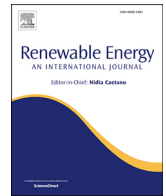


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Assessing a sustainable aviation fuel supply chain from winter canola and its carbon intensity considering feedstock yield variations

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ABSTRACT

Replacing conventional aviation fuel (CAF) with sustainable aviation fuel (SAF) has been suggested as a vital means to decarbonize the aviation industry. We considered winter canola a feedstock for SAF production through the hydro-processed esters and fatty acids pathway in the Southeast United States. We incorporated feedstock yield variations in a stochastic mixed-integer linear programming model to optimize the SAF supply chain. Results suggest the potential SAF production for Nashville International Airport (BNA), from an existing oil extraction mill and 0.19 million hectares (ha) of winter canola cultivation, range from 129 million liters yearly (MLY) to 246 MLY with a 90 % likelihood. With additional investment and expanded winter canola cultivation to 0.61 million ha, the expected SAF supply to BNA could increase to 348 MLY. An additional 212 MLY can be supplied to Memphis International Airport. After considering the co-product revenues, the expected breakeven cost for SAF is \$1.1 per liter. The SAF's carbon intensity falls into the range from 31 g of carbon dioxide equivalent per megajoule of fuel (g CO₂e MJ⁻¹) to 43 g CO₂e MJ⁻¹, with 90 % probability, which is at least 50 % lower than CAF.

Abbreviations

\$	US Dollar
BNA	Nashville International Airport
CAF	Conventional aviation fuel
CI	Carbon intensity
g CO ₂ e MJ ⁻¹	Grams of carbon dioxide equivalent per megajoule of fuel
GHG	Greenhouse gas
ha ⁻¹	Per hectare
HEFA	Hydro processed esters and fatty acids
LCA	Life cycle assessment
MEM	Memphis International Airport
MILP	Mixed-integer linear programming
MLY	Million liters yearly
MT	Metric ton
OEM	Oil extraction mill
SAF	Sustainable aviation fuel

1. Introduction

According to the International Air Transport Association (IATA), air

travel has recovered from the COVID-19 shock, with global passenger traffic in 2024 rising 10.4 % compared to 2023 and reaching 3.8 % above the 2019 levels [1]. Over a business-as-usual trajectory, cumulative aviation CO₂ emissions from 2021 to 2050 are expected to total 21.2 gigatons [2], underscoring the urgency to curb the aviation sector's carbon footprint. In response, the global aviation industry committed to achieving net-zero carbon emissions by 2050 at the 77th IATA Annual General Meeting in October 2021 [3]. To achieve this target, the aviation industry has been exploring various approaches to decarbonize the sector, such as improving efficiency, using carbon offsets, and developing net-zero carbon fuels [4]. In addition to technical innovations and management improvement, sustainable aviation fuel (SAF) has been identified as the key means to decarbonize the aviation sector [5]. SAF possesses chemical and physical properties that resemble conventional aviation fuel (CAF), enabling seamless integration into existing infrastructure without any modifications while adhering to established technical and safety standards [6].

As of 2025, eleven conversion processes for SAF production had been approved by ASTM International [7]. Approximately 85 % of projected SAF production in the next five years is anticipated to come from Hydro-processed esters and fatty acids (HEFA) [8]. Such dominance of

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HEFA is expected to continue for at least the next 10–15 years due to the increased availability of oil feedstocks (such as vegetable oil, cooking oil, and animal fats) [9], mature production technology, superior efficiency, and lower capital and operational costs [10]. Producing SAF from oilseeds via the HEFA pathway at a commercial scale requires a robust supply while avoiding competition with food crops and forest land to mitigate direct or indirect land use changes [11].

Winter canola (*Brassica napus*), a versatile oilseed of the Brassicaceae family, has emerged as a promising feedstock for the HEFA pathway as it can be easily incorporated into existing corn-soybean rotations [12]. Compared to traditional oilseed crops such as soybeans, winter canola offers distinct advantages for SAF production. Its higher oil yield (40–45 %) compared to soybeans (18–20 %) and its lower carbon intensity make it a more efficient and environmentally sustainable feedstock for SAF [13]. Recent collaboration between Bayer and Neste to establish a winter canola value chain in the U.S. underscores its growing industrial relevance for renewable fuel production [14]. Additionally, integrating winter canola as a cover crop in existing cropping systems has been proposed to address concerns about displacing summer field crops with energy crops and minimizing considerable land-use change [15]. Combining winter canola into a crop rotation enhances the double cropping system, having advantages like minimal residue for low-till soybean planting and an early harvest window compared to winter wheat [16]. However, winter canola yield could vary due to various agronomic [17], environmental, and genetic factors [18]. Feedstock yield plays a critical role in the SAF supply chain optimization decisions [19]. Thus, the present study aims to assess the impacts of feedstock uncertainty on the supply chain and CI of SAF produced through the HEFA pathway.

The SAF supply chain network is a stochastic system that consistently experiences state fluctuations and is subject to high levels of risk [20]. Thus, it is essential to consider the uncertainties while developing the SAF supply chain model, enabling the decision-maker to respond, adapt, and recover from disruptions efficiently [21]. The stochastic programming model is a solid, reliable, and practical approach to addressing stochastic elements in decision-making problems [22]. The model uses a two-stage structure where the first step involves strategic decisions, while the second step addresses operational adjustments under uncertainty realization [23]. Utilizing probability distributions to capture uncertain parameters allows decision-makers to analyze a broader range of possible outcomes [24]. Also, Bairamzadeh et al. [25] and Zakaria et al. [26] have shown that stochastic optimization models yield more effective and robust biofuel supply chain plans than deterministic models.

The life cycle assessment (LCA) of a SAF supply chain is essential to verify its decarbonization potential and eligibility for carbon reduction credits. Carbon intensity (CI), measured in grams of carbon dioxide equivalent per megajoule of fuel ($\text{g CO}_2\text{e MJ}^{-1}$), quantifies GHG emissions across SAF's life cycle and enables comparison with CAF [27]. CI is the primary environmental metric and is the most widely adopted measure in regulatory frameworks. Regulatory programs, such as the International Civil Aviation Organization's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), require SAF to achieve at least a 10 % reduction in life cycle emissions compared to CAF [28]. Similarly, the U.S. Renewable Fuel Standard mandates a minimum 50 % reduction in life cycle GHG emissions relative to 2005 fossil-based fuels [29]. The Inflation Reduction Act of 2022 further supports these efforts by providing federal tax incentives based on CI reductions [30].

Despite continuing progress in the SAF supply chain from field to airports, three research gaps persist in the related literature. First, most SAF supply-chain models are deterministic and do not capture feedstock yield uncertainty and its downstream effects on system economics and CI. Second, relatively few studies evaluate winter canola supply subject to established crop rotations and the realistic land availability for SAF. Finally, many LCA studies report the point estimates of CI without propagating yield variability to assess SAF policy eligibility.

We addressed these gaps by embedding yield uncertainty in a two-stage stochastic mixed-integer linear programming (MILP) model for the winter canola-based HEFA SAF supply chain in Tennessee and Kentucky, which have a conducive environment for winter canola production and the opportunity to expand the double-cropping area. In this study, we used a Monte Carlo simulation to generate probabilities associated with varying winter canola yields. These probabilities were then used in a stochastic MILP model to estimate the potential SAF production and the unit cost of SAF from winter canola, incorporating feedstock yield variations (both temporal and spatial), and the potential cultivation area based on the historical land use data. Our analysis accounted for both production costs and potential co-product revenue to gauge the economic viability of SAF production from this feedstock. Additionally, we determined the optimal SAF supply chain configuration while considering yield variability. Finally, we estimated the CI of SAF under various yield scenarios to provide a comprehensive understanding of the environmental impact of winter canola-based SAF production. The findings from this study are expected to inform key stakeholders, including policymakers, investors, and farmers, with essential insights necessary for making informed decisions before committing to large-scale investments in the SAF industry.

2. Study area

Tennessee and Kentucky in the Southeastern U.S. (Fig. 1) are the study areas, given their favorable conditions for growing winter canola. These states have mild winters, sufficient growing season precipitation, and the opportunity to double-crop with traditional annual summer crops. However, the adoption rate of cover crops in the study area has been low, with Kentucky's cover crop adoption rate of 10.1 % and Tennessee's 9.6 % in 2022 [31]. In addition, in 2023, the land usage for other secondary crops, such as winter wheat, in these states has been moderate and constituted a small share (~4 %) of total U.S. wheat production [32]. Therefore, introducing winter canola in the study area can enhance land use efficiency, optimize crop rotations, improve soil health, reduce erosion, and increase growers' revenue.

According to the United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) for the year 2023 [32], Kentucky and Tennessee's annual corn and soybean harvested area was over two million hectares (ha), primarily located in the fertile soils in the western region (see Fig. 1). However, less than 350,000 ha were harvested for winter wheat in the same period. Furthermore, the 2022 census of agriculture reported that only 272,463 ha were used for cover crops [31]. The relatively small area of cover crops and winter cash crops in the two states is due to several reasons. First, some areas available for corn and soybeans in summer are unsuitable for winter crops because of flooding and environmental or topographical conditions in the winter. Second, even if the land is suitable for winter crop production, farmers may choose not to do it because of potential farming issues, such as reduced summer crop yields, increased production costs and risk, uncertain market prices, and changing planting and harvesting dates. Thus, instead of assuming all corn and soybean harvested areas available for winter canola, which likely overestimates the winter canola supply in the area, we considered the winter wheat cultivation areas for at least one year over the past decade as the potential location to produce winter canola.¹ The CropScape portal provides a comprehensive spatial dataset of historical crop planting patterns. Winter wheat and winter canola share similar growing conditions, such as planting timelines and cold tolerance, making this a reasonable proxy. Applying the wheat frequency layer from the CropScape portal of the USDA NASS [33], we identified around 1.2 million ha of winter wheat harvest area as the potential supply regions. Such an assumption better reflects the

¹ We also considered areas used for other cover crops, but their share was negligible in the study area.

