Title

Supply Chain Optimization of Sustainable Aviation Fuel from Carinata in the Southeastern United States

Author

Farhad Hossain Masum[1], Ed Coppola[2], John Field[3], Daniel Geller[4], Sheeja George[5], Jonathan Miller[2], Michael J. Mulvaney[6], Sanjay Nana[2], Ramdeo Seepaul[5], Ian Small[5], David Wright[5], Puneet Dwivedi[1]

[1] Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602

[2] Applied Research Associates, Albuquerque, NM 87110

[3] Oak Ridge National Laboratory, Oak Ridge, TN 37830

[4] College of Engineering, University of Georgia, Athens, GA 30602

[5] North Florida Research and Education Center, Quincy, FL 32351

[6] Plant and Soil Sciences, Mississippi State University, Starkville, MS 39762

Corresponding Author

Farhad Hossain Masum, Ph.D.

Warnell School of Forestry and Natural Resources

University of Georgia

180 E Green St Athens GA 30602

Email: mm44295@uga.edu

Abstract

Carinata is a purpose-grown oilseed feedstock for renewable fuels, including sustainable aviation fuel (SAF) that can replace conventional aviation fuel (CAF). Given carinata is a new crop in the Southeastern United States, it is crucial to analyze its sustainability from a supply chain perspective. This study developed a mixed-integer linear programming (MILP) model and simulated for 20 years, starting from a farm (county-level data) and ending at the airport. About 2.06 million ha in Alabama, Florida, and Georgia combined were found suitable for carinata production. Given the three-year rotation period, about 0.69 million ha can be cultivated annually, approximately 65% of which was in Georgia. About 2.4% of the combined SAF annual demand of four major airports (about 210,372 t) in the study area is satisfied at that level of carinata cultivation. However, all available SAF was supplied to the Atlanta airport as this decision minimizes the supply chain cost. A total of 1,343 storage units, one oil extraction mill, and one biorefinery were needed to meet this overall demand. We found that SW Georgia is the top supplier of carinata seeds. The unit cost of production and carbon intensity were estimated to be \$0.89 L^{-1} (or \$26.79 GJ^{-1}) and 0.91 kg CO_2e L^{-1} (or 27.28 kg CO_2e GJ^{-1}), respectively. This carbon intensity of carinata-based SAF was 67.8% lower than that of CAF. With variations included in SAF demand, yield, and soil carbon sequestration, carbon savings remained between 66.5% and 67.8%. Given the GHG advantage of SAF over CAF, there is justification for subsidies required to make SAF competitive.

Highlights

- A supply chain optimization framework for sustainable aviation fuel (SAF) is presented.
- Potential carinata cultivation area and yield in the Southeastern United States is reported.
- Optimal material flow from farms to airports is modeled.
- Break-even price and life cycle carbon emissions are estimated.
- About \$206 per metric ton of CO_2 abated would be necessary to make SAF competitive.

Keywords: life cycle assessment, jet biofuel, aviation sector, sustainability, economic analysis, renewable fuel

Word count – 6147

Abbreviation

\$	US dollars	L	liter
CAF	Conventional Aviation Fuel	Mha	million hectares
CO_2	Carbon dioxide	ML	million liters
CO_2e	Carbon dioxide equivalent	Mt	Million tonnes
GHG	Greenhouse gas	t	Metric ton or tonne
kg	kilogram	SAF	Sustainable Aviation Fuel

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1. Introduction

Commercial aviation is bouncing back after a temporary period of low activities due to COVID confinement and low emissions in 2020 [1]. Research indicates that, by 2050, there will be a 20% increase in aviation activities globally compared to the 2018 level [2]. According to the International Air Transport Association (IATA), conventional aviation fuel (CAF) consumption may increase by 23% at the end of 2030 compared to the 2018 level [3]. Since aviation is responsible for approximately 3.5% of global warming, a projected increase in activities that could lead to more emissions has raised concerns related to GHG-induced climate change [4]. IATA has set a target to reduce GHG emissions to 325 million tonnes (Mt) by 2050, which is 50% lower compared to 2005 levels (650 Mt) and 65% lower compared to the 2019 level (925 Mt) [5]. To achieve this target and avoid the impact of mentioned increased activity, airlines are adopting a combination of strategies, including aerodynamics, engine efficiency, supply chain optimization, improvements in ground operations, and switching to renewable fuel options [6–9]. However, significant improvements in engine technology and aerodynamics require a technological leap, and continuous efficiency gains have slowed recently. For example, the fuel efficiency of international aviation was reported to improve by 2.4% annually between 2000 and 2009, which was reduced to 1.9% annually between 2010 and 2009 [10].

On the other hand, replacing CAF with biomass-based sustainable aviation fuel (SAF) has gained popularity in recent years to achieve significant GHG emissions from the aviation sector. While 33 million liters (ML) of SAF were used by commercial flights in 2019, 83 ML of SAF were projected to be produced in 2021 [3,11]. However, these estimates were dwarfed by the global CAF consumption, around 227 billion L in 2021 and predicted to be 318 billion L in 2022 [12]. The United States alone consumed about 38.9 and 52.2 billion L of CAF in 2020 and 2021, respectively [13]. It is vital to notice that these estimates reflect low aviation activity due to the pandemic. The same consumption estimates before the pandemic were 65.5 and 67.6 billion L in 2018 and 2019, respectively. Aviation activity seems to be reaching the pre-pandemic intensity as, during the first six months of 2022, about 30 billion L of CAF has already been consumed in the United States. Since approximately 90% of emissions from the CAF lifecycle is from the combustion of the carbon content of the fuel [14], replacing CAF with SAF from renewable sources could be an effective strategy to minimize related GHG emissions.

Previous assessments of SAF produced from oilseed crops have found over 50% and up to 80% relative carbon savings compared to CAF in the United States [15–22]. In the Energy allocation method, Ukaew et al. [15] showed that lifecycle GHG emissions of HEFA (Hydroprocessed Esters and Fatty Acids) SAF from canola seeds ranged from 36 to 49 g CO_2e MJ^{-1}. On the displacement allocation, the estimate went down as low as -12 g CO_2e MJ^{-1}, significantly lower than the CAF GHG intensity of 88 g CO_2e MJ^{-1}. SAFs from camelina and jatropha showed higher GHG reduction potential (at least 86%) compared to other conversion processes such as hydrothermal liquefaction (at least 77%) and alcohol-to-jet conversion (at least 60%) [19].

