oil takes place in tropical regions with deforestation [78], which causes environmental concerns. As a result, EU policies evolved to promote the use of sustainable sources as feedstock [79]. This helped to the development of additional supply chains, and nowadays the cheapest feedstocks for HEFA fuels are used cooking oil (UCO) and waste oils such as tallow [9,46]. Still, their supply might be limited since these feedstocks are also used by the road sector for biodiesel production [80]. Non-edible vegetable oils might be more sustainable than traditional edible oils due to the possibility of cultivation on marginal land with lower inputs such as fertilizer and water [81].

For this work, five oil sources were selected for an in-depth LCA study: jatropha (*Jatropha curcas*), pennycress (*Thlaspi arvense*), castor (*Ricinus communis*), Solaris energy tobacco (*Nicotiana tabacum* L. *cv. Solaris*), and salicornia (*Salicornia* bigelovii). Plant oils from these feedstocks are non-edible and seed oil content ranges from 28 to 47% (Table 1 and references therein). Average yields, co-products from the oil extraction process and their assumed uses have been listed in Table 1. Conservative yield assumptions have been used for the analyzed crops. Oilseed feedstocks that already have LCA values within CORSIA have also been included for comparison purposes.

Jatropha-based HEFA fuel was one of the first SAFs to be used for flight tests [87]. The prospect of high oil yield, along with the capability of the plant to grow on marginal lands with low input, made jatropha appealing as a biodiesel feedstock in the early 2000s [88]. The oil extraction step from jatropha produces husk and shell in addition to the meal. The meal from jatropha is toxic and it cannot be utilized as fodder unless it is detoxified [89] However, there are studies showing its potential use as fertilizer [90–93]. Husk and shell could be used for energy production through combustion [37] or anaerobic digestion [93]. Several studies have examined GHG emissions from jatropha-based diesel and jet fuel [30,37,44,73,93,94]. Stratton et al. (2010) reported a range of emissions from 31.8 gCO_2e/MJ to 45.1 gCO_2e/MJ from jatropha-HEFA jet [37]. A scenario-based deterministic approach was used to account for the variability, but LUC was not included. Meal, husk, and shell were considered as co-products from the oil extraction step, and they were assumed to be used for energy production through combustion. Bailis et al. (2010) estimated the emissions from jatropha-HEFA jet to be 40 gCO_2e/MJ in Brazil, using energy-based allocation for the baseline case [73]. Seed cake and husk were considered as co-products from the oil extraction step. Aggregate results including DLUC ranged from 13 gCO_2e/MJ to 141 gCO_2e/MJ,

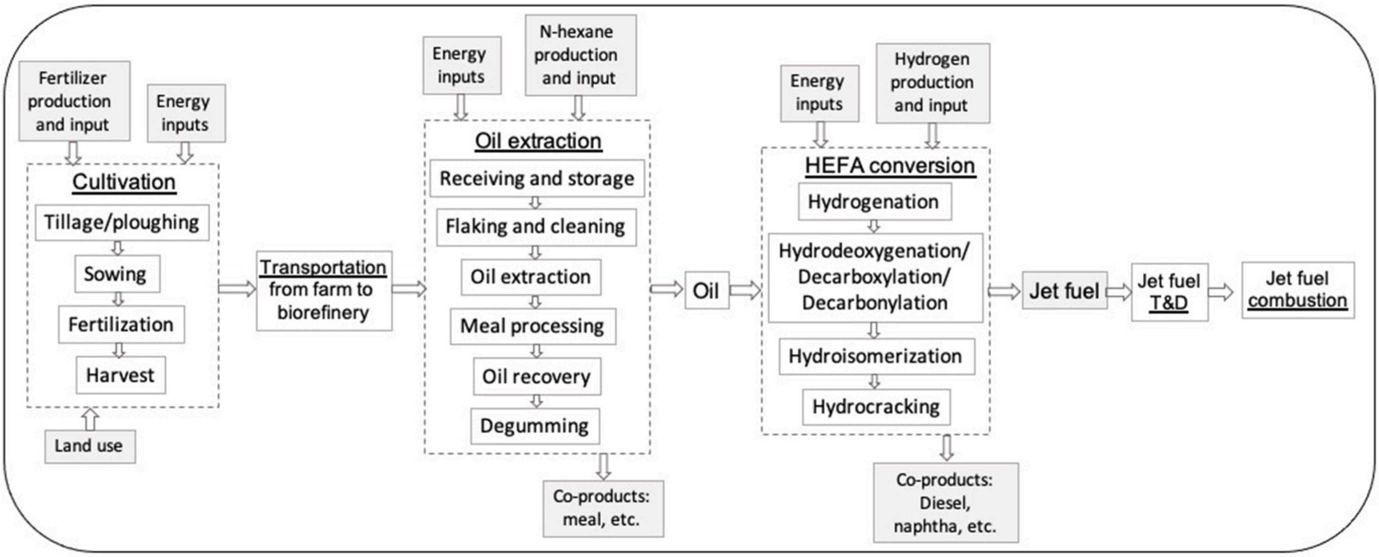

Fig. 1. Details of the system boundary for the HEFA-jet fuel pathway from oilseed feedstocks, HEFA: Hydroprocessed esters and fatty acids, T&D: Transportation and distribution.

Table 1
Properties and geographical distributions of various vegetable oils.

Feedstock	Distribution	Yield (t/ha-yr)	Oil content (wt%)	Oil extraction co-products/use	References
Camelina	N. America, EU	1.9	36.0	Meal/fodder	[82]
Castor	India, Brazil, China	1.1	47.0	Meal/fertilizer	[83]
Jatropha	Asia, Africa, S. America	2.5	35.0	Meal/fertilizer, husk/energy, shell/energy	[37]
Palm	Malaysia, Indonesia	17.9	22.4	Meal/fodder	[84]
Pennycress	Eurasia, N. America	1.0	34.0	Meal/fodder	[85]
Rapeseed	EU	3.4	44.0	Meal/fodder	[84]
Salicornia	Africa, Middle East, S. America, China, US	2.0	28.2	Meal/fodder, straw/energy	[37]
Soybean	N. America, Brazil	3.2	19.1	Meal/fodder	[84]
Energy Tobacco	China, Brazil, India, US, Greece	2.1	38.0	Meal/fodder	[86]

depending on land type used for the cultivation of jatropha. Han et al. (2013) estimated the emissions from jatropha HEFA to be 54 gCO_2e/MJ using similar co-product assumptions as in Stratton et al. (2010), and without the inclusion of LUC [30]. Finally, Liu et al. (2021) estimated the GHG emissions from jatropha to be between 32 and 107 gCO_2e/MJ in north-east China, depending on different planting conditions [95]. Energy-based allocation was used to distribute the emissions between oily cake and oil.