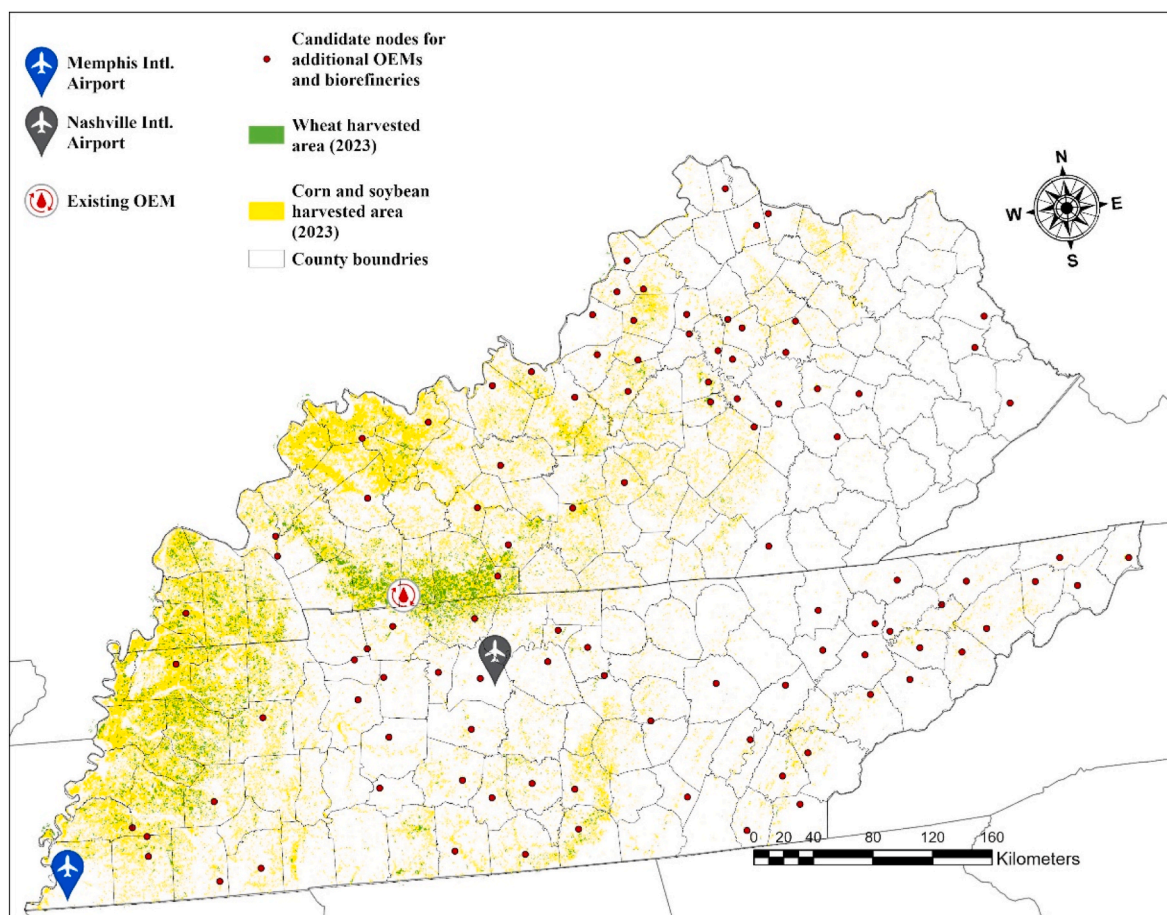


Fig. 1. Study area map for winter canola-based SAF supply chain.

regional producers' potential to adopt the relatively new secondary crop and prevents overestimating winter canola production in this study.

This study focuses on two major airports, Memphis International Airport (MEM) and Nashville International Airport (BNA), in the study area (see Fig. 1). The two airports consumed more than 2 billion liters of jet fuel annually before the COVID-19 pandemic and are expected to expand fuel consumption over the next decade due to increased populations and air traffic. The Trenton Organic Crush Plant in Trenton, KY is currently the only existing crushing facility for canola in the study area. Industrial parks in the region offer potential sites for additional crushing and SAF conversion facilities.

3. Analytical framework and methods

3.1. System boundary

This study modeled the winter canola-based SAF supply chain in four components illustrated in Fig. 2: farms, oil extraction mills (OEMs), biorefineries, and airport(s). Winter canola will be established and harvested at farms; OEMs purchase and convert canola oilseed into crude oil and canola meal. The crude oil will be transported to biorefineries to produce SAF and other co-products via the HEFA pathway. The SAF will then be transported to the associated airports. Our two-stage stochastic MILP model selects the feedstock cultivation area and facility investment in the first stage. Given the first-stage decisions, operational decisions like SAF production and procurement of additional feedstocks, subject to uncertainty in feedstock availability, are made in the second stage to maximize the expected profit.

The existence and proximity of crushing facilities play a crucial role in farmers' decisions to adopt oilseed crops. According to Embaye et al.

[34], farmers with nearby crushing facilities are 18 % more likely to adopt oilseed crops than those without nearby facilities. The availability of a nearby crushing facility reduces uncertainty for farmers, facilitates the market establishment for winter canola, and lowers shipping costs. Given the OEM's influence, we evaluated two cases to assess the potential of SAF production subject to the assumption of OEM availability in the system.

Case I. This case focuses on assessing near-term production utilizing the existing OEM on the border of Tennessee and Kentucky. It assumes that farmers and SAF producers rely on the existing OEM to crush oilseeds for SAF facilities, pending the construction of additional crushing facilities. The model determines the optimal size and location of the biorefinery using industrial parks as potential choices.

Case II. In this case, the long-term, large-scale production of SAF will utilize more area for winter canola cultivation, thus requiring the establishment of multiple OEMs alongside the existing OEMs and biorefineries in the region. We considered industrial parks a potential location for these additional facilities. The model identifies the optimal number, location, size, and capacity of the required OEMs and biorefineries, optimizing the SAF supply chain.

In both cases, we used the existing road network to find the shortest transportation distances between the supply chain components. The feedstock supply regions were decomposed into a grid of 130-square-kilometer hexagons. Also, we adjusted the land opportunity cost by incorporating the net revenue of winter wheat production and the frequency of wheat harvest within each hexagon. For instance, if a given hexagon had winter wheat cultivation for n years within the last decade, we scaled the total opportunity cost by a factor of $n/10$. Similarly, we

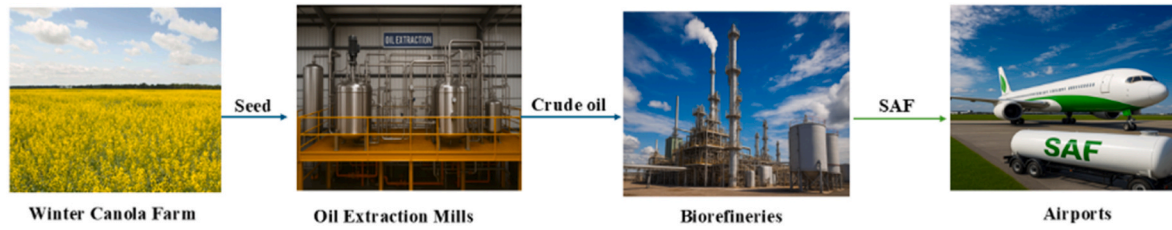


Fig. 2. System boundary of winter canola-based SAF production.

assigned the different productivity levels to each hexagon based on the winter wheat productivity of each county [35]. We then used the ratio of the hexagon's productivity to the state's average productivity as the yield factor. For instance, if a hexagon had a productivity $m\%$ lower than the state average productivity, we used a yield factor of $[1-(m/100)]$. In contrast, if a hexagon had productivity $m\%$ higher than the average, we used a yield factor of $[1+(m/100)]$.

3.2. Oilseed yield scenarios

Winter canola yield varies yearly, which mandates considering several scenarios for winter canola availability when developing a two-stage stochastic supply chain optimization model. The Monte Carlo simulation was used to generate scenarios for winter canola supply. The PERT (Program Evaluation Research Task) distribution developed by Malcolm et al. [36] has been commonly applied to agricultural risk management. Its adaptability and ability to replicate various yield distributions make it highly effective for crop yield modeling. By relying on minimum, maximum, and most probable values, the PERT distribution simplifies calculations and avoids the complexities and potential over-fitting issues of econometric estimation [37].

In this study, we considered winter canola yield as a random variable with a mean value (2800 kg ha^{-1}), representing the most probable outcome within a PERT distribution range of $[1,400, 4200] \text{ kg ha}^{-1}$ based on recent experimental data² [38]. We ran the Monte Carlo simulation using this distribution for 1000 iterations, generating 20 yield intervals, each with a probability distribution derived from the simulated yield under each scenario, as illustrated in Fig. 3.

3.3. Mathematical framework

A stochastic MILP model was developed considering the winter canola yield uncertainty. The two-stage stochastic optimization is a recourse model that requires decision-makers to determine the optimal investments before operations and then maximize the expected profit under various yield scenarios in the second stage. Following Sharma et al. [23], we incorporated land use choice and winter canola establishment in the investment decision in the first stage to adequately capture the impact of stochastic yields on investment. Table 1 defines all the subscripts, parameters, and variables used in the model, while Table 2 presents the values of the parameters used in the MILP model.