Carinata (*Brassica carinata*), an oil seed crop, can also be converted into drop-in ready SAF using several ASTM-approved pathways [23] and reduce 68% GHG emissions in the process [24]. Carinata seeds have higher oil contents (44% of seed) compared to camelina, canola, or sunflower (between 41% and 43% of seed) [25]. While maximizing the energy product, the catalytic hydrothermolysis jet conversion method can convert 25.27% of the oil to SAF [26], which is approximately twice compared to the HEFA maximum distillate process (12.8% of the oil) [27]. The CHJ process produces additional energy products such as renewable diesel and naphtha, 37.2% and 16.1% of oil, respectively [26], which generates additional revenue. Previous testing of CHJ-based SAF showed no difference in engine operability using CHJ fuel blends from Applied Research Associates (ARA) compared to CAF [26].

Carinata has shown superior yield potential during the winter months in the southeastern United States [28–33]. Besides adding revenue from SAF and other energy products, carinata can provide additional revenue from animal feed during oil extraction [14,34,35]. It may provide other benefits similar to winter cover crops, such as reducing soil erosion [36], improving soil structure [37], and recycling soil nitrogen [38]. Being a winter crop, it also avoids food-vs-fuel debate. Besides the environmental benefits, there are economic justifications for biomass-based SAF. Global conflicts, such as especially the war between Russia and Ukraine, has made the fossil fuel market volatile, and CAF price has increased from \$0.69 L^{-1} to \$1.27 L^{-1} between February 2022 and June 2022 [39]. Given the circumstances, renewable home-grown SAF may provide suitable economic alternative for the United States. Historically, SAF required financial subsidies as it is typically more expensive than CAF [40–42]. However, increased CAF prices make SAF more lucrative as it indicates lower cost of carbon abatement to make SAF cost competitive compared to CAF.

The global airline industry's fuel bill is predicted to be around $192 billion in 2022 [12]. Before the pandemic, in 2019, the United States alone spent $36.5 billion on purchasing CAF [13]. In the first six months of 2022, the CAF bill for the United States was already $26.2 billion. The economic significance of this industry makes a strong argument for making it less vulnerable to volatility. Reducing dependence on CAF by replacing it with SAF can help create a more resistant aviation sector and a more sustainable bioeconomy. To minimize the cost and continued usage of SAF, it is of utmost importance to identify the least cost pathways in the supply chain and to determine optimal locations to create necessary infrastructures such as storage facilities, oil extraction mills, and biorefineries. Linear programming models are valuable tools to achieve such objectives and make economically and environmentally favorable decisions in the bioenergy sector [43–49]. These models combine spatial and temporal variables to produce a realistic future outcome of investment choices.

In this study, we estimated the potential production of carinata in Alabama, Florida, and Georgia. We fed the yield estimates into a mixed-integer linear programming (MILP) model to determine the optimal supply chain configuration for producing SAF from carinata using the CHJ (Catalytic Hydrothermolysis Jet) process and replacing 2.5% of the combined CAF demand from four major airports (Atlanta in GA, Miami in FL, Orlando in FL, and Birmingham in AL) in the region. We selected these airports as they are major airports of the selected states and together supported 97.5 million passengers annually in the pre-pandemic years [50]. Out of selected airports, Atlanta and Miami are hubs for several airlines. Almost every airline has a target of using certain percentages or quantity of SAF over the next coming years—Delta (10%), United (5.7 billion liters), American (1.9 billion liters) [51–53]—it is quite likely that selected airports would be sourcing SAF. We determined optimal locations of firming, infrastructure for grain storage, crushing facilities, and biorefineries and projected the optimal flow of materials (seed, oil, and SAF) in the supply chain over 20 years. We estimated the break-even price of SAF, accounting for the value of various co-products, and associated life cycle GHG emissions. These results can be used to determine subsidies required to sustain SAF, estimate GHG benefits of SAF over a long planning horizon, and, most importantly, make a decision about adopting carinata-based SAF. This study fills the literature gap for infrastructure and other crucial supply chain decisions related to SAF production from carinata. This study also provides the first look on the impact of supply chain decisions in unit cost of production and GHG emissions of SAF from carinata in this region. This study will directly feed into the recenetly announced sustainable aviation fuel grand challenge which aims to replace 100% conventional aviation fuel by 2050.

2. Methods

2.1. DayCent Modeling of Carinata Yield Potential

The DayCent model [54] was adapted to make spatially explicit estimates of potential seed yield and changes in soil carbon when carinata is integrated into annual crop rotations across the frost-safe region of 163 counties in northern Florida, South Alabama, and South Georgia [30], as described in Field et al. [31]. DayCent was calibrated based on above- and below-ground biomass data observed in carinata field trials conducted over the winter of 2015/2016 at the University of Florida North Florida Research & Education Center in Quincy, Florida, under a range of nitrogen (N) fertilizer application treatments [33]. The model was subsequently validated against data from other university field trials [55,56] and data from five commercial-scale production plots in Georgia collected by Agrisoma Biosciences, Inc (now NuSeed Inc.).

The analysis assumed that carinata would be grown as a winter cash crop once every third winter within existing annual crop rotations in the region (modeled as a three-year cotton–cotton–peanut rotation). We considered conventional crop management practices, including field tillage before carinata planting in the middle of November, a split application of 90 kg of N fertilizer per hectare, and harvest in late May following physiological maturity and a three-week dry-down period. This carinata production was simulated across all cultivated annual cropland within the study region, as identified in the 2016 National Land Cover Database. Changes in SOC levels under carinata were evaluated relative to business-as-usual management of the cotton–cotton–peanut rotation, with those crops calibrated as per the DayCent simulations used in the annual EPA Inventory of United States Greenhouse Gas Emissions and Sinks [57]. Area-weighted DayCent results were aggregated to the county scale for further analysis.