Pennycress can be cultivated as a winter crop in rotation with conventional summer crops such as sunflower, soybean, and corn. It has the potential to be used as feedstock for biofuels with a low impact on the food supply or land use [96,97]. The oil extraction step for pennycress yields a meal that is rich in protein content (31%) [45]. However, the meal contains high levels of glycosinolates and erucic acid, which might prevent its use as fodder [98]. Fan et al. (2013) deterministically estimated the emissions from HEFA jet fuel to be 32.7 gCO_2e/MJ jet fuel [45]. In this study, pennycress meal was assumed to be used as animal feed due to its high protein content. As a result, the emissions were allocated between the oil and the meal according to their energy content. Mousavi et al. (2021) used a stochastic method and found the emissions from pennycress to be in the range of 35–49 gCO_2e/MJ of fuel [39]. Pennycress meal was assumed to be combusted to supply on-site energy, and not considered for use as animal feed. Neither of these studies considered the land use change effects from pennycress cultivation.

Castor is originally a tropical season perennial plant that can also grow in temperate climates as an annual crop [99]. The seeds have high oil content (up to 50 wt %), more than twice as much as soybean; as a result, the oil yield from castor can be as high as 2 t/ha-yr [100]. Castor oil is the only commercial source of ricinoleic acid, which is a hydroxylated 18-carbon fatty acid used for various chemical products such as lubricants, paints, cosmetics, and shampoo. Meal from the oil extraction step for castor is toxic and cannot be used as fodder without detoxification [99]. There are reports on its potential use as fish feed [101], fertilizer [102], an absorbent for removal of textile dyes [103], in addition to other possibilities [83]. There have been experimental studies on the hydroprocessing of castor oil to produce jet fuel [104,105], and multiple references on castor-based biodiesel including the GHG emissions associated with its production [106–109]. Only recently, life cycle GHG emissions from castor-HEFA production in north-east China was reported to range between 41 and 78 gCO_2e/MJ SAF depending on different planting conditions [95].

Tobacco is a widely cultivated plant throughout the world, with its leaves used for the production of smoking products. Asian countries, especially China, account for more than half of its worldwide production, while in the EU Greece is a big producer that exports most of its production [84]. As the demand for tobacco production declines, the producers look for other alternatives to utilize tobacco [110]. Tobacco seeds are considered a by-product of the tobacco leaf production and they are mostly left in the field unused [111]. These seeds have a moderate oil yield, which can be used for biofuel production [112]. Recently, a nicotine-free version of the tobacco plant non-genetically modified organism (GMO) was developed to be used as biomass feedstock [113]. Energy tobacco (also known as Solaris), unlike the tobacco used for smoking, contains no nicotine in the leaves and maximizes the production of flowers/seeds, reducing leaf growth [114]. The meal from the oil extraction step can be used as animal feed with its high crude protein content (33%) [115]. There have only been a few publications on the properties of energy tobacco [86,111,114] and Solaris-based biodiesel formation [116], including an LCA study on GHG emissions from Solaris-based biodiesel [117]. To the best of our knowledge, there have been no peer-reviewed articles on GHG emissions from Solaris-HEFA jet fuel, although there are reports claiming the emissions benefits from Solaris-based SAF can reach 83% [113,118].

Salicornia is a member of the halophyte family, which is known for its ability to grow in brackish water on marginal lands [119]. The amount of seed oil produced from salicornia is small compared to the straw biomass of the plant [37]. On the other hand, salicornia straw can be gasified and converted into other energy products via Fischer Tropsch (FT) synthesis, pyrolysis, etc. [120]. Stratton et al. (2010) reported the emissions from Salicornia-HEFA considering different scenarios to account for the variability [37]. Salicornia meal was assumed to be used as meal, whereas straw was used for the production of FT fuels. The emissions ranged between 30.5 gCO_2e/MJ and 66.1 gCO_2e/MJ when LUC was not considered. The aggregate emissions, including LUC scenarios, were between −19.2 gCO_2e/MJ and 32.2 gCO_2e/MJ. Finally, a recent study by Warshay et al. (2017) provided information on LCA of an integrated seawater energy agriculture system (ISEAS) that includes Salicornia as a component for HEFA fuel production [120]. Their results indicate that ISEAS-HEFA yields GHG emissions savings of between 38% and 68% when compared with fossil jet fuel.

2.3. HEFA process

The HEFA process converts triglycerides in the lipidic feedstocks into paraffin-rich liquids through the hydrogenation, deoxygenation, hydroisomerization and hydrocracking processes [121]. Hydrogenation is the catalytic addition of hydrogen to saturate the double bonds of the lipid chain. Hydrogen addition is also used to remove the carbonyl group and to break the glycerol compound, forming propane and chains of free fatty acids (FFA) [121]. Afterwards, the carboxylic acid that remains attached to the FFA has to be removed, and this can be done in three different ways: hydrodeoxygenation, decarboxylation and decarbonylation. Finally, hydro-isomerization and hydrocracking are required to improve the biofuel qualities (such as better cold flow properties), and to adjust the product slate.

The chain length of the triglycerides from vegetable oils is mostly within the diesel range (C_{15}–C_{22}) (SM1) [40]. Therefore, additional hydrocracking is needed to obtain jet fuel range hydrocarbons (C_9–C_{15}). As a result, jet fuel is produced along with co-products such as naphtha (C_5–C_8), and light gases ($<C_4$). The product slate can be adjusted according to market needs. Multiple companies have patented HEFA production technologies, and these differ in the consumption of hydrogen gas and energy, as well as the final product slate produced.

The fatty acid profile of the lipidic feedstock may be important for the HEFA process since the amount of unsaturated fatty acids and their chain lengths would determine the hydrogen supply of the process. Higher chain length fatty acids would require more hydrocracking, which would result in the production of more co-products. If the hydrocracking amount is not adjusted well, the process will result in lighter range products, such as propane mix and naphtha, which are less valuable than diesel and jet fuel [40].

Han et al. (2013) estimated the amount of hydrogen and utilities (i.e., natural gas and electricity) needed for the hydroprocessing step of soybean, palm, rapeseed, jatropha, and camelina oils based on their fatty acid profile using literature data [30]. They found a maximum of 2.2 gCO_2e/MJ SAF emissions difference for the HEFA conversion step of the highest (camelina) and lowest (palm) emitting oils analyzed. This was not as significant as the difference from cultivation emissions of these feedstocks. In CORSIA, the utilities needed in the HEFA process and the resulting fuel product slate were assumed to be the same for different oilseeds, such as soybean, rapeseed/canola, and camelina [20]. In this work, we followed a similar approach and used the same HEFA processing data for the conversion of analyzed oils.