The optimization was obtained by maximizing the net present value of expected profit, considering the associated probability for each random winter canola yield scenario (s), as outlined in equation (1) below:

$$\begin{aligned} \text{Max} : E(\text{profit}) = \sum_t \left(\sum_s \text{Prob}_s (SR_{t,s} + CR_{t,s} - OEC_{t,s} - CC_{t,s} - TC_{t,s} \right. \\ \left. - AFC_{t,s}) - PC_t \right) \times (1 + IRR)^{-t} \end{aligned} \quad (1)$$

where $SR_{t,s}$ represents revenue from SAF, $CR_{t,s}$ represents revenue from co-products, PC_t , $OEC_{t,s}$, $CC_{t,s}$, $TC_{t,s}$, and $AFC_{t,s}$ represents oilseed production cost, oil extraction cost, conversion cost, total transportation cost, and additional feedstock cost, respectively.

Equation (2)–(10) define all the variables mentioned in Equation (1). Equation (2) estimates the total winter canola seed production cost (PC_t), which is scenario-independent, by summing the product of the area harvested in each hexagon (AH_i) and the unit cost of winter canola establishment and cultivation (E) and adjusted land opportunity cost for each hexagon ($L \times LF_i$). Equations (3) and (4) estimate the total oil extraction cost ($OEC_{t,s}$) and conversion cost ($CC_{t,s}$).

$$PC_t = \sum_i \left(AH_i \times (E + L \times LF_i) \right) \quad (2)$$

$$OEC_{t,s} = \sum_o \sum_c \left((DVM_{o,c} \times CO_c) + YO_{o,c,t,s} \times OO \right) \quad (3)$$

$$CC_{t,s} = \sum_b \sum_d \left((DVB_{b,d} \times CB_d) + YB_{b,d,t,s} \times OB \right) \quad (4)$$

Equation (5) represents the total transportation costs, which includes the cost of transporting winter canola seed from harvesting sites to OEM ($TCHO_{t,s}$), crude oil transportation cost from OEM to bio-refineries ($TCOB_{t,s}$), and SAF transportation cost from bio-refineries to the airport ($TCBA_{t,s}$).

$$TC_{t,s} = TCHO_{t,s} + TCOB_{t,s} + TCBA_{t,s} \quad (5)$$

The following equation (6)–(8) further define these terms, where $ATCHO_{i,o}$, $ATCOB_{o,b}$, and $ATCBA_{b,m}$ are the average costs of transporting oilseed or products between their origin and intended destination. Equation (9)–(11) detail these average costs of transportation. These costs are calculated by considering factors such as labor (LC) and truck costs (TTC), travel distances ($DHO_{i,o}$, $DOB_{o,b}$, $DBA_{b,m}$), truck speeds (SHO , SOB , SBA), and loading times ($TLLT$, $TULT$) for a round trip.

$$TCHO_{t,s} = \sum_i \sum_o \sum_c \left(\text{Field}2\text{OEM}_{i,o,c,t,s} \times ATCHO_{i,o} \right) \quad (6)$$

$$TCOB_{t,s} = \sum_o \sum_b \sum_d \left(XO_{o,b,d,t,s} \times ATCOB_{o,b} \right) \quad (7)$$

$$TCBA_{t,s} = \sum_b \sum_d \sum_m \left(XB_{b,d,m,t,s} \times ATCBA_{b,m} \right) \quad (8)$$

$$ATCHO_{i,o} = (TLC + LC) \times (2 \times (DHO_{i,o} / SHO) + TLLT) / LW \quad (9)$$

$$ATCOB_{o,b} = TTC \times (2 \times (DOB_{o,b} / SOB) + TULT) / LW \quad (10)$$

² The yield range and distribution parameters were verified using the results of the 2022 National Winter Canola Variety Trial [50], which reported yields in the study area are consistent with the selected PERT distribution.

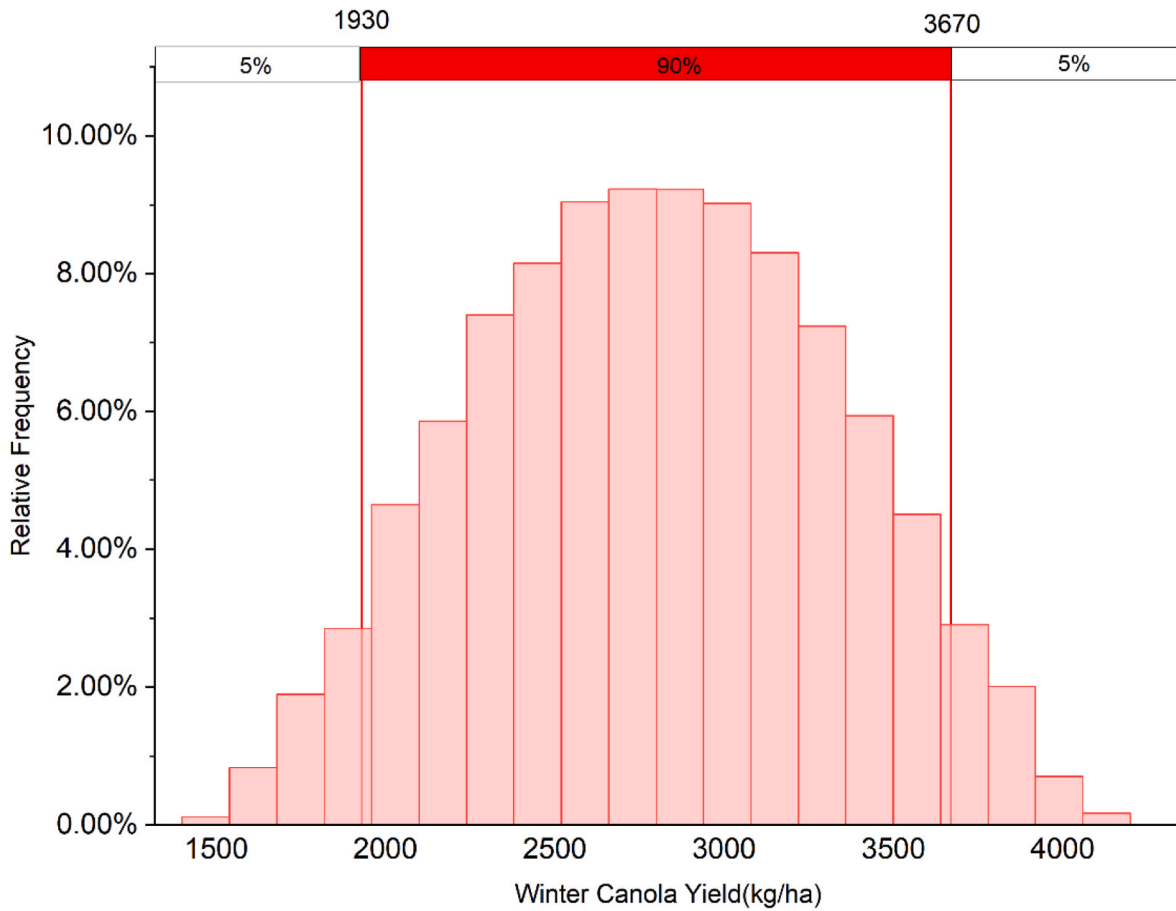


Fig. 3. Probability distribution of simulated yield.

$$ATCBA_{b,m} = TTC \times (2 \times (DBA_{b,m} / SBA) + TULT) / LW \quad (11)$$

Equation (12) estimates the revenue from different co-products (CR_t , s). These co-products include canola meal, propane, naphtha, and diesel. Canola meal revenue is calculated as the product of the total amount of seed supplied to OEMs ($Field2OEM_{i,o,c,t,s}$), the conversion ratio of seed to meal ($Seed2Meal$), and the meal price (MP). Similarly, propane, naphtha, and diesel revenues are obtained by multiplying the total volume of crude oil sent from OEMs to biorefineries ($XO_{o,c,b,d,t,s}$) by their respective conversion ratios ($Oil2Prop$, $Oil2Naptha$, $Oil2Diesel$) and prices (PP , NP , DP).

$$CR_{t,s} = \sum_i \sum_o \sum_c (Field2OEM_{i,o,c,t,s} \times Seed2Meal \times MP) + \sum_o \sum_c \sum_b \sum_d ((XO_{o,c,b,d,t,s} \times Oil2Prop \times PP) + (XO_{o,c,b,d,t,s} \times Oil2Naptha \times NP) + (XO_{o,c,b,d,t,s} \times Oil2Diesel \times DP)) \quad (12)$$

Equation (13) estimates the penalty cost for lower feedstock yield conditions, defined as the expenses of acquiring additional winter canola ($AF_{o,c,t,s}$) from outside the study area at a fifty percent markup on the market price ($CAFP$).

$$AFC_{t,s} = \sum_o \sum_c AF_{o,c,t,s} \times CAFP \quad (13)$$

Equation (14) addresses the area requirement for alternate-year cultivation of winter canola in the system. Equation (15)–(18) formulate the mass balance constraints related to the OEM. Specifically, equation (15) ensures that the total oilseed transported from the hexagon to the OEM for scenarios s and year t ($Field2OEM_{i,o,c,t,s}$) does not exceed the total canola seed produced in that particular scenario and

year. Equation (16) guarantees a material balance ($Seed2Oil$) from oilseed ($\sum_i Field2OEM_{i,o,c,t,s}$) to the extracted crude oil ($YO_{o,c,t,s}$). Equation (17) ensures that the volume of crude oil transported from OEM is equal to the volume received at the biorefinery ($\sum_b \sum_d XO_{o,c,b,d,t,s}$), while Equation (18) defines the upper bounds UO_c of annual output in OEMs of various sizes.

$$2AH_i \leq Area_i \quad \forall i \quad (14)$$

$$Field2OEM_{i,o,t,s} \leq AH_i \times Y_s \times YF_i \quad \forall i, t \text{ and } s \quad (15)$$

$$YO_{o,c,t,s} = \sum_i Field2OEM_{i,o,c,t,s} \times Seed2Oil \quad \forall o, c, s, t \quad (16)$$

$$YO_{o,c,t,s} = \sum_b \sum_d XO_{o,c,b,d,t,s} \quad \forall o, c, t, \text{ and } s \quad (17)$$

$$YO_{o,c,t,s} \geq UO_c \times DVM_{o,c} \quad \forall o, c, t, \text{ and } s \quad (18)$$

Equation (19)–(21) formulate all constraints related to the biorefinery. Equation (16) guarantees a mass balance (crude oil versus SAF). Equation (20) ensures the total volume of SAF transported from the biorefinery to the airport ($\sum_m XB_{b,d,m,t,s}$) matches the output of the biorefinery ($YB_{b,d,t,s}$). Equation (21) defines the upper bounds UB_d of annual output in refineries of various sizes.

$$YB_{b,d,t,s} = \sum_o \sum_c XO_{o,c,b,d,t,s} \times Oil2SAF \quad \forall b, d, t, \text{ and } s \quad (19)$$

$$YB_{b,d,t,s} = \sum_m XB_{b,d,m,t,s} \quad \forall b, d, t, \text{ and } s \quad (20)$$

$$YB_{b,d,t,s} \geq UB_d \times DVB_{b,d} \quad \forall b, d, t, \text{ and } s \quad (21)$$

Table 1
Definitions of subscripts, parameters, and variables.