2.2. Data and Model

The system boundary for our model is illustrated in Figure 01. The carinata supply chain was evaluated over 20 years or 80 quarters. The seed produced in 163 counties included in the analysis can either go directly to oil extraction mills (OEM) or into storage (STO). The model endogenously decided to supply seed directly to the oil extraction mills or a storage unit in each quarter. Mathematically, seeds would go directly to the oil extraction mills in the first quarter when the seed is available. The remaining seed would go to the storage to satisfy demand in oil extraction mills in subsequent quarters. Oil extracted from seed in the oil extraction mill would be transported to the biorefineries (BIO) to satisfy the quarterly demand. SAF from the biorefinery would be transported to the airport(s). Four airports are considered for this study—Atlanta Hartsfield International Airport in Georgia, Birmingham-Shuttlesworth International Airport in Alabama, Miami International Airport, and Orlando International Airport in Florida. The optimization scenario was set up to replace 277.9 ML of annual jet fuel consumption within those four airports (2.4% of their combined annual fuel consumption), where the model was free to allocate the percentage of carinata-based SAF supplied to each airport. Initial exploratory analysis indicated a total potential of approximately 208 - 347 ML of carinata-SAF in this region, equivalent to between 1.8% and 3% of annual demand from the four major airports in the region. For our detailed supply chain optimization study, we selected a target of 278 ML of annual carinata–SAF production (2.4% of total regional demand). Total quarterly demand in these airports is reported in the supporting information in tonnes (Table S1) [58]. To convert between tonne and liter, we used 1321 L t^{-1} of SAF [14].

We developed a MILP model in General Algebraic Modeling System (GAMS) Studio, version 1.4.5, and solved it using the CPLEX solver. The model was used to determine the cost-minimizing configuration of which counties should produce carinata, where associated OEM, STO, and BIO infrastructure should be located, and which airports should be supplied with carinata SAF. The analysis also estimated the life-cycle carbon intensity of the resulting SAF, though this was not part of the objective function. Sets, scalars, parameters, and variables used in the model are presented in Table 1. Values of all parameters presented in Table 1 are presented in Table 2. Distances between county centers and between county centers and the airports are available in the supporting information (Table S2 and S3, respectively). Carbon sequestration in soil, obtained from the Daycent model, was also included in the carbon intensity calculation. All costs were subject to a 1.9% annual inflation rate and a 6% discount rate, adopted from common business practices.

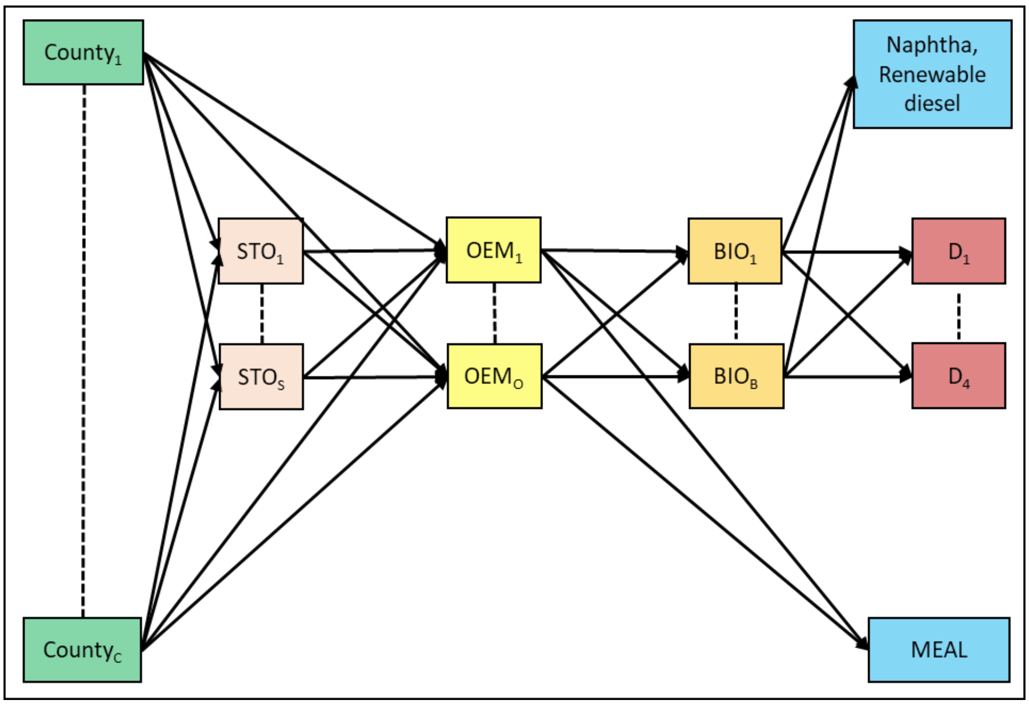

Figure 01: System boundary of the model. STO, OEM, BIO, and D stand for storage units, oil extraction mill, biorefinery, and demand nodes (airports), respectively. STO_S, OEM_O, and BIO_B refer to S^{th} number of storage, O^{th} number of oil extraction mills, and B^{th} number of biorefineries, respectively. D_1 to D_4 refers to the four airports considered for the study. Carinata seed flows between the county and STO/OEM, oil flows from OEM to BIO, and SAF flows from BIO to D. MEAL is animal feed, generated during oil extraction in OEM. Naphtha and renewable diesel are co-products generated in the BIO, during refining oil to SAF.

Table 01: Sets, scalars, parameters, and variables definitions used in the model

Sets	**Definitions**
c	Counties in the study area
s	Candidate counties for storage
o	Candidate counties for OEMs
b	Candidate counties for biorefineries
d	Demand nodes, i.e. airports
q	Quarters in a year, 3 months in every quarter
Scalars	**Definitions**
SCAP, OCAP, BCAP	Establishment cost of storage, OEMs, and biorefineries, respectively
SCT, OCT, BCT	Capacity of each storage, oil extraction mill, and biorefinery, respectively
Seed2Oil	Ratio of carinata seeds to oil
Seed2Meal	Ratio of carinata seeds to meal
Oil2SAF	Ratio of carinata oil to SAF
Oil2Naphtha	Ratio of carinata oil to naphtha
Oil2Diesel	Ratio of carinata oil to diesel
DemandShare	Share of total SAF demand must be met at the airports
Parameters	**Definitions**
$Area_c$	Area available for planting carinata seeds in county c
$Price_q$	Price of carinata seeds in quarter q
Y_c	Yield of carinata seeds in county c
PP_q	Production possibility in quarter q
$Handling_q$	Loading or unloading cost of seeds in quarter q
SC_q	Operational cost for storage
OC_q	Operational cost in the oil extraction facilities
BC_q	Operational cost in the biorefineries
$Mealprice_q$	Price of carinata meals in quarter q
$Propaneprice_q$	Price of propane in quarter q
$Naphthaprice_q$	Price of naphtha in quarter q
$Dieselprice_q$	Price of diesel in quarter q
$TC1_{c,s,q}$	Transportation cost of seed from field to storage facilities in quarter q
$TC2_{c,o,q}$	Transportation cost of seed from field to oil extraction facilities in quarter q
$TC3_{s,o,q}$	Transportation cost of seed from storage to oil extraction facilities in quarter q
$TC4_{o,b,q}$	Transportation cost of oil from oil extraction facilities to biorefineries in quarter q
$TC5_{b,d,q}$	Transportation cost of oil from biorefineries to airports in quarter q
$Demand_d$	Demand of SAF at the airport d
Variables	**Definitions**
$AH_{c,q}$	Area cultivated and harvested to produce carinata seeds
STO_s	Number of storage facilities created in county s
OEM_o	Number of OEMs created in county o
BIO_b	Number of biorefineries created in county b
$Stock_{s,q}$	Seed present in the storage facilities
$Field2Storage_{c,s,q}$	Seed transported from field to storage
$Field2OEM_{c,o,q}$	Seed transported from field to oil extraction facilities
$Storage2OEM_{s,o,q}$	Seed transported from storage to oil extraction facilities
$Oil_{o,b,q}$	Oil transported from oil extraction facilities to biorefineries
$SAF_{b,d,q}$	SAF transported from biorefineries to airports