2.4. Model design for addressing uncertainty

2.4.1. Stochastic modeling

For the analysis, probability density functions (PDF) are assigned to most model parameters using literature data. Triangular or PERT distributions were employed for PDFs in the previous studies when few data points exist and the type of distribution was unknown, but minimum, maximum, and most likely values were available [53,122,123]. In this work, triangular distributions are defined for most of the parameters using minimum, average and maximum values. Input parameters such as fertilizer, diesel use for farming, electricity, natural gas, and hydrogen are treated as stochastic variables. A detailed list of these parameters and their variability is provided in SM2-SM6 in the supporting documentation. A Monte Carlo simulation was run using Crystal Ball® (a spreadsheet-based application used for simulations and forecasting) with 20,000 iterations at 95% confidence level to estimate the uncertainties caused by the variability of input parameters.

Emission factors for the physical inputs are deterministic and they are taken from the Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) database [124] and the EU's Joint Research Center's (JRC) input data for GHG default emissions from biofuels in EU legislation [125]. The 100-year global warming potential of other GHG gases methane and nitrous oxide is also deterministic and values from IPCC's 5th assessment report are used [74].

2.4.2. Scenario analysis: treatment of co-products

During the production of SAF, other products with commercial value may be obtained. For example, soy meal is produced during the crushing of oil from soybeans. These products should also be taken into account during an LCA, since LCA results are significantly impacted by the methodological choices regarding the treatment of co-products [43]. The allocation of emissions between the main product and co-product(s) occurs using an allocation ratio, which can be based on properties of the products such as mass, energy or market value [43]. A displacement credit is applied if the co-product is assumed to displace a similar product in the global market. GHG emissions equivalent to the life cycle GHG emissions from the production of the displaced product are then subtracted. According to the ISO standards for LCA, allocation of life cycle emissions between co-products should be avoided where possible by expanding the system boundaries [126]. This is also known as the displacement or substitution method. However, identifying the product to be displaced is not always a straightforward task, and the results are sensitive to the share of the co-product to be assessed in the product slate.

Under CORSIA [20] and EU Renewable Energy Directive (RED) [127], total emissions are allocated proportionally to the main product and the co-products based on their energy content using lower heating values (LHV). If electricity is produced as a co-product, the displacement method is used instead of energy allocation under the EU RED. Following the approach in these two regulatory systems, energy-based allocation (E) was applied in the present study to distribute the emissions between the co-products that are produced during the fuel production processes. A scenario analysis was conducted for mass-(M) and market-based ($) allocation methods for the oil extraction step, with emissions between fuel co-products allocated using energy-based allocation (E) in all scenarios.

In case of market-based (economic) allocation, when no historical prices are available for the vegetable oils assessed here, the minimum selling price (MSP) from TEA studies in the literature is utilized [45,128]. Table 1 lists co-products from the oil extraction step of the analyzed feedstocks and their assumed uses. Additional details are provided in the supporting document (SM7).

2.4.3. Sensitivity analysis

Local sensitivity of LCA results to seed oil content, nitrogen fertilizer, and hydrogen gas (H_2) has been analyzed. The values for these parameters were changed by ± 20% (one-at-a-time) to observe the effect on the overall results. Sensitivity to the hydrogen production methods was included. The baseline methodology uses steam methane reforming (SMR) from natural gas for hydrogen production, which is the most common technology used today. In addition, hydrogen production from "electrolysis" (water splitting) using renewable electricity, and hydrogen production from "coal" were considered.

A scenario in which the oilseed meal is assumed to be discarded was also included. This scenario is called "no meal" and it shows the case where the oil carries all the emissions burden from cultivation, and oil extraction steps. This scenario is included to understand the consequences from the treatment of meal as a residue, resulting in low material use efficiencies as meal is produced in larger amounts than oil in most cases.

2.5. *Direct land use change (DLUC)*

The quantification of DLUC follows the IPCC guidelines [63] for the calculation of the annual GHG emissions and removals from land converted into cropland under the Tier 1 approach (equation in SM8). DLUC emissions arise from differences in land carbon stocks before and after land conversion into oilseed production, considering the following carbon pools: above- and below-ground biomass (AGB, BGB), dead wood and litter, and soil organic carbon (SOC) in mineral soils. Carbon stocks in AGB, BGB, and reference soils have been taken from IPCC (2006), which remain the recommended guidelines until the 2019 values are validated [129]. An amortization period of 25 years is considered to annualize emissions from carbon stock changes, although this takes place as a one-time effect following land conversion. Flows of N_2O emissions from mineralized N due to SOC changes are also included.

Scenario analysis is applied to assess uncertainty in DLUC emissions due to assumptions on both the land uses to be converted (and associated carbon stocks) and agricultural practices for SAF feedstock production after land conversion. Different scenarios are defined per oilseed feedstock, including conversion of (secondary) forests and different types of grasslands (severely degraded, improved, or nominally managed) into cropland; as well as conversion from long-term cultivated cropland (with annual crops) into oilseeds for SAF production. In addition to the five feedstocks assessed here, DLUC values are also estimated for more conventional oilseed feedstocks already included in CORSIA, namely camelina, palm, rapeseed, and soybean. These feedstocks have ILUC values [70], but DLUC values are not yet assigned to them in CORSIA.

Since CORSIA does not allow for the use of SAFs produced at the cost of land classified as primary forests, wetlands and peatlands after January 1, 2008, only secondary forests are considered in the case of forestland conversion. For the same reason, emissions from peatland oxidation do not need to be accounted. Typical sourcing regions are assumed per feedstock – considering major producing regions – to identify carbon stocks associated with each land use prior to land conversion depending on the climatic zone and soil type [63]. For instance, jatropha, soybean, oil palm, energy tobacco, and castor bean are assumed to be produced in tropical locations. Pennycress, rapeseed, and camelina mostly grow in temperate climates, while *Salicornia bigelovii* is productive in tropical dry climates [130–132]. Additional scenarios are defined to capture variability in crop management and input intensity after land conversion, as these determine SOC losses under Tier 1 approach.

Oilseed production also generates carbon gains through carbon sequestration in crop biomass, as well as potential SOC gains in the case of improved soil management relative to previous uses. These gains are also included for estimating net carbon stock changes. Average crop yields and carbon embodied in agricultural biomass are estimated from the literature, assuming that both vary with the fertilizer input intensity. Conservative yield values are preferably considered, given the wide variability detected for some feedstocks (SM9). For instance, energy tobacco yields vary from 2.1 t/ha in the EU conditions [86] to >6 t/ha for Brazil [117]. In their review, Van Eijck et al. (2014) identified jatropha yields in the range 0.4–12 t/ha, depending on the production location [133]. However, the range in Table SM9 for jatropha is consistent with average yields for irrigated jatropha (high input intensity) in Brazil, USA and India, based on the spatially-explicit estimates from the Global Agro-ecological Zones (GAEZ) v4 database [134].