Indices	Definition
<i>i</i>	Hexagon location for winter canola production
<i>o</i>	Industrial park sites for oil extraction mill
<i>b</i>	Industrial park sites for bio-refinery
<i>c</i>	OEM size
<i>d</i>	Biorefinery size
<i>m</i>	Location for airport
<i>t</i>	Index of time (year)
<i>s</i>	Index of scenario
Parameters	
$Area_i$	Area available for planting winter canola in hexagon <i>i</i>
<i>E</i>	Per unit winter canola establishment and cultivation cost
<i>L</i>	Per unit land opportunity cost
<i>CAFP</i>	Per unit additional feedstock purchase cost
Y_s	Winter canola yield in scenario <i>s</i>
YF_i	Yield adjustment factor for hexid <i>i</i>
LF_i	Land opportunity cost adjustment factor for hexid <i>i</i>
UO_c	The upper bound of crude oil that can be extracted in size <i>c</i> OEM
UB_d	The upper bound of SAF that can be produced in size <i>d</i> biorefinery
<i>Seed2Oil</i>	The ratio of winter canola seed to oil
<i>Seed2Meal</i>	The ratio of winter canola seed to meal
<i>Oil2SAF</i>	The ratio of crude oil to SAF
<i>Oil2Naphtha</i>	The ratio of crude oil to naphtha
<i>Oil2Diesel</i>	The ratio of crude oil to diesel
<i>Oil2Prop</i>	The ratio of crude oil to propane
<i>MP</i>	Meal price
<i>NP</i>	Naphtha price
<i>PP</i>	Propane price
<i>DP</i>	Diesel price
CB_d	Annual equivalent of capital expenditure for a size <i>d</i> biorefinery
CO_c	Annual equivalent of capital expenditure for a size <i>c</i> OEM
<i>OO</i>	Operational expenditure for a refinery
<i>OB</i>	Operational expenditure for a biorefinery
$ATCHO_{i,o}$	Average oilseed transportation costs
$ATCOB_{o,b}$	Average crude oil transportation costs
$ATCBA_{b,m}$	Average SAF transportation costs
<i>IRR</i>	Discount interest rate (%)
$DHO_{i,o}$	Distance between hexagon ID <i>i</i> to OEM <i>o</i>
$DOB_{o,b}$	Distance between OEM <i>o</i> to biorefinery <i>b</i>
$DBA_{b,m}$	Distance between biorefinery <i>b</i> to airport <i>m</i>
<i>SHO</i>	Speed of truck transporting oilseed
<i>SOB</i>	Speed of truck transporting crude oil
<i>SBA</i>	Speed of truck transporting SAF
<i>LC</i>	Labor cost (\$/hour)
<i>TLC</i>	Truck cost without labor (\$/hour)
<i>TTC</i>	Tank truck cost, including labor (\$/hour)
<i>TLLT</i>	Oilseed load time
<i>TULT</i>	Oil load time
Binary decision variables	
$DVM_{o,c}$	Dummy variable that indicates whether industrial park <i>o</i> has been selected as size <i>c</i> OEM (1 yes, 0 otherwise)
$DVB_{b,d}$	Dummy variable that indicates whether industrial park <i>b</i> has been selected as size <i>d</i> biorefinery (1 yes, 0 otherwise)
Continuous decision variables	
AH_i	Area cultivated and harvested to produce canola seed
$Field2OEM_{i,o,c,t,s}$	Total seed supplied from hexid <i>i</i> to OEM <i>o</i> of size <i>c</i> in scenario <i>s</i>
$AF_{o,c,t,s}$	Additional feedstock required for <i>c</i> size OEM <i>o</i> in scenario <i>s</i>
$YO_{o,c,t,s}$	Amount of crude oil crushed by <i>c</i> size OEM <i>o</i> in year <i>t</i> and scenario <i>s</i>
$XO_{o,c,b,d,t,s}$	Amount of oil sent from <i>c</i> size OEM <i>o</i> to <i>d</i> size biorefinery <i>b</i> in scenario <i>s</i>
$YB_{b,d,t,s}$	Amount of SAF produced by <i>d</i> size biorefinery <i>b</i> in scenario <i>s</i>
$XB_{b,d,m,t,s}$	Amount of SAF sent from <i>d</i> size biorefinery <i>b</i> to airport <i>m</i> in scenario <i>s</i>
$TCHO_{t,s}$	Total oilseed transportation cost in scenario <i>s</i> and year <i>t</i>
$TCOB_{t,s}$	Total crude oil transportation cost in scenario <i>s</i> and year <i>t</i>
$TCBA_{t,s}$	Total SAF transportation cost in scenario <i>s</i> and year <i>t</i>
$TC_{t,s}$	Total transportation cost in scenario <i>s</i> and year <i>t</i>
$OEC_{t,s}$	Total oil extraction cost in scenario <i>s</i> and year <i>t</i>
PC_t	Total winter canola oil seed production cost in year <i>t</i>
$CC_{t,s}$	Total conversion cost in scenario <i>s</i> and year <i>t</i>
$SR_{t,s}$	Total SAF revenue in scenario <i>s</i> and year <i>t</i>
$CR_{t,s}$	Total co-products revenue in scenario <i>s</i> and year <i>t</i>
$AFC_{t,s}$	Total additional feedstock cost in scenario <i>s</i> and year <i>t</i>

Table 2
Different parameters used in the model.

Item	Unit	Value	References
Establishment and cultivation cost of winter canola	\$/ha	535	[38]
OEM operational cost	\$/MT seed	9.5	[19]
OEM capital cost	Million \$ for 500,000 MT capacity	36	[39]
Biorefinery age	Year	20	[40]
Biorefinery salvage value	% of capital cost	10	[40]
Biorefinery capital cost	million \$ for 1025 M liters SAF capacity	456.5	[40]
Biorefinery operational cost	\$/liter of product	0.5	[40]
Conversion factor of canola seed to oil	%	44	[18]
Conversion factor of canola seed to canola meal	%	56	[18]
Conversion factor of crude oil to SAF	%	71	[40]
Conversion factor of crude oil to naphtha	%	8	[40]
Conversion factor of crude oil to propane	%	11	[40]
Conversion factor of crude oil to diesel	%	10	[40]
Canola meal price	\$/kg	0.4	[41]
Naphtha price	\$/liter	0.9	[40]
Propane price	\$/liter	0.4	[40]
Diesel price	\$/liter	1	[40]
Interest rate	%	10	[40]

3.4. Carbon intensity estimation

The LCA of the optimal solution from the stochastic supply chain model includes all inputs and outputs related to canola cultivation, such as fertilizer, herbicides, insecticides, diesel for non-road transportation, natural gas, and electricity. It also includes other energy sources for transportation, oil extraction, and conversion in biorefineries. The carbon dioxide equivalent (CO₂ eq) emissions were calculated using the Intergovernmental Panel on Climate Change (IPCC) 100-year global warming potential factors for carbon dioxide (CO₂), methane (CH₄), and nitrous oxides (N₂O) to determine the grams of CO₂ eq produced per MJ of SAF. The global warming potential values applied were 1, 28, and 265 for CO₂, CH₄, and N₂O, respectively, based on the IPCC's 100-year timescale assessment methodology [42]. The LCA doesn't encompass soil organic carbon sequestration or induced land-use changes, as this study assumes the winter oilseeds will be planted on the constrained winter wheat land between crop rotations (described in section 2); thus, the iLUC issue is presumably modest.

The LCA was conducted utilizing the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) 2025 model [43] developed by Argonne National Laboratory, which provides comprehensive life-cycle emission factors for feedstock cultivation, oil extraction, transportation, and biorefinery conversion processes. Agricultural input data, including fertilizer application rates, pesticide usage, diesel consumption, and other farming inputs, were obtained from state-level agricultural extension databases to ensure region-specific accuracy and representativeness. These agricultural input parameters were subsequently integrated with corresponding GREET emission factors to quantify cultivation-stage emissions. Emission factors for oil extraction and HEFA conversion processes were sourced directly from the GREET database to maintain methodological consistency across all supply chain stages. Environmental burdens were allocated between sustainable aviation fuel and co-products using a two-stage allocation methodology: mass allocation was applied at the oil extraction stage, while energy allocation was employed at the biorefinery stage. This allocation framework adheres to ISO 14040/44 guidelines and maintains consistency with the established GREET methodology for multi-product

systems. In this study, carbon intensity (in $\text{gCO}_2\text{e MJ}^{-1}$) was selected as the primary environmental metric because it is the most widely adopted measure in regulatory frameworks (e.g., CORSIA, LCFS, IRA 45z) and directly determines SAF's sustainability relative to fossil jet fuel in related literature [44].