Table 2: Value of parameters used in the model

Scalars/Parameters	Values
SCAP	$125,000 [40]
OCAP	$161,30,000 [40]
BCAP	$262,923,855 (personal communication with Applied Research Associate)
SCT	1134 t of seed [40]
OCT	449,057 t of oil per quarter [40]
BCT	79,379 t of fuel per quarter [40]
Seed2Oil	0.4329 [25]
Seed2Meal	0.56 [25]
Oil2SAF	0.2527 [26]
Oil2Naphtha	0.179 [26]
Oil2Diesel	0.372 [26]
DemandShare	0.025
Price	441 per t (Nuseed Incorporated)
Handling	$4.4 per t (personal communication with Agrowstar, Davisboro, Georgia)
SC	$8.8 per t of seed per quarter (personal communication with Agrowstar, Davisboro, Georgia)
OC	$19.54 per t of oil [40]
BC	$454.15 per t of fuel (personal communication with Applied Research Associate)
Mealprice_q	$320 per t of meal [59,60]
Naphthaprice_q	$533.4 per t of naphtha [61]
Dieselprice_q	$981.29 per t of diesel [62]

The objective function of the mathematical model is as follows –

$$\min \text{SAFCOST} = \min\left(Seedcost + Capitalcost + Operationalcost + TC - Coproduct\right) \quad (1)$$

where,

$$Seedcost = \sum_{c,q}\left(AH_{c,q} \times Y_c \times PP_q \times Price_q\right) \quad (2)$$

$$Capital\ cost = \sum_{s}\left(STO_s \times SCAP\right) + \sum_{o}\left(OEM_o \times OCAP\right) + \sum_{b}\left(BIO_b \times BCAP\right) \quad (3)$$

$$\begin{aligned} Operational\ cost &= \sum_{c,s,q}\left(FieldStorage_{c,s,q} \times Handling_q\right) \\ &+ \sum_{s,o,q}\left(Storage2OEM_{s,o,q} \times Handling_q\right) + \sum_{s,q}\left(stock_{s,q} \times SC_q\right) \\ &+ \sum_{o,b,q}\left(Oil_{o,b,q} \times OC_{o,q}\right) + \sum_{b,d,q}\left(SAF_{b,d,q} \times BC_{b,q}\right) \end{aligned} \quad (4)$$

$$TC = \sum_{c,s,q}\left(TC1_{c,s,q} \times Field2Storage_{c,s,q}\right) + \sum_{c,o,q}\left(TC2_{c,o,q} \times Field2OEM_{c,o,q}\right) + \sum_{s,o,q}\left(TC3_{s,o,q} \times Storage2OEM_{s,o,q}\right) + \sum_{o,b,q}\left(TC4_{o,b,q} \times OIL_{o,b,q}\right) + \sum_{b,d,q}\left(TC5_{b,d,q} \times SAF_{b,d,q}\right) \quad (5)$$

$$Coproduct = \sum_{c,o,q}\left(Field2OEM_{c,o,q} \times Seed2Meal \times Mealprice_q\right) + \sum_{s,o,q}\left(Storage2OEM_{c,o,q} \times Seed2Meal \times Mealprice_q\right) + \sum_{o,b,q}\left(Oil_{o,b,q} \times Oil2Propane \times Propaneprice_q\right) + \sum_{b,d,q}\left(Oil_{o,b,q} \times Oil2naphtha \times Naphthaprice_q\right) + \sum_{b,d,q}\left(Oil_{o,b,q} \times Oil2diesel \times Dieselprice_q\right) \quad (6)$$

Equation (2) estimated the total cost of seeds at a rate of $441 per t (NuSeed Incorporated). Equations (3) and (4) estimated the total capital and operational cost, respectively, of storage, OEMs, and biorefineries. The first two items in equation (4) referred to the handling cost of loading and unloading in the storage unit. Equation (5) estimated the total transportation cost. This includes transporting seeds from field to storage, field to OEM, storage to OEM, transporting oil from OEMs to biorefineries, and transporting SAF from biorefineries. Seed transportation cost was estimated at the rate of \$0.10 t^{-1} km^{-1} based on \$3.5 km^{-1} and 25 t of truck capacity (Personal communication with Butch Cobb, Grain Accounting Supervisor and Hedge Manager, Agrowstar, Davisboro, Georgia). Oil and fuel transportation cost [63] was estimated at the rate of \$0.10 t^{-1} km^{-1}. Equation (6) estimated the total revenue earned from co-products. For the CHJ pathway, co-products are carinata meal, diesel, and naphtha.

The constraints for the mathematical model are as follows-

$$AH_{c,q} \leq \frac{Area_c}{3}, for\ every\ c\ and\ q \tag{7}$$

$$Stock_{s,q} = \frac{Stock_{s,q-1}}{1.01} + \sum_c Field2Storage_{c,s,q} - \sum_o Storage2OEM_{s,o,q}, for\ every\ s\ and\ q \tag{8}$$

$$\sum_s (Field2Storage_{c,s,q} + \sum_o Field2OEM_{c,o,q} \leq AH_{c,q} \times Yield_c \times PP_q, for\ every\ c\ and\ q \tag{9}$$

$$Stock_{s,q} \leq STO_s \times SCT, for\ every\ s\ and\ q \tag{10}$$

$$\sum_b OIL_{o,b,q} \leq OEM_o \times OCT, for\ every\ o\ and\ q \tag{11}$$

$$\sum_d SAF_{b,d,q} \leq BIO_b \times BCT, for\ every\ b\ and\ q \tag{12}$$

$$\sum_b OIL_{o,b,q} = Seed2Oil \times \left(\sum_s Storage2OEM_{s,o,q} + \sum_c Field2OEM_{c,o,q} \right), for\ every\ o\ and\ q \tag{13}$$

$$\sum_d SAF_{b,d,q} = Oil2SAF \times \sum_o Oil_{o,b,q}, for\ every\ b\ and\ q \tag{14}$$

$$\sum_{b,d} SAF_{b,d,q} \geq \sum_{d} Demand_d \times DemandShare, for\ every\ q \quad (15)$$