In the case of pennycress and camelina, these are considered to be double-cropped, replacing winter fallow between typical summer crops [96]. This has beneficial effects for weed control, potentially increasing yields and adding value, while delivering further environmental services [135–138]. Specifically, it is assumed that both pennycress and camelina are double-cropped with soybean or sunflower, capturing typical options in the US and the EU [85,96,137,139]. Thus, DLUC emissions from these two crops are additionally allocated between the first and second crop, also based on relative yields [84] and LHVs [140,141]. The average allocation factor between soybean and sunflower scenarios is used. DLUC emissions are expressed in gCO_2e/MJ by considering the same allocation assumptions and conversion efficiencies as for the rest of life cycle GHG emissions (see Section 2.5.2).

2.6. *Life cycle inventories*

Each unit process is described briefly in this section and relevant energy and material flows have been listed (Table 2). For more details and data references, readers are referred to the supporting material (Tables SM2-SM6).

2.6.1. *Feedstock cultivation and transportation*

Inputs for the cultivation stage are similar for all the oilseed crops that are studied. Fertilizers such as nitrogen (N), potassium (K) and

Table 2
Life cycle inventories for HEFA fuel production from castor, jatropha, pennycress, salicornia and energy tobacco for the baseline scenario based on mean values from the probability distribution functions.

Parameter	Castor	Jatropha	Pennycress	Salicornia	E. Tobacco
Cultivation: per kg dry seeds (except as noted)					
Seed yield (kg/ha)	1100	2500	1000	2000	2100
Seed moisture content (%)	3.5	5.8	12	6.4	5
Seed oil content (wt %)	47	35	34	28.2	38
Oil extraction efficiency (%)	96	96	96	96	96
N fertilizer (g)	32.8	27.6	63.5	50.6	56.1
P fertilizer (g)	17.3	24.5	31.8	–	36.8
K fertilizer (g)	13.7	20.1	18.2	–	31.7
Pesticides (g)	–	2.9	–	–	0.33
Herbicide (g)	–	–	–	–	0.41
Diesel (MJ)	1.2	1.1	0.17	26.7	0.13
Oil extraction (per kg oil)					
Seeds (kg)	2.1	2.8	2.7	3.5	2.6
Natural gas (MJ)	2.4	1.8	3.1	4.0	3.0
Electricity (MJ)	0.4	–	0.53	0.38	0.51
N-hexane (MJ)	0.14	0.18	0.18	0.23	0.17
Co-product, meal (kg)	1.1	0.73	1.7	2.4	1.6
Co-product, straw (kg)	–	–	–	25.0	–
Co-product, electricity (MJ)	–	8.5	–	–	–

phosphorus (P), and diesel use for farming equipment are the main inputs for the cultivation step. Herbicides and pesticides are also needed for some of the crops. Direct and indirect N_2O emissions from the use of synthetic nitrogen fertilizer are quantified in line with the IPCC Tier 1 methodology (SM10). Data related to the transportation step for the oilseed crops have been adapted from soybean transportation based on assumptions from ICAO Supporting Document [20].

2.6.2. *Oil extraction*

Feedstock recovery from the oilseeds requires an extraction step. This can be done by the mechanical pressing of seeds followed by extraction with a non-polar solvent, such as n-hexane, in order to increase the oil yield. This type of solvent extraction is used at large-scale production facilities and provides up to 99% oil extraction efficiency [142]. However, there may not be any commercial oil extraction facilities available for the discussed feedstocks in this study. As a result, assumptions were made for the energy consumption for the extraction step using data from similar crops such as soybean and rapeseed. The modified model by Sheehan et al. (1998) [143] on soybean oil extraction was used to calculate the energy inputs of the oil extraction step for each oilseed feedstock. The following process steps are included: receiving and storage of the seeds, seed preparation (flaking and cleaning), oil extraction, meal processing, oil recovery, solvent recovery, oil degumming and waste treatment. The seeds are assumed to be dried at the farm in the open air. Hexane amount needed for the extraction is adjusted according to the data from Schneider et al. (2013) [144], which is an LCA study on the oilseed crushing practices in the EU. Another variable is the amount of oil contained in the seed. The effect of this change on the oil extraction step is also captured by assuming low, baseline, and high values for the oil content, and calculating the utilities for the extraction step accordingly.

2.7. *Fuel production and transportation*

For the fuel production step, the HEFA conversion data and product slate assumptions from CORSIA have been employed [20]. In CORSIA, the GREET database and JRC's E3 database have been used as data sources. GREET uses the HEFA production technology by Honeywell UOP in the US [124], whereas E3 uses NEXBTL technology by Neste in the EU [145]. For the jet fuel T&D step, the data comes directly from the CORSIA emissions inventory [20].

3. Results and discussions

3.1. *Life cycle GHG emissions*

Box-and-whisker plots in Fig. 2a show the WTWa GHG emissions for the HEFA fuels from the five oilseed feedstocks that were investigated in this study, using default energy-based allocation. Attributional LCA results without the inclusion of DLUC for the investigated feedstocks show life cycle GHG emissions below the CORSIA fossil-fuel baseline of 89.0 gCO_2e/MJ. Castor-HEFA has the lowest median emissions value (39.5 gCO_2e/MJ), while pennycress-HEFA has the highest (48.2 gCO_2e/MJ) among the five HEFA pathways studied. The variability is higher for pennycress-, jatropha- and energy tobacco-HEFA than castor- and salicornia-HEFA. This is mainly due to the wider range of data for the probability distribution of N fertilizer for the former feedstocks. For energy tobacco-HEFA, the emissions range from 32.5 to 55.9 gCO_2e/MJ SAF, showing the highest variability around the median value (±26%). Following a sensitivity analysis, N fertilizer is found to be the most important contributor to variance in all cases (SM11). Natural gas and hydrogen consumption for the HEFA conversion step are other key parameters.

Fig. 2b shows the GHG emissions by process steps for each feedstock for different HEFA fuels, while underlying values are included in SM12. The main contributors to the GHG emission results are farming and fuel production steps. Fertilizer and diesel fuel use for farming causes the higher emissions from cultivation, whereas hydrogen and natural gas are the main sources of emissions from the fuel production process.