Equation (22) estimates the CI for each yield scenario in the winter canola-based SAF supply chain, which is displayed as:

$$CI_{SAF,s} = \left(GHG_{sp} + GHG_{transSeed,s} + GHG_{OE,s} + GHG_{tranCrudeoil,s} + GHG_{Con,s} + GHG_{transSAF,s} \right) / SAF_s \quad (22)$$

Equation (23)–(28) further define the variables in equation (19). Equations (29) and (30) represent the allocation factor in OEMs (AFO) and biorefineries (AFB).

$$GHG_{sp} = GHG_{seed} \times \sum_i AH_i \quad (23)$$

$$GHG_{transSeed,s} = \sum_{i,o,c} Field2OEM_{i,o,s} \times DHO_{i,o} \times GHG_{trans} \quad (24)$$

$$GHG_{OE,s} = \sum_o YO_{o,s} \times GHG_{OEM} \times AFO \quad (25)$$

$$GHG_{tranCrudeoil,s} = \sum_{o,b} XO_{o,b,s} \times DOB_{o,b} \times GHG_{trans} \quad (26)$$

$$GHG_{Con,s} = \sum_b YO_{b,s} \times GHG_{Refinery} \times AFB \quad (27)$$

$$GHG_{transSAF,s} = \sum_{b,m} XB_{b,m,s} \times DBA_{b,m} \times GHG_{trans} \quad (28)$$

$$AFO = \text{mass}(\text{crude oil}) / [\text{mass}(\text{crude oil}) + \text{mass}(\text{canola meal})] \quad (29)$$

$$AFB = \text{energy}(\text{SAF}) / [\text{energy}(\text{SAF}) + \text{energy}(\text{co-products})] \quad (30)$$

Equation (23) calculates the total GHG emissions during the cultivation stage (GHG_{sp}), which is scenario independent as the same amount of inputs is applied to produce winter canola per unit of land, where GHG_{seed} is the unit emissions related to the cultivation equal to 483.7 kg CO_2 equivalent ha^{-1} of the winter canola [43]. Equations (24), (26) and (28) compute the emissions from transporting winter canola seed ($GHG_{transSeed,s}$), crude oil ($GHG_{tranCrudeoil,s}$), and SAF ($GHG_{transSAF,s}$), respectively, where GHG_{trans} represents the unit emission of trucking. Equation (25) calculates the emissions in OEMs ($GHG_{OE,s}$), where GHG_{OEM} represents the unit emissions related to the oil extraction at 0.3 kg CO_2 equivalent per liter of crude oil [43]. Equation (27) computes the emissions in HEFA biorefinery ($GHG_{Con,s}$), where $GHG_{Refinery}$ represents the unit conversion emissions at 0.5 kg CO_2 equivalent per liter of SAF [43].

4. Results and discussion

4.1. Supply chain configuration

The optimal land allocation for winter canola cultivation and facilities location for Cases I and II, determined by the stochastic optimization model, is shown in Fig. 4a and b, respectively. The model was solved using GAMS software on an Intel Core processor with 32 GB RAM, providing results after approximately 52 h with an optimal gap of 0.05. In Case I, 0.2 million ha of land is chosen for feedstock cultivation, with around 85 % of the utilized land located in Kentucky. These lands are selected as they are near the only existing OEM, thus lowering transportation costs. The model selects one biorefinery of 265 million liters yearly (MLY) SAF production capacity (around 373 MLY total production capacity) to adjust the wide range of feedstock yield variations.

In Case II, with additional investment in OEMs, around 0.6 million ha

of land in 114 counties (56 in Kentucky and 58 in Tennessee) are cultivated annually for winter canola. Six additional OEMs, in addition to the existing OEM, are placed. Two biorefineries are sited to supply BNA, with one having a SAF production capacity of 302 MLY SAF (nearly 425 MLY total production capacity) in Tennessee and the other having 190 MLY (nearly 268 MLY total capacity) in Kentucky. One biorefinery serving MEM with a SAF production capacity of 302 MLY (nearly 425 MLY total capacity) is situated in southwest Tennessee. The facilities are located near areas with higher oilseed production capacity.

4.2. SAF production

Given the variability in winter canola yield, the volume of SAF supplied to the targeted airports fluctuates widely. As illustrated in Fig. 5a, the estimated volume of SAF supplied to BNA in Case I could fluctuate between 129 MLY and 246 MLY. In Case II (Fig. 5b), total SAF supply may vary from 370 MLY to 711 MLY with a 90 % likelihood. Specifically, the supply for BNA ranges from 227 MLY to 439 MLY, while for MEM, it ranges from 143 MLY to 272 MLY. The variations in winter canola yield present a tangible risk of shortfalls in meeting SAF production targets in both cases. To avoid supply chain disruptions, decision-makers need to arrange additional feedstocks when winter canola yield is low. In the low-yield scenarios, acquiring an extra 14,000 MT to 836,000 MT of oilseed is necessary to meet the SAF target, incurring considerable additional costs.

Fig. 6a and b illustrate the expected value of winter canola seed supply, crude oil, and SAF flows in Case I and II, respectively.³ When the supply chain relies on the existing OEM in Case I (Fig. 6a), SAF is exclusively supplied to BNA airport. Annually, the expected quantity of harvested oilseed is 580,852 metric tons (MT), with 85 % of the supply sourced from Kentucky to the existing OEM. The expected SAF received at BNA is 190 MLY. In Case II (Fig. 6b), with additional infrastructures that include multiple OEMs and biorefineries, the supply chain is configured to supply both BNA and MEM. The expanded winter canola cultivation leads to the expected annual harvest of around 1.7 million MT of oilseed, with 55 % harvested and crushed in Kentucky. Most oils are sent to the biorefineries in Tennessee to produce SAF, with 347 MLY to BNA and 212 MLY to MEM.

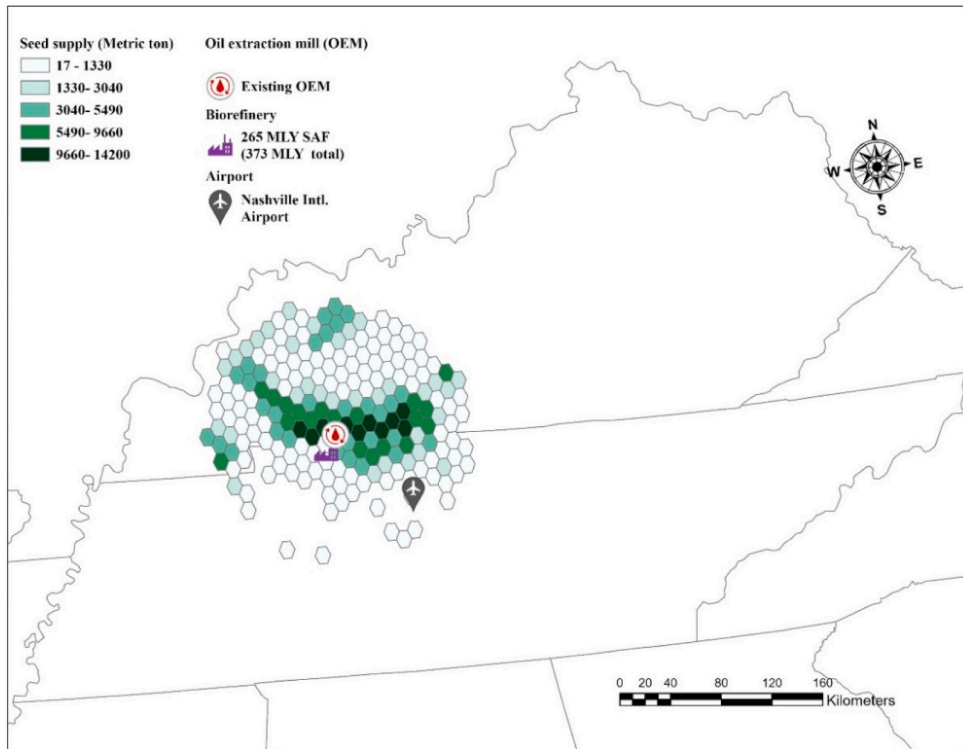
4.3. SAF production cost

Winter canola yield variability introduces substantial risks to the economic viability of SAF production. Our analysis indicates that, after considering co-product revenues, SAF production costs fluctuate between \$0.6 to \$1.7 per liter for Case I and \$0.7 to \$1.7 per liter for Case II, with a 90 % likelihood, as shown in Fig. 7a and b. Lower feedstock yields increase the per unit cost of SAF production due to the higher average seed cost, the lower facility utilization rate, and the purchase of additional feedstock at a higher price. Under the low yield scenarios (less than the most probable yield value), the unit cost can escalate to between \$1.1 and \$2.1 per liter. Furthermore, the procurement of additional feedstock can account for 4 %–38 % of the total production cost, highlighting the substantial impact of yield variability on SAF's economic feasibility.