Equation (7) states that one-third of all available areas can be used. It was because carinata production is only recommended once every three years in the same field to reduce disease problems [64]. Equation (8) states that the stock present in a given quarter depends on the rate of decay in the storage unit (assumed to be 1% per quarter), incoming and outgoing seeds. Equation (9) states that the total seed transported to the storage and oil extraction mill cannot exceed the total production of seeds. Equation (10) to (12) states that storage, OEMs, and biorefineries cannot exceed their respective capacities. Equation (13) and (14) states the conversion between seed and oil and oil and fuel, respectively. Equation 15 states that the combined demand that must be met in the airports where "DemandShare" was 2.5%.

2.3. Unit Cost and GHG Estimation

The unit cost of SAF was estimated with the following equation –

$$Cost\ of\ SAF\ (\$\ L^{-1}) = \frac{SAFCOST\ (\$)}{Total\ SAF\ produced\ (L)} \quad (16)$$

Total GHG emission was estimated by the following equation -

$$GHG = GHG_{seed} + GHG_{OEM} + GHG_{BIO} + GHG_{TRANS} - GHG_{SOC} \quad (17)$$

where,

$$GHG_{seed} = \sum_{c,q} (AH_{c,q} \times PP_q \times Yield_c \times seedGHG) \times seed2oil \times oil2fuel \quad (18)$$

$$GHG_{OEM} = \sum_{o,b,q} (OIL_{o,b,q}) \times oemGHG \times Seed2Oil \times Oil2Fuel \tag{19}$$

$$GHG_{BIO} = \sum_{b,d,q} (SAF_{b,d,q}) \times bioGHG \times oil2fuel \tag{20}$$

$$GHG_{TRANS} \tag{21}$$
$$= TransGHG\ x \left[Seed2Oil \times Oil2Fuel\ x \left\{ \sum_{c,s,q} \left(Field2Storage_{c,s,q} \times distance1_{c,s} \right) \right. \right.$$
$$\left. + \sum_{c,o,q} \left(Field2OEM_{c,o,q} \times distance2_{c,o} \right) + \sum_{s,o,q} \left(Storage2OEM_{s,o,q} \times distance3_{s,o} \right) \right\}$$
$$\left. + \ Oil2Fuel \times \left\{ \sum_{o,b,q} \left(Oil_{o,b,q} \times distance4_{o,b} \right) \right\} + \sum_{b,d,q} \left(SAF_{b,d,q} \times distance5_{b,d} \right) \right]$$

$$GHG_{SOC} = \sum_{c,q} (AH_{c,q} \times PP_q \times Yield_c \times SOC_c \times Seed2Oil \times Oil2Fuel) \tag{22}$$

Equation (18) estimates the total GHG emission from seed production where seedGHG was the unit emissions related to seed production, 0.423 t CO_2 t^{-1} of seed [24]. Equation (19) and (20) estimates the total emissions related to operations in the OEMs and biorefineries where oemGHG and bioGHG were 0.077 t CO_2 t^{-1} of oil and 0.729 t CO_2 t^{-1} of SAF, respectively [24]. Equation (21) estimates the total emissions related to the transportation of seeds or oil or fuel [65], where TransGHG was 0.000104 t CO_2 t^{-1} km^{-1}. Equation (22) estimates the total soil organic carbon (allocated to SAF) sequestered in the field.

2.4. Sensitivity Analysis

For sensitivity analysis, we used county-wise variation in seed yield and soil organic carbon changes—one standard deviation above and below the mean. Variations are reported in the supporting information (Table S4 and S5). Based on this variation, we estimated the range of break-even price and net GHG emission. While 3% CAF demand would be met with SAF with high seed yield, 1.8% would be replaced with low yield. Higher and lower SOC changes were associated with the high-yield and low-yield scenario, respectively.

3. Results and Discussion

3.1. DayCent and GAMS Model Results

Approximately 2.06 Mha in 163 counties (26, 42, and 93 counties in Alabama, Florida, and Georgia, respectively) were found suitable for carinata production in the study area (Figure 2). Considering carinata production once every three years, about 0.78 Mha could be cultivated with carinata in any given winter. About 65% of that suitable area was in Georgia, followed by Alabama (18%) and Florida (17%). The average seed yield was 2.89 t ha^{-1}. On average, about 37.85 kg C t^{-1} of carinata seeds were sequestered in the soil in the study area. The highest and lowest soil organic carbon (SOC) sequestration was 172.5 (Sumter County, Florida) and -152.89 (Taliaferro county, Georgia) t ha^{-1} of carinata seeds, respectively. Potential seed yield, potential SOC sequestration, and availability of suitable area results by county are available in the supporting information (Table S4 – S6).