Pennycress has the lowest seed yield at 1.0 t/ha-yr, which results in higher fertilizer use per kg seeds compared to other crops. Nitrogen fertilizer use results in N_2O emissions, which is a gas with a much higher GWP. As a result, emissions from the cultivation step of pennycress are higher than the other oilseed crops. Salicornia cultivation is diesel-intensive, but the distribution of emissions between the seed and the straw decreases the burden on the seed, resulting in similar overall emissions from the cultivation step as other feedstocks. The same allocation factor (16.9%, SM7) is also applied to the feedstock transportation step of salicornia, which results in lower emissions (0.11 gCO_2e/MJ jet) when compared to other feedstocks. Salicornia has a

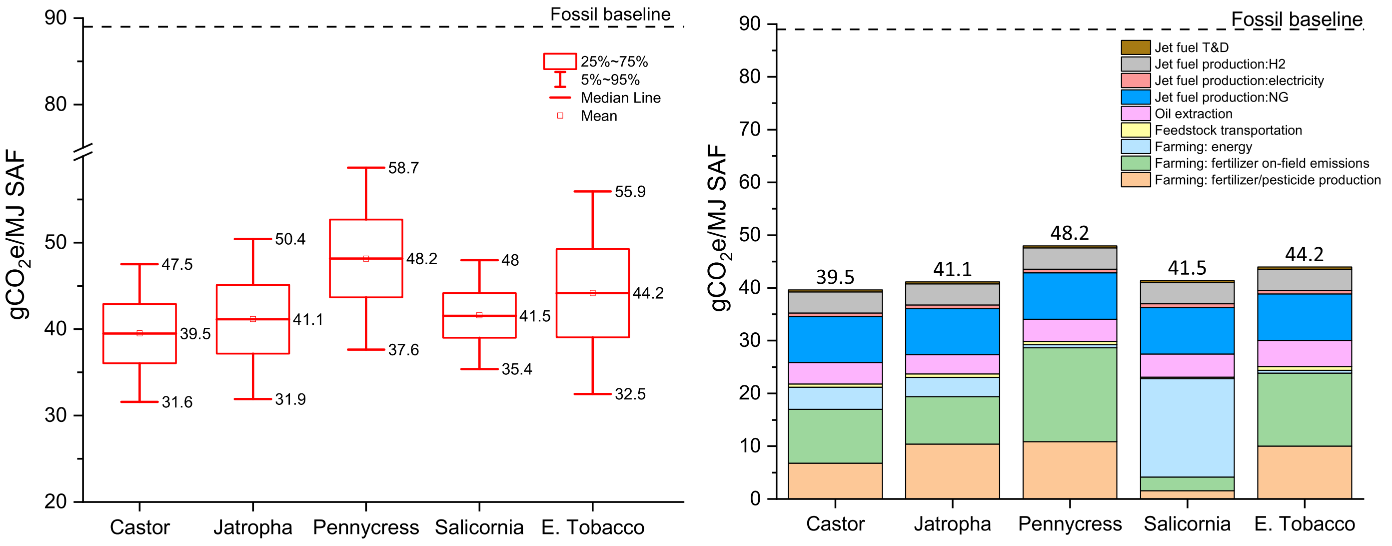

Fig. 2. (a) Box-and-whisker plot showing the WTWa emissions from HEFA-oilseed pathways and the associated uncertainty. Center lines represent the median values, the edges of boxes represent the 25th and 75th percentiles, and the limiting bars represent the 5th and 95th percentiles of the distributions resulting from 20,000 Monte Carlo simulations. (b) Greenhouse gas emissions of oilseed-HEFA pathways in gCO_2e/MJ SAF, showing the contribution from each process step; median values from the stochastic analyses are used. E. Tobacco: Energy tobacco, NG: Natural gas, SAF: Sustainable aviation fuel, T&D: Transportation and distribution.

narrower probability distribution due to the availability of fewer data points for the cultivation inputs (Fig. 2a). Jatropha-HEFA has the lowest emissions from the oil extraction step, while energy tobacco-HEFA has the highest. Although both crops have similar yields and similar oil content, the allocation factor to the oil is lower for jatropha due to the produced electricity, which reduces the emissions from the extraction step allocated to the oil and hence to the fuel.

3.2. Scenario analysis

Fig. 3 shows the median results from stochastic analysis when different allocation methods are used. Detailed results of this stochastic analysis are included in SM13. Mass allocation (M) of emissions between the oil extraction co-products lower the GHG emissions for all of the analyzed HEFA pathways. This is because meal is obtained in greater amounts than oil through the extraction step in most cases, resulting in a higher share of emissions allocated to the meal (SM7). Hence, the allocation factor for the oil decreases relative to that based on energy allocation, since the oil has a higher LHV than the meal. The decrease in GHG emissions relative to those in Fig. 2 is smallest for jatropha (7%), and largest for salicornia (35%).

For market-based allocation ($) of emissions between oil extraction co-products, overall emissions increase due to the generally lower price of the meal and the higher price of the oils, which translates into a higher allocation factor for the oil (SM7). The emissions increase is largest for salicornia at 46% and smallest for jatropha at 1%. For the rest of the feedstocks, the increase in results with respect to the energy-based allocation is around 20%.

3.3. Sensitivity analysis

The results of the sensitivity analysis are displayed in Table 3. Changing the amount of nitrogen application affects the overall emissions results on average by ± 9%, except for the case of salicornia. As explained in Section 3.1, since the burden on the seed is lower for salicornia than the other pathways, the amount of nitrogen use does not affect the GHG emission results per MJ of SAF as much as it does in other feedstocks.

Varying the hydrogen amount changes the results by ± 2%, while changing the hydrogen production method has a greater effect. When/if electrolysis is used for hydrogen, the GHG emissions decrease by around 9%, whereas using coal (with no carbon capture) instead of SMR from natural gas increases the GHG emissions by around 8%.

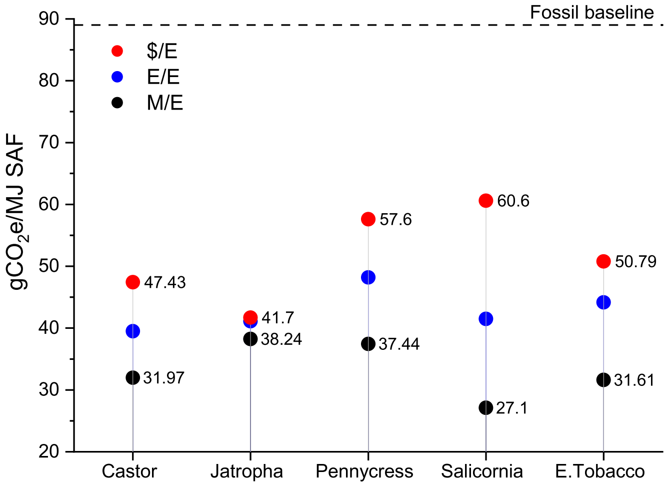

Fig. 3. Attributional LCA results of oilseed-HEFA pathways in gCO_2e/MJ SAF when different allocation methods are used for the oil extraction step, median values from the stochastic analyses are displayed. Allocation type used for oil extraction and fuel production steps co-products: E/E: energy/energy, M/E: mass/energy, $/E: market/energy, SAF: Sustainable aviation fuel.