The expected cost of SAF production is estimated at around \$2 per liter in both cases. Fig. 8 provides a comprehensive breakdown of these cost components. The conversion cost accounts for the highest share (45 %) of the total unit cost, followed by feedstock production costs, including establishment, management, and land opportunity costs, which comprise 28 % of the total per-unit cost. Oil extraction costs represent 22 % of the cost, whereas transportation costs amount to 4 % of the per-unit cost. After considering co-product revenue, including canola meal, naphtha, diesel, and propane, which totals \$0.9 per liter,

³ The figures focus solely on SAF and exclude co-products to enhance clarity.

a) Case I



b) Case II

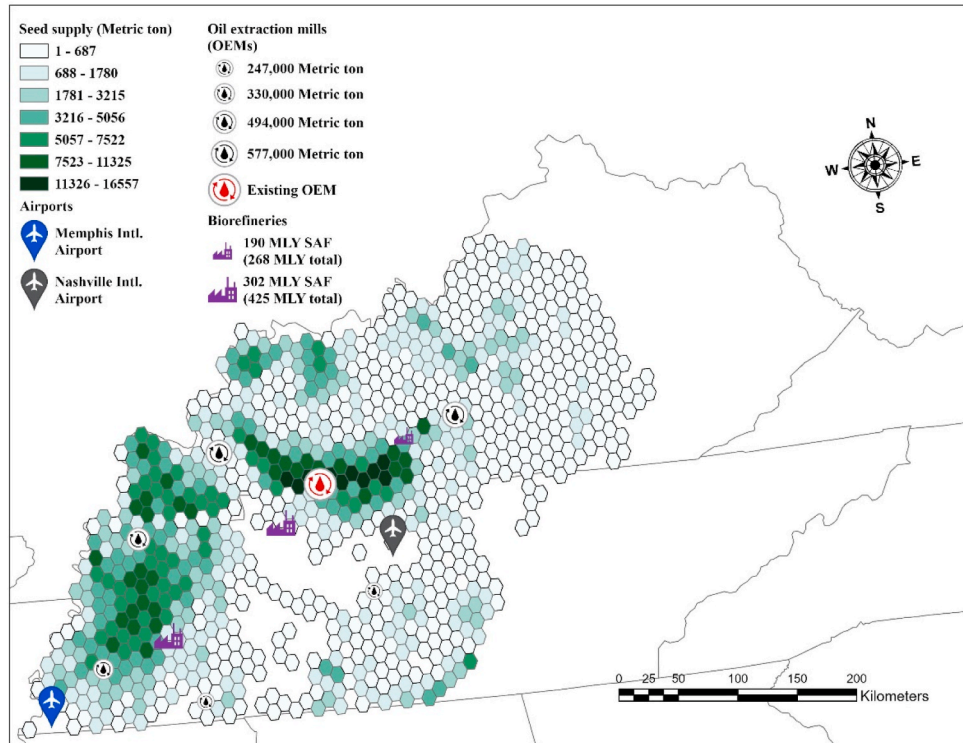
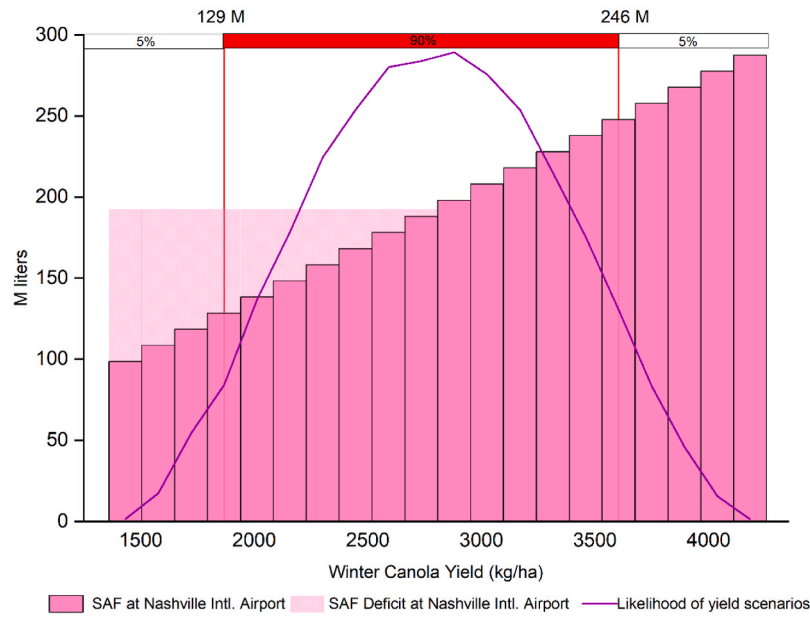


Fig. 4. Optimal supply chain placement.

a) Case I



b) Case II

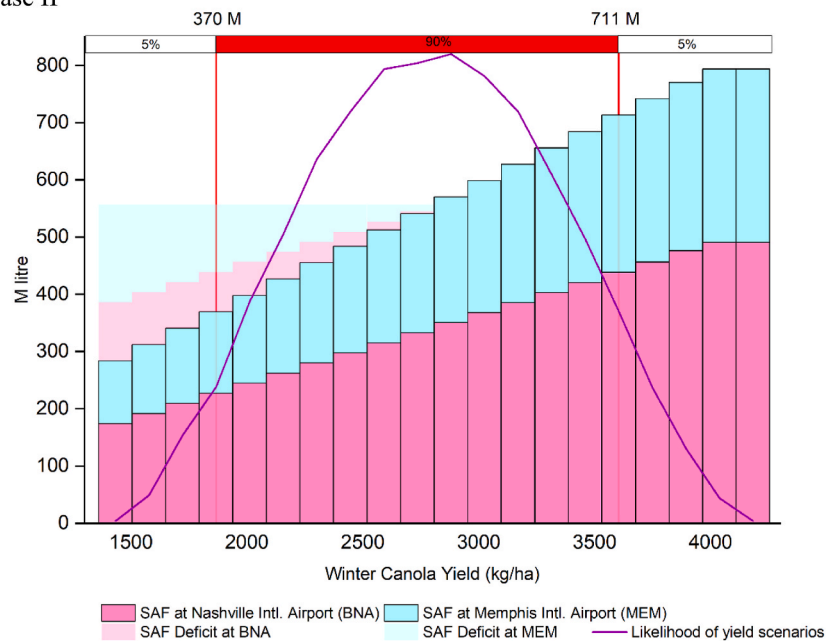


Fig. 5. SAF production in different winter canola yield scenarios.

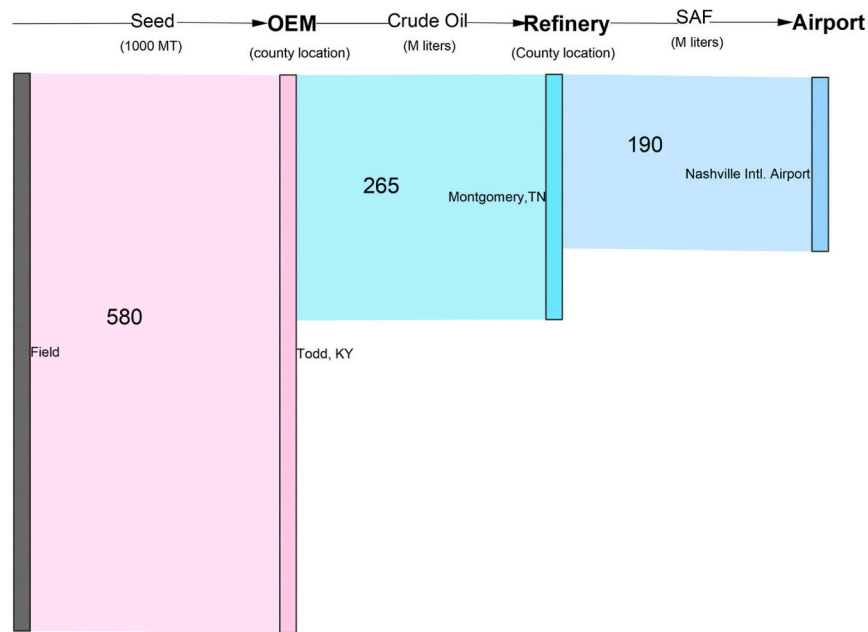
the expected breakeven cost is \$1.1 per liter, which is higher than the average price of jet fuel (\$0.7 per liter) for 2023 [45].

The expected cost aligns with previous studies on the SAF production cost from the HEFA pathway using other oilseeds incorporating co-product revenues. Li et al. [39] estimated the cost of camelina-based HEFA SAF to vary between \$0.4 and \$1.7 per liter based on the plant capacity, feedstock cost, and co-products credits, while Mousavi-Avval and Shah [46] estimated the cost of \$1.2 per liter for pennycress-based HEFA SAF. The difference in the estimated breakeven costs may be attributed to varying seed yield, feedstock prices, facility sizes, and system boundaries considered in these studies.

4.4. Carbon intensity of supply chain

The variability in winter canola yield introduces fluctuations in the CI of the SAF supply chain, highlighting the critical relationship between feedstock yield and the environmental sustainability of SAF. Fig. 9a and b displays the CI over the different yield scenarios in Case I and II, respectively. Our estimates show that the CI of SAF in the two cases ranges from 31 g CO₂e MJ⁻¹ to 43 g CO₂e MJ⁻¹, with a 90 % likelihood