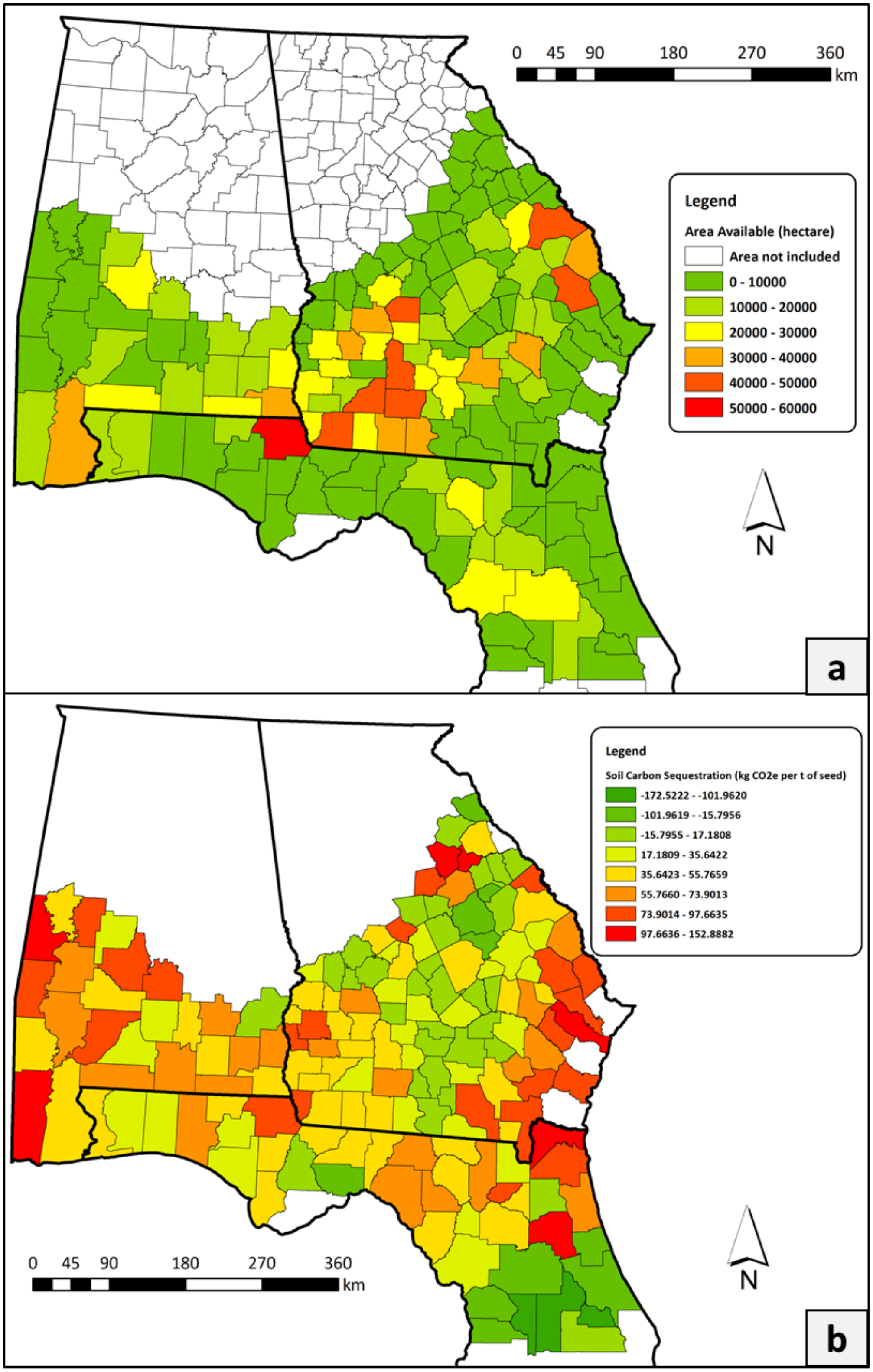

Figure 2: Results from the Daycent model – (a) Area available (ha) and (b) Soil organic carbon sequestration (kg CO_2e t^{-1} of seed) in the study area.

The optimization model in GAMS provided results after approximately 83 hours with a relative optimal gap of 0.06. The net cost was $4.17 billion for twenty years of operation, which included $15.2 billion of expenditure and $10.23 billion of co-product credit. Expenditures included $12.15 billion in seed cost, $447 of capital establishment cost, $181 million in handling cost, $365 million in storage cost, $229 million in OEM operational cost, $1.35 billion in biorefinery operational cost, and $485 million of transportation cost.

3.2. Area Cultivated and Production

The supply chain optimization model calls for cultivating carinata on approximately 0.65 Mha in the first quarter of every year, resulting in 1.95 Mt of seed from the region (Figure 3). This includes 100% of the annually available cropland area in Georgia (0.44 Mha), 89% in Florida (0.11 Mha), and 86% in Alabama (0.1 Mha). The cultivated area did not vary annually since the demand and demand share (2.4%) in the airport was assumed to be constant. Decatur county in Georgia had the highest area cultivated (16,630 ha). The highest area cultivated in Alabama and Florida were Houston (10,081 ha) and Jackson County (17,051 ha), respectively. Area cultivated and production in each county in the study area are presented in Supporting Information (Table S7 and S8, respectively).

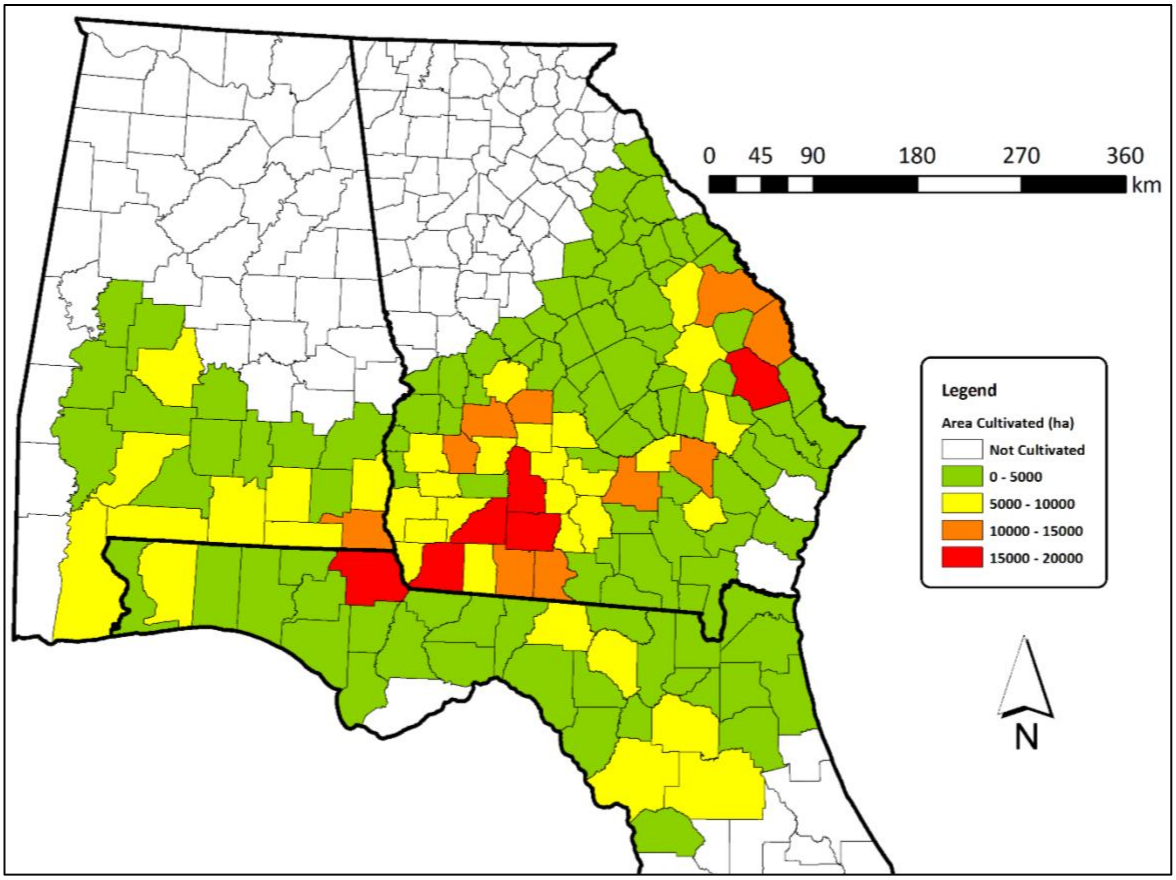

Figure 3: Area cultivated (ha) in the study area.