The “no meal” scenario highlights the effect of using the meal for other applications on the GHG emission intensity of the SAF. If the meal cannot be utilized as a co-product of value, then all emissions are allocated to the oil, increasing the overall emissions considerably. The emissions increase by 28.9% and 71.8% for castor and salicornia, respectively, for minimum and maximum cases.

3.4. DLUC emission results

Emissions from DLUC vary greatly with assumptions both on the land uses converted to produce the feedstock as well as on the crop management after land conversion. Fig. 4 shows DLUC factors for all scenarios, highlighting in orange/red those cases where the DLUC factor alone already exceeds the CORSIA minimum GHG reduction requirement; that is, DLUC greater than 80.1 gCO_2e/MJ. More detailed DLUC factors broken down by source are available in the supporting information (SM14).

In the case of camelina and pennycress, it is assumed that these do not require high input application, as soybean contributes to N fixation in soil through double-cropping. Hence, only low or medium fertilizer input application scenarios are included in the scenario analysis. Similarly, it is considered that perennial plants (oil palm, jatropha) only require reduced tillage or no tillage practices.

Annual crops are generally associated with higher DLUC factors, especially when produced at the cost of carbon-rich ecosystems such as tropical forests or tropical shrubland. The highest DLUC factor across scenarios is estimated for castor bean produced at the cost of tropical rainforest, with 80% of emissions arising from biomass losses. Producing energy tobacco and castor bean on grassland also delivers DLUC factors greater than 80.1 gCO_2e/MJ, partially due to the relatively lower yields. In other words, energy tobacco and castor bean could not meet the CORSIA threshold unless produced in arable land or degraded grassland, or grassland with high input application in the case of energy tobacco. These patterns are comparable to those of soybean produced in tropical and subtropical climates, such as South America. In contrast, other lower-yielding crops, mainly camelina and pennycress, generate DLUC emissions lower than 80.1 gCO_2e/MJ in all scenarios except when produced at the cost of temperate forest. This is because a large share of DLUC emissions is allocated to the main crop based on energy allocation. Salicornia shows the best performance among oilseed feedstocks, with DLUC factors smaller than 80.1 gCO_2e/MJ across all scenarios, due to co-product allocation assumptions, i.e., straw for fuel production. However, the lowest DLUC factor among oilseeds is obtained for jatropha produced on long-term cultivated land, with no tillage and low input application (−83.4 gCO_2e/MJ). This is mainly related to SOC gains and carbon sequestration in crop biomass, which are both substantially larger in perennial crops than in annual crops. In contrast, jatropha production at the cost of tropical forest or shrubland results in net DLUC emissions, as was observed for oil palm. It is important to note that DLUC factors are higher than estimated ILUC factors for CORSIA feedstocks when secondary forest or shrublands are converted into SAF production; even improved grassland in the case of rapeseed and camelina (>49.4 and 38.4 gCO_2e/MJ, respectively vs. 24.1 gCO_2e/MJ and −13.4gCO_2e/MJ).

3.5. Total life cycle GHG emissions including DLUC

Scenario-specific DLUC factors (Fig. 4) are combined with median GHG emissions to estimate net GHG savings associated with each scenario and evaluate eligibility for CORSIA (Fig. 5). When low and high input application is considered for DLUC estimation, WTWa emissions are also adjusted accordingly, assuming lower or higher fertilizer doses and associated emissions from both production and on-field application. These are estimated by using the lowest and highest inputs from the probability density function of N fertilizer in line with the scenario

Table 3
Sensitivity analysis for oilseed-HEFA pathways, “gCO_2e/MJ SAF” results followed by percent change with respect to the baseline, E/E: energy/energy.

	Base	Seed oil content		N fertilizer		H_2 use		H_2 production		No meal
	E/E	−20%	+20%	−20%	+20%	−20%	+20%	Electrolysis	Coal	
Castor-HEFA	39.5	40.7	38.4	36.2	42.7	38.7	40.3	35.7	43.0	50.9
		+3.1%	−2.7%	−8.2%	+8.2%	−2.0%	+2.0%	−9.6%	+8.9%	+28.9%
Jatropha-HEFA	41.1	44.2	38.8	38.1	44.2	40.4	41.9	37.3	44.7	56.0
		+7.4%	−5.8%	−7.4%	+7.4%	−1.9%	+1.9	−9.3%	+8.6%	+36.3
Pennycress-HEFA	48.1	49.0	47.2	42.9	53.3	47.3	48.9	44.2	51.6	78.1
		+1.9%	−1.7%	−10.8%	+10.8%	−1.7%	+1.7%	−8.1%	+7.5	+62.4%
Salicornia-HEFA	41.5	41.0	42.0	40.7	42.3	40.7	42.4	37.5	45.2	71.3
		−1.3%	+1.1%	−1.9%	+1.9%	−2.0%	+2.0%	−9.6%	+8.9%	+71.8
E. Tobacco-HEFA	44.2	45.9	42.7	39.8	48.6	43.4	45.0	40.3	47.8	61.0
		+3.9%	−3.2%	−10.0%	+10.1%	−1.8%	+1.9%	−8.7%	+8.2%	+38.0%