a) Case I



b) Case II

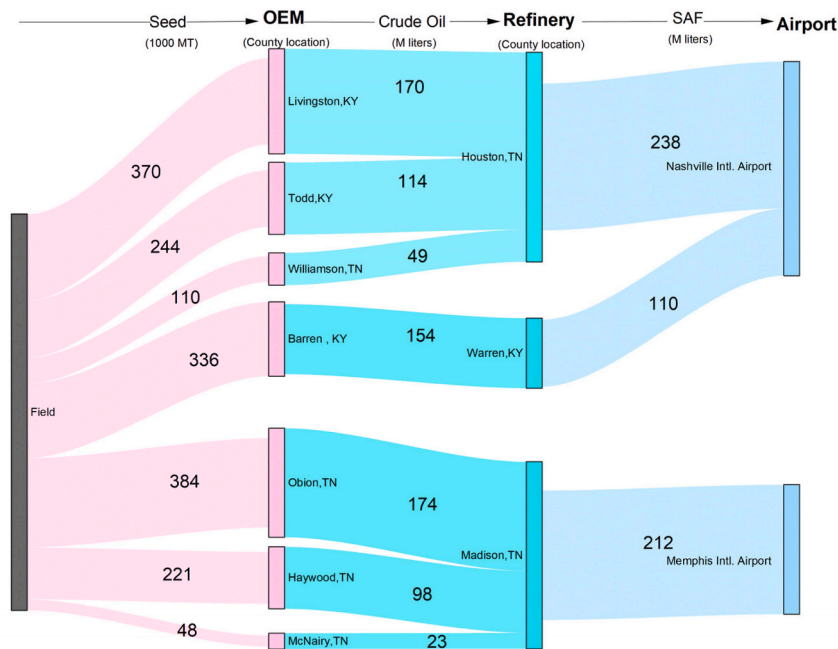


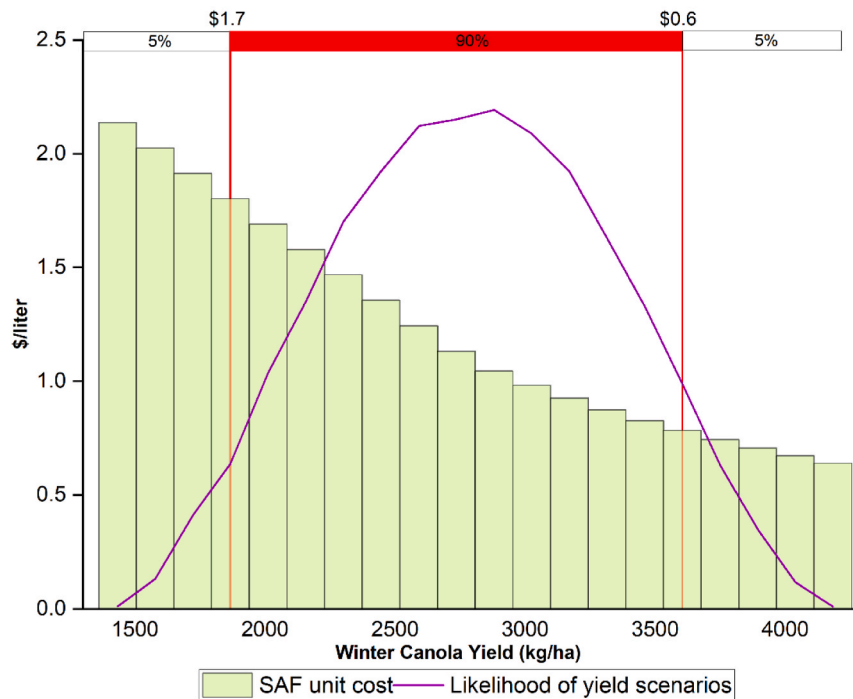
Fig. 6. Winter canola seed, crude oil, and SAF flow in the supply chain.

and an expected value of $35 \text{ g CO}_2\text{e MJ}^{-1}$.⁴ The wide range of CI is mainly due to winter canola production, which accounts for 39%–55% of life-cycle GHG emissions. The higher carbon emission during winter

⁴ The CI estimates did not account for induced land-use change (iLUC). Inclusion of the iLUC would increase the CI. However, this study assumes the winter canola will be planted on the constrained winter wheat land (described in the second paragraph in section 2); thus, the iLUC issue is presumably modest.

canola production is primarily driven by synthetic N-fertilizers and related N-fertilizers' emissions, which collectively contribute 16–23 $\text{g CO}_2\text{e MJ}^{-1}$ [45]. When winter canola yields are low on a given ha, the input use per kg of seed increases, thereby escalating the CI. Our results are aligned with previous studies. For instance, Obnamia et al. [47] estimated that canola production accounts for 56%–65% of life cycle GHG emissions for canola-based SAF. Similarly, Gupta et al. [48] found that the rapeseed cultivation stage accounts for 69% of the life cycle emissions from rapeseed oil-based biodiesel production. Beyond cultivation, the HEFA conversion process contributes 27%–37% of life cycle

a) Case I



b) Case II

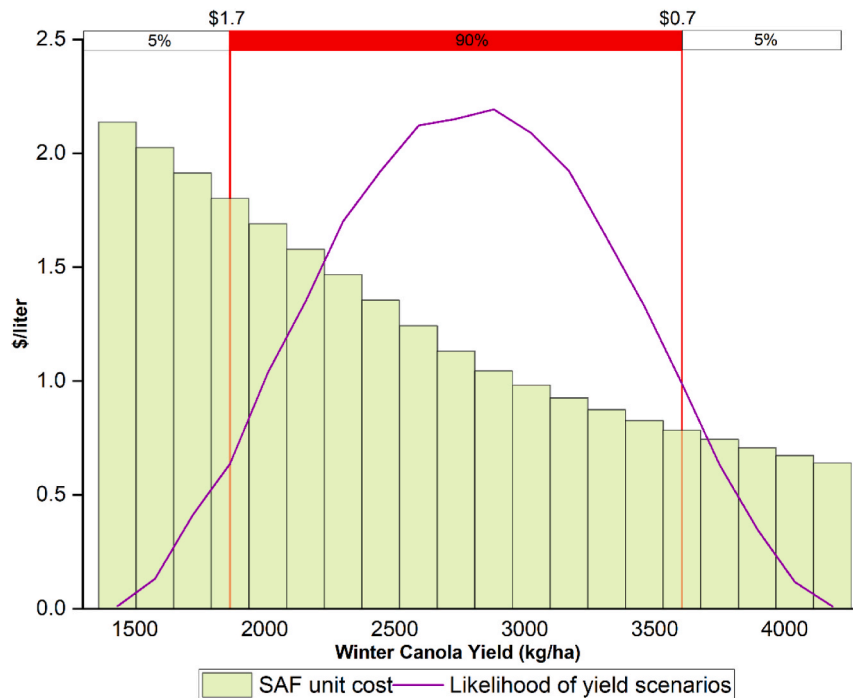


Fig. 7. Stochastic per unit cost of SAF production.

emissions, while oil extraction and transportation account for 16 %–20 % of the total emissions footprint.

Our findings suggest SAF from winter canola in our study area, with a CI ranging from 31 g CO₂e MJ⁻¹ to 43 g CO₂e MJ⁻¹, could reduce carbon emissions from CAF (88 g CO₂e MJ⁻¹) by 51 %–65 % under a 90 % likelihood, without considering iLUC. The fluctuations in CI associated

with feedstock yield variations, as demonstrated in our study, underscore the need for strategies that stabilize and enhance winter canola production. Effective management of yield variations through improved agricultural practices and strategic planning could ensure that winter canola-based SAF remains eligible for tax credits and Renewable Identification Numbers credits, making it economically competitive with

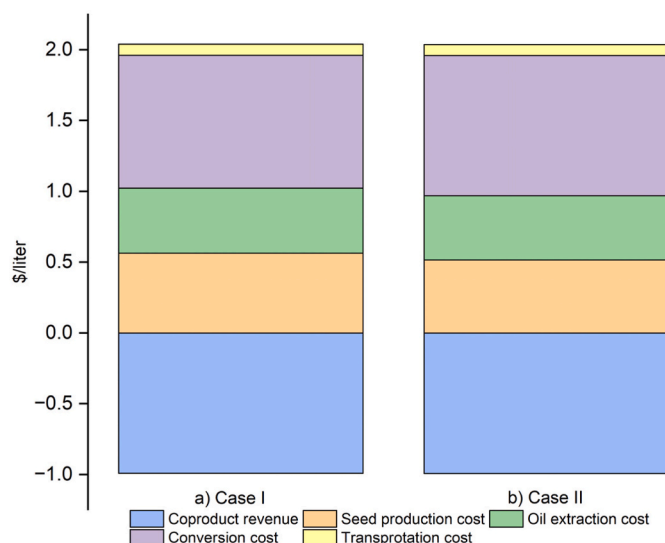


Fig. 8. Share of Expected SAF cost by component.

CAF.

Our study improves previous biofuel and SAF supply chain research by directly linking feedstock yield variations and distribution to SAF production, unit cost, and CI. Earlier studies either link costs and emissions through deterministic optimization (e.g., Basile et al. [49]) or address uncertainties without covering life-cycle GHG emissions (e.g., Bairamzadeh et al. [25]). In contrast, our approach combines economic, life-cycle, and spatial analyses in a single framework. By explicitly linking feedstock yield, costs, facility location, and CI, we provide stakeholders with a clear tool to evaluate the effects of feedstock variability. Our findings help decision-makers improve the efficiency and sustainability of SAF production from winter oilseeds and demonstrate the scientific value of our work.

4.5. Sensitivity analysis

To quantify the potential impacts of the variations in the input data and parameters on the model outputs, a series of one-at-a-time sensitivity analyses were conducted for Case II on three key parameters: i) land availability for winter canola cultivation, ii) seed oil content, and iii) crude oil to SAF conversion efficiency. The three parameters are influential to feedstock supply and demand for SAF production, thus are aligned with the scope of this study, which focuses on the impact of feedstock availability variation on the SAF supply chain. The parameter ranges were chosen to reflect agronomic variability, process uncertainty, and adoption constraints, while remaining consistent with values reported in the literature. Figures for sensitivity analysis are presented in the Supporting Information file.