3.3. The flow of materials in the supply chain

The optimal supply chain features 1,343 storage units across all three states, i.e., 1036 in Georgia, 93 in Florida, and 214 in Alabama (Figure 04). The number of storage units created in each county is presented in Supporting Information (Table S9). Only one crushing facility is needed to support this supply chain, located in Lee County, Georgia. Similarly, only one biorefinery is needed, located in Sumter County, Georgia. No crush facility or biorefinery was placed in either Alabama or Florida.

In quarter (Q1), when carinata seed is harvested, about 0.48 Mt of seed is transported to the oil extraction mill directly from the field, and the remaining 1.47 Mt is transferred to storage (Figure 5). About 238, 102, and 1131 thousand t of seed annually went to the storage untis created in Alabama, Florida, and Georgia, respectively. All seeds (100%) going directly from the farm to the oil extraction mill in Georgia were supplied from within the state. No seed was transported from Florida or Alabama to the oil extraction mill directly in any year. County-level quantity of seed transferred from farm to storage and oil extraction mills are presented in Supporting Information (Table S10 and S11, respectively).

In Q2, Q3, and Q4 of every year, 481 thousand tons of seed were transported from storage to the oil extraction mill in Lee County, Georgia. Total regional seed stock was about 0.98 and 0.49 Mt at the end of Q2 and Q3, respectively, after accounting for transfers to the mill and decay during storage. At the end of Q4, the stock was depleted as the remaining seeds made their way to the oil extraction mill. The quantity of seed transported from storage to the oil extraction mill is presented in Supporting Information (Table S12). About 208 thousand t of oil and 269 thousand t of animal feed were produced at the oil extraction mill each quarter, which is about 46% of its capacity. Biorefinery in Sumter county annually supplied 52,593 t of SAF (66% of capacity) to Atlanta airport each quarter. Most of the croplands potentially available for carinata production were relatively closer to the Atlanta airport, so the optimized supply chain sends all 69.5 ML of SAF produced to that airport.

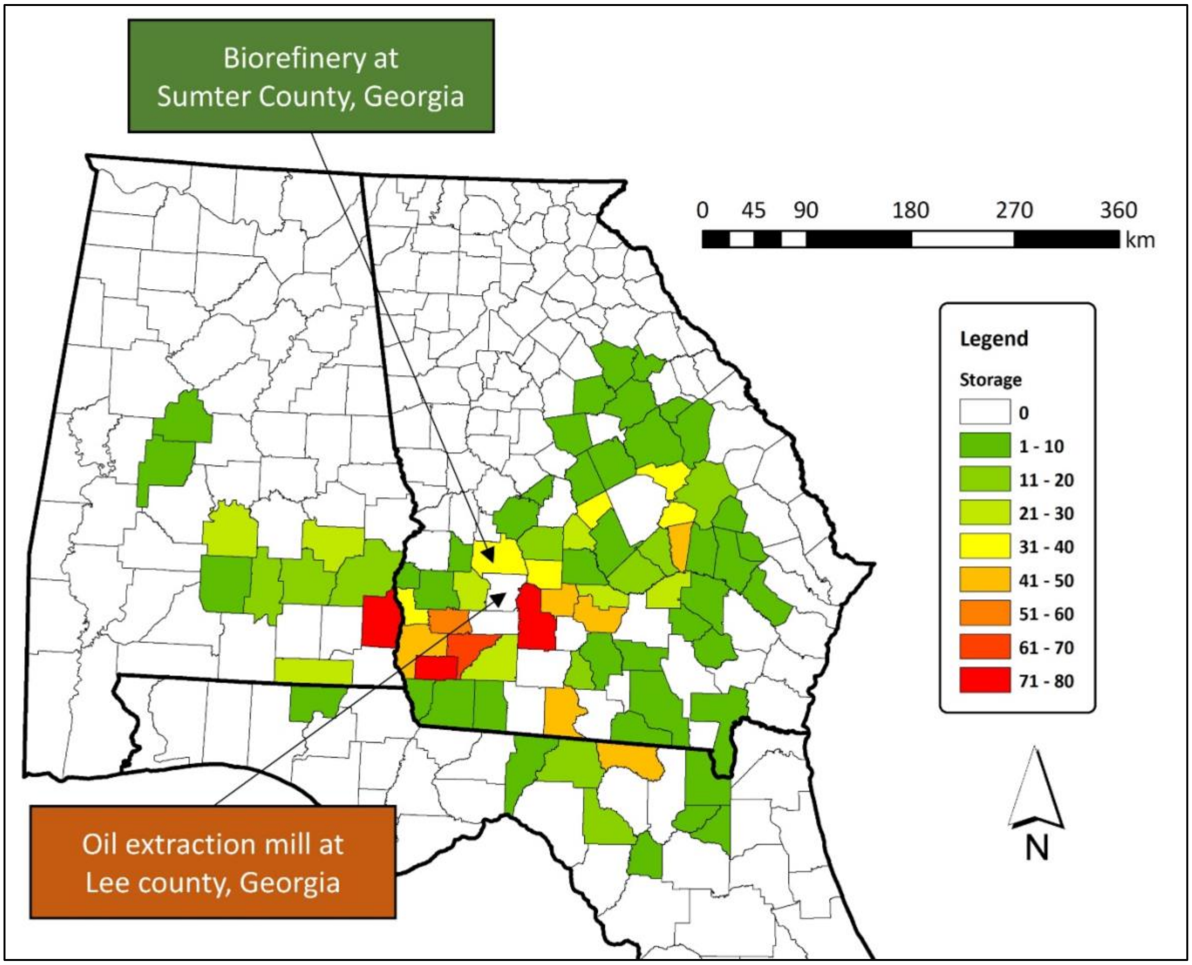

Figure 4: Location of storage, oil extraction mill, and biorefinery. Note: No oil extraction mill or biorefinery was created in Alabama and Florida.