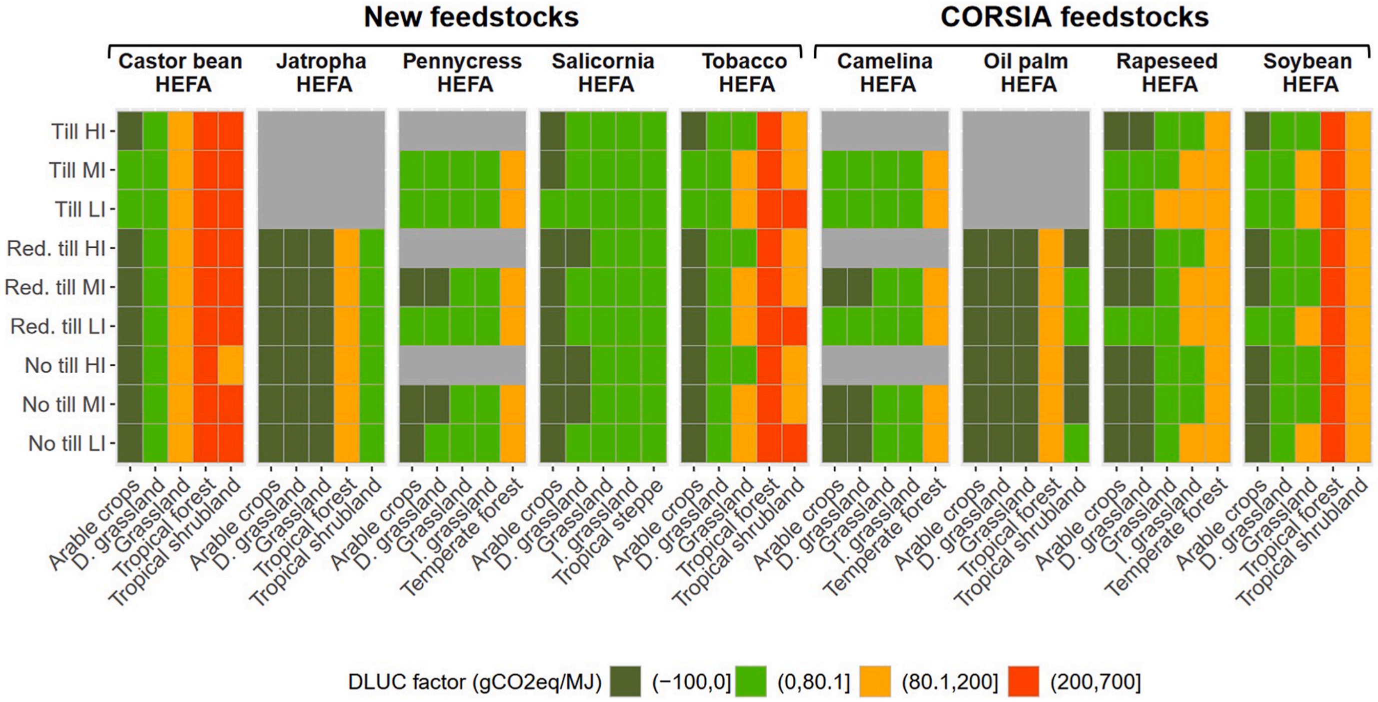

Fig. 4. Scenario-based DLUC emission factors (gCO_2e/MJ) for oilseed feedstocks to be employed in HEFA pathways. Non-feasible combinations are grayed-out. D: Degraded; HI: High input intensity; I: Improved; LI: Low input intensity; MI: Medium input intensity; Red: Reduced, CORSIA: Carbon offsetting and reduction scheme for international aviation, DLUC: Direct land use change, HEFA: Hydroprocessed esters and fatty acids.

chosen for DLUC estimations (Table SM14). For comparison purposes, traditional oilseed feedstocks from CORSIA are also included with their DLUC emissions from Section 3.4. In the case of CORSIA feedstocks, “core-LCA” emissions from the CORSIA document are used [70]. For palm-HEFA, the open-pond value from CORSIA is utilized.

The inclusion of DLUC emissions in the life cycle changes GHG emissions dramatically for all feedstocks; these emissions were, in principle, below the CORSIA threshold (Fig. 2). Fig. 5 distinguishes between combinations of feedstock-scenarios that qualify for CORSIA (green), those that do not (red), and those that still provide GHG emissions savings (white) but not enough (<10%) to qualify for CORSIA.

When the scenarios defined in Section 2.6 are considered, castor bean and energy tobacco have especially high DLUC factors when produced at the cost of carbon-rich ecosystems, due to relatively lower yields (Fig. 4). When including core-LCA emissions, salicornia-HEFA yields GHG savings greater than 10% across all scenarios, except for tropical steppe loss with low input intensity. Pennycress-HEFA does not meet the CORSIA threshold when produced on grassland with full tillage, on improved grassland, and on temperate forest. Similarly, camelina HEFA only meets the minimum GHG-saving requirements when produced at the cost of arable land or degraded grassland; as well as grassland with medium input intensity or no tillage. HEFA fuels produced from jatropha and oil palm show better GHG performance than HEFA fuels produced from annual crops such as soybean, rapeseed, castor bean, and energy tobacco. Both perennial crops meet the CORSIA threshold unless tropical forests are lost; or tropical shrubland in the case of jatropha. Energy tobacco- and castor-HEFA only yield GHG savings greater than 10% when grown on arable land; or on degraded grassland (mainly with reduced or no tillage and/or high input intensity). In contrast, soybean- and rapeseed-HEFA provide GHG savings greater than 10% in almost all scenarios that entail conversion of degraded grassland.

Under CORSIA, crops cultivated at the cost of primary forests, wetlands and peatlands on land converted after January 1, 2008 are not eligible for SAF production. In line with CORSIA sustainability criteria, it can be expected that oilseeds for HEFA are mainly produced on grasslands or previously cultivated arable land. Fig. 6 specifically shows DLUC results from these two scenarios of converted land uses (with reduced tillage and medium input intensity after conversion as default scenario), and how these affect net GHG emissions under of all oilseed-