4.5.1. Land availability

To evaluate uncertainty in the land availability assumption, we adjusted the land availability parameter by $\pm 20\%$ from the baseline level at 1.2 million ha (i.e., from 0.96 to 1.44 million ha), representing plausible uncertainty in producer adoption and regional suitability. Under baseline conditions, total SAF supply in Case II is estimated to range from 370 to 711 MLY with 90 % probability. When land availability is reduced by 20 %, the SAF supply range contracts to 322–621 MLY, reflecting both lower seed availability and reduced facility utilization. Conversely, when land availability is increased by 20 %, the SAF supply range expands to 488–942 MLY, allowing higher refinery throughput and increased SAF output to both BNA and MEM. Expected SAF supply to BNA falls between 262 MLY (land reduced by 20 %) and 372 MLY (land increased by 20 %), while MEM receives 196 MLY with a

20 % land reduction and 321 MLY with a 20 % land increase. Unit costs (net of co-product revenues) vary with scale and utilization: \$0.7–\$2.0/L (-20% of land) and \$0.5–\$1.7/L ($+20\%$ of land). Higher costs with reduced land reflect under-utilization of crushing/refining capacity; expanded land improves utilization and narrows the upper tail of costs. Since life-cycle parameters per acre are unchanged, CI is invariant to land availability.

4.5.2. Seed oil content

The baseline winter canola seed oil content was set at 44 %, consistent with reported averages for different varieties grown under U. S. conditions. Agronomic studies typically report 38–48 % oil by seed weight, with variation across cultivars, management practices, and environments [18]. To reflect this natural variability, we varied the oil-content parameter by $\pm 10\%$ relative to the baseline (i.e., 39.6–48.4 %). This interval lies within experimentally observed values and captures plausible uncertainty in realized oil yield. Varying seed oil content by $\pm 10\%$ from the 44 % baseline (39.6–48.4 %) shifts the distribution of total SAF supply. Under a 90 % likelihood, SAF supply ranges from 363 to 701 MLY in the -10% of seed oil content case and expands to 439–847 MLY in the $+10\%$ case. Accordingly, BNA receives 345 MLY and MEM receives 171 MLY under the -10% oil-content case; whereas BNA receives 382 MLY and MEM receives 256 MLY when seed oil content increases by 10 %. Unit costs change inversely with oil content: $0.7\text{--}2.2\ \$\text{L}^{-1}$ (-10%), $0.7\text{--}1.7\ \$\text{L}^{-1}$ (baseline), and $0.4\text{--}1.6\ \$\text{L}^{-1}$ ($+10\%$) in a 90 % probability; corresponding expected costs are 2.2, 2.0, 1.9 \$ L^{-1} . Since changes in seed oil content affect the effective yield of farming inputs per unit of oil produced, the CI of SAF also varies. Life-cycle CI rises under the low-oil content case ($33\text{--}46\ \text{g CO}_2\text{e MJ}^{-1}$) and falls under the high-oil content case ($30\text{--}41\ \text{g CO}_2\text{e MJ}^{-1}$).

4.5.3. Conversion rate from crude canola oil to SAF

The crude canola oil to SAF conversion in the baseline was set at 72 % following Brandt et al. [40]. Sensitivity bounds were established by varying this parameter by $\pm 10\%$ (i.e., 64.8 %–79.2 %). The upper bound aligns with GREET [43], which reports a conversion efficiency of approximately 79 %. In Case II, the 90 % probability interval of SAF supply narrows to 366–705 MLY when lowering 10 % of conversion rate, whereas it widens to 439–847 MLY under the $+10\%$ case. Relative to baseline, expected airport shipments are 319 MLY to BNA and 201 MLY to MEM in the -10% case. When the conversion rate improves by 10 %, 365 MLY of SAF is delivered to BNA and 281 MLY to MEM. SAF unit costs vary inversely with conversion efficiency, ranging from \$0.7 to \$2.2 per liter in the -10% scenario and \$0.4 to \$1.7 per liter in the $+10\%$ scenario, with corresponding expected costs of \$2.2 and \$1.9 per liter, respectively. Consequently, the lifecycle CI rises in the low conversion rate case, ranging from 34 to 47 $\text{g CO}_2\text{e MJ}^{-1}$, while it decreases when the conversion rate is increased by 10 %, falling to a range of 30–40 $\text{g CO}_2\text{e MJ}^{-1}$.

5. Conclusion

The development of winter canola-based SAF presents an exciting opportunity to decarbonize the aviation sector while delivering economic benefits. Our study highlights the impact of feedstock yield uncertainty in shaping both the economic and environmental performance of SAF production. With production costs ranging from \$0.6 to \$1.7 per liter and CI fluctuating between 31 and 43 $\text{g CO}_2\text{e MJ}^{-1}$, with a 90 % probability, the findings underscore the need for proactive strategies to manage feedstock yield variability. Decision-makers and investors are encouraged to prioritize investments in technologies and practices that mitigate supply chain risks, ensuring the long-term viability of SAF.

Developing winter canola-based SAF not only supports decarbonization but also offers valuable agronomic and economic advantages. By improving soil health and enhancing summer crop yields, winter canola supports sustainable agricultural practices. Economically, it provides

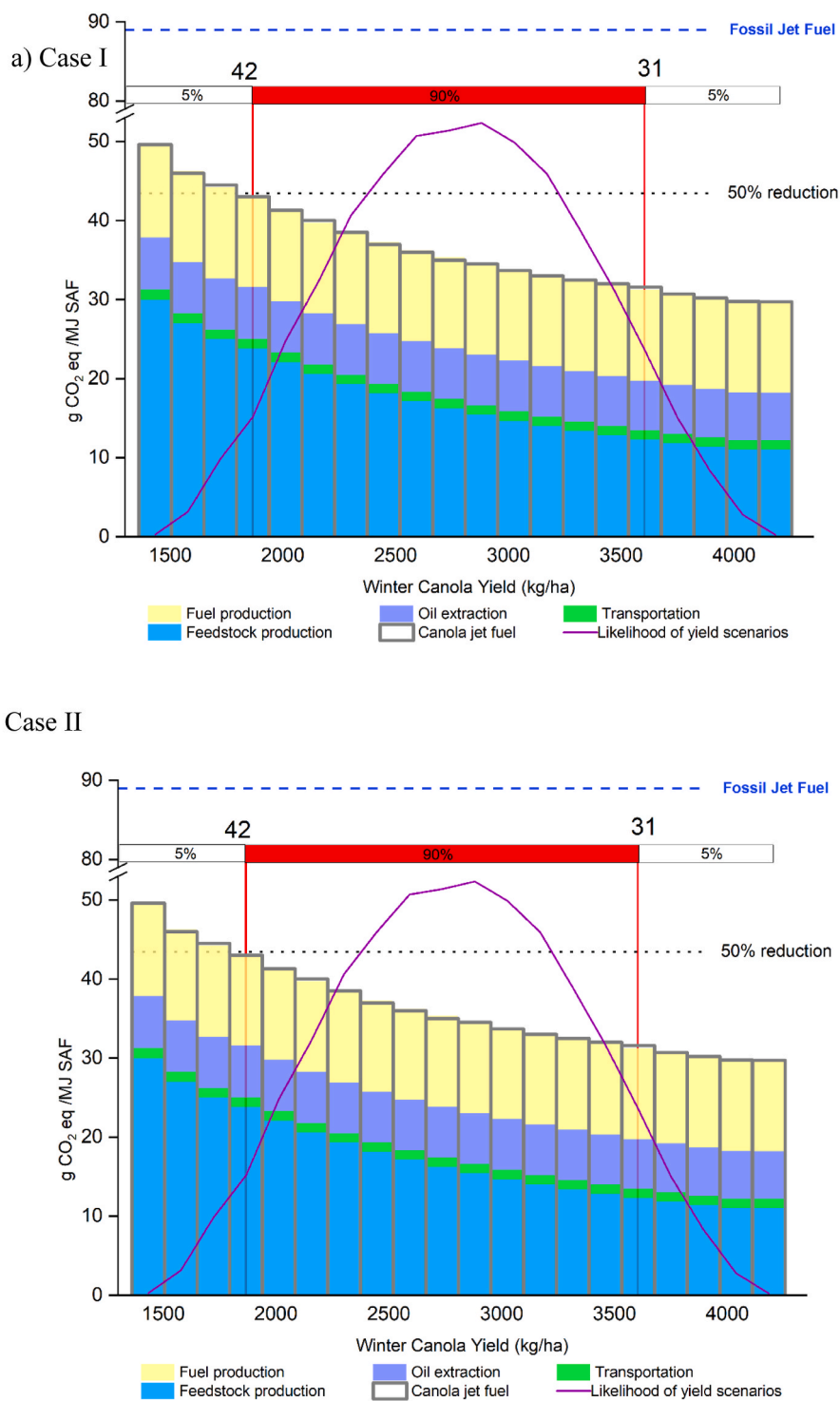


Fig. 9. Carbon intensity of winter canola-based SAF on different yield scenarios.

farmers with additional revenue and stimulates regional development through new markets and job creation in oil extraction and conversion facilities. These benefits position winter canola as a sustainable and economically viable feedstock for SAF production.

Future research can extend this study by incorporating factors that cause feedstock yield uncertainty, such as soil quality and climate variability, along with additional experimental data from diverse locations and years. Also, differences in agronomic practices or economic factors between winter canola and winter wheat may lead to deviation in winter canola's performance and adoption in specific areas. Finally,

iLUC is not considered in the estimated CI in this study, as the available land for winter canola in this study is assumed from the constrained winter wheat area; thus, the impact of iLUC is presumably moderate. Future studies could incorporate the iLUC in the estimate of CI if different land use assumptions are made. Also, field studies and farmer surveys could be incorporated to refine land suitability estimates and optimize investment strategies. Exploring other feedstocks and SAF pathways could further enhance the resilience and scalability of SAF. Advancing both research and industrial efforts can unlock the full potential of SAF, driving environmental progress and economic benefits

toward sustainable aviation.

CRedit authorship contribution statement

K. Bolakhe: Writing – original draft, Software, Investigation, Formal analysis, Data curation. **T.E. Yu:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **V.R. Sykes:** Writing – review & editing, Validation, Data curation. **S.A. Smith:** Writing – review & editing, Validation. **C.N. Boyer:** Writing – review & editing.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.renene.2026.125291>.

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