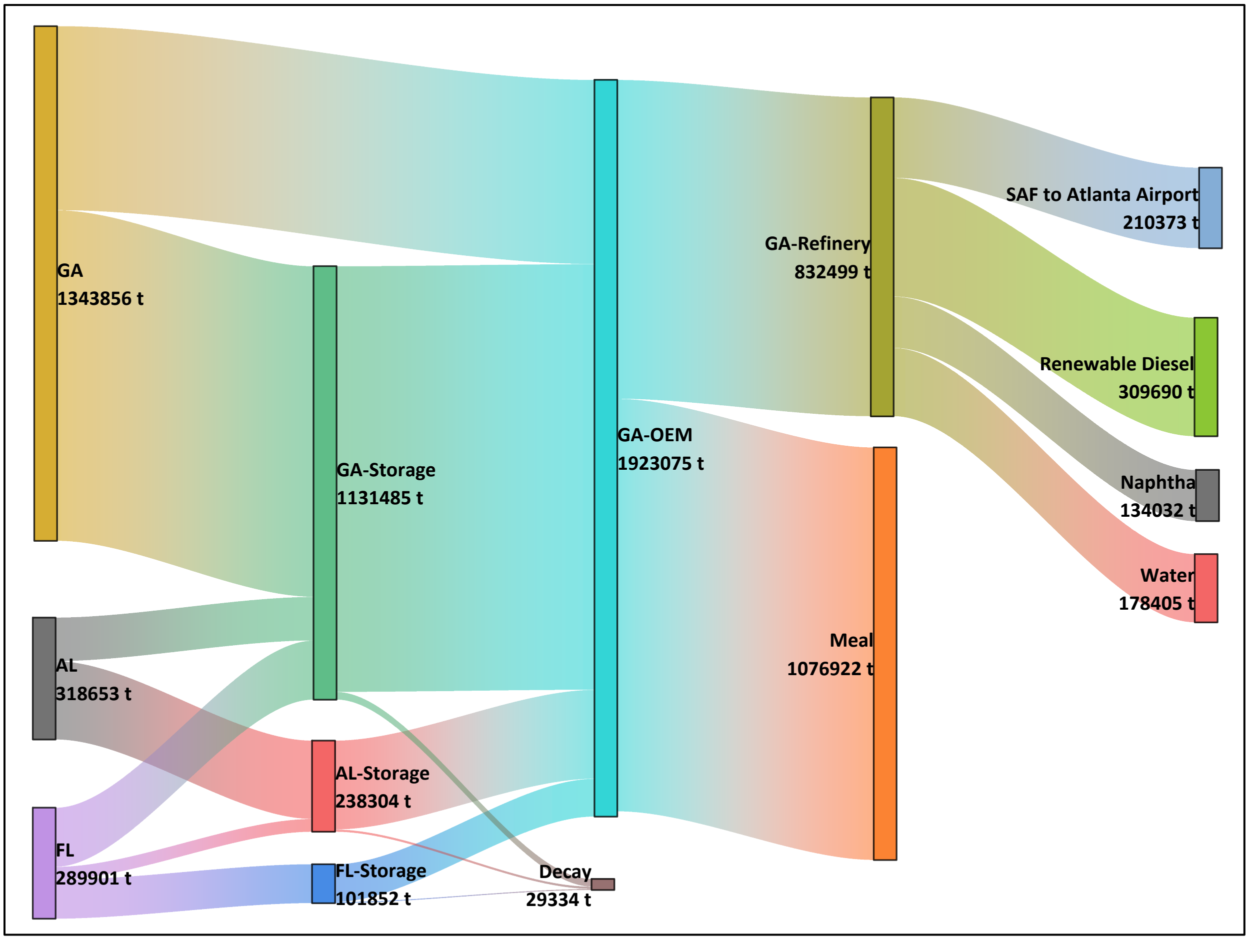

Figure 05: Annual material flow within the supply chain. AL, FL, and GA stand Alabama, Florida, and Georgia, respectively. AL-, FL-, and GA-Storage refers to the storage facilities created in those states, respectively. One oil extraction mill (OEM) in Miller County, Georgia supplied oil to the biorefinery in Early county, Georgia.

3.4. Unit production cost and life-cycle GHG emissions

The total cost of SAF, without the co-product revenue, was \$81.94 GJ^{-1} (Figure 06). With the co-product revenue (\$55.15 GJ^{-1}), the net cost was reduced to \$26.79 GJ^{-1} or \$0.89 L^{-1}. This high percentage of co-product revenue was due to the high ratio of co-products (meal, renewable diesel, and naphtha). However, this estimate was 79% higher compared to the current cost of CAF (\$14.98 GJ^{-1}). About 80% of the total expenses were attributed to the seed production stage before accounting for the co-product revenue. The second most expensive phase was refining the oil to produce SAF, which constituted about 9% of the total cost. Co-product revenue compensated for 67% of the total cost. Our cost estimate was lower than Nguyen and Tyner 2021 [66] (\$31.37 GJ^{-1}) and Eswaran et al. 2021 [67] (\$32.57 GJ^{-1}). However, this estimate was higher than estimates for SAF using HEFA (Hydro-processed Esther and Fatty Acid) technology reported by Chu et al. 2017 [40] (\$18.88 GJ^{-1}), Li et al. 2018 [68] (\$20.14 GJ^{-1}), and McGarvey and Tyner 2018 [69] (\$25.92 GJ^{-1}) but lower than Alam et al. 2021 [24] (\$32.26 GJ^{-1}). The difference may be explained by the higher seed yield per hectare, lower seed price, and differences in the system boundary incorporated in their studies. Wang 2019 [70] reported that SAF price could range between \$0.91 and \$2.74 $L^{-1,}$ and our estimate is comparable to the lower estimate.

About 27.3 kg CO_2e GJ^{-1} or 0.91 kg CO_2e L^{-1} of GHG emission was attributed to SAF throughout the supply chain. This estimate suggests that SAF from carinata can provide 67.7% GHG savings compared to CAF. Operations at the biorefinery were the most carbon-intensive stage in the life cycle due to energy use, constituting approximately 60% of all emissions. Seed production was the second-highest GHG intensive stage (34% of all emissions). Oil extraction constituted about 6% of all