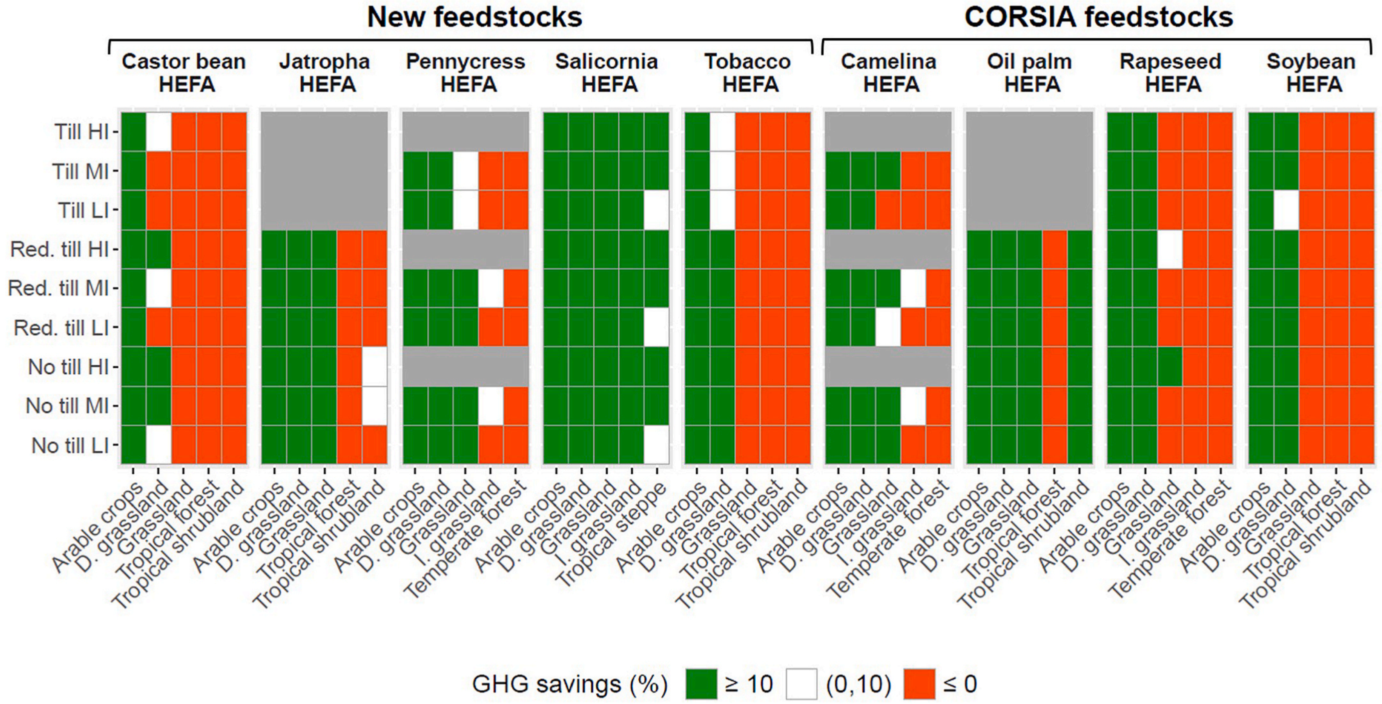

Fig. 5. Scenario-based GHG savings (%) for HEFA pathways relative to the CORSIA fossil fuel comparator (89 gCO_2e/MJ). Non-feasible combinations are grayed-out. D: Degraded; HI: high input intensity; I: Improved; LI: low input intensity; MI: medium input intensity; Red: Reduced. Green: scenarios with GHG savings (%) ≥ 10, white: scenarios with $0 <$ GHG savings (%) <10, red: scenarios with no reduction in GHG emissions. CORSIA: Carbon offsetting and reduction scheme for international aviation, GHG: Greenhouse gas emissions, HEFA: Hydroprocessed esters and fatty acids.

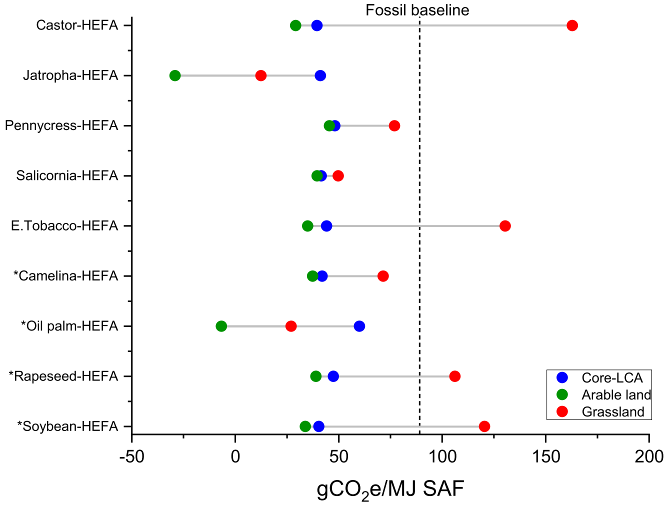

Fig. 6. GHG emissions from oilseed-HEFA pathways including DLUC emissions. Core-LCA: WTWa GHG emissions without DLUC emissions. DLUC emissions factors are included to the WTWa emissions for two scenarios: grassland into cropland, and arable land into cropland. * indicates CORSIA feedstocks. HEFA: Hydroprocessed esters and fatty acids, LCA: Life cycle assessment, SAF: Sustainable aviation fuel

HEFA fuels considered.

Pennycress-HEFA provides 45.8% emissions benefit without the inclusion of DLUC. When including emissions from grassland conversion into penycress (77.0 gCO_2e/MJ), GHG emissions savings are reduced to 13.5%. The effect of DLUC emissions is more significant for castor and energy tobacco. WTWa emissions from these crops are 39.5 and 44.2 gCO_2e/MJ SAF, respectively, without DLUC. However, the inclusion of DLUC for grassland conversion increases the emissions to 162.9 and 130.4 gCO_2e/MJ SAF, well above the fossil jet reference. Jatropha is still the best-performing crop when including DLUC emissions from grassland conversion, with 12.4 gCO_2e/MJ SAF overall emissions, providing 86.1% of GHG emission reductions. This is mainly due to the carbon sequestration in SOC and biomass relative to both, grassland and arable land. Grassland conversion also reduces GHG savings for salicornia-HEFA (with 49.7 gCO_2e/MJ or a 44.2% decrease vs 53.4% without DLUC). Among CORSIA feedstocks, camelina- and palm-HEFA provide GHG emission benefits of 19.7% and 69.7% for the grassland conversion scenario.

Converting arable land instead of grassland yields greater emission savings for all new feedstocks assessed. For instance, this scenario delivers 67.2% and 60.7% emission savings for castor and energy tobacco, respectively. GHG emissions from pennycress-HEFA are 45.5 gCO_2e/MJ SAF when arable land is converted, providing 48.9% emissions reductions. Jatropha delivers the greatest GHG emissions savings when cultivated on arable land (-29.1 gCO_2e/MJ or 132.7% emission savings). This indicates that arable land is the preferred land use to be converted into SAF production with the goal of reducing GHG emissions relative to conventional kerosene. However, this may come at the cost of other uses (food, feed), with subsequent ILUC and food security implications. These are out of the scope of this study, as their quantification would require CLCA approaches.

4. Conclusions

SAFs are seen as one of the most promising alternatives to achieve the emission reduction goals from aviation in the short-to medium-term. In order to be sustainable SAF should deliver GHG savings relative to fossil kerosene based on LCA. However, uncertainty associated with the LCA calculations should be considered in detail when estimating the potential emission benefits from these fuels. Our stochastic assessment of GHG emissions from castor-, jatropha-, pennycress- and salicornia-HEFA fuels covers the range of deterministic results reported in the literature (Section 2.2) when land use change is not included. No peer-reviewed LCA studies for energy tobacco-HEFA jet fuel have been found in the literature, and our work will be the first example of this pathway. In addition, emission results are found to be most sensitive to the hydrogen production method and nitrogen fertilizer use.

The results indicate that DLUC is a more significant source of uncertainty than parametric uncertainty and allocation assumptions in the LCI analysis. The IPCC Tier 1 approach provides carbon stocks at the continent level, while both yields and carbon stocks are subject to spatial variability, potentially leading to further uncertainty in DLUC estimates. Results also show that DLUC emissions can be higher than those estimated from ILUC in CORSIA feedstocks [70]. Further harmonization of DLUC estimations in CORSIA is desirable, as it is associated with multiple choices, starting with the producing region and major land uses.

Author contribution

Gonca Seber: Conceptualization, Methodology, Investigation, Formal analysis, Knowledge, Writing- Original draft, Visualization, Neus Escobar Methodology, Investigation, Formal analysis, Knowledge, Writing-Original draft, Visualization Hugo Valin: Methodology, Writing-Review & Editing, Supervision, Knowledge, Funding acquisition Robert Malina: Methodology, Writing-Review & Editing, Supervision, Knowledge, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

The research efforts from Hasselt University and IIASA were supported by the European Union's H2020 project ALTERNATE "Assessment on Alternative Aviation Fuels Development" (Grant 875538).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112945.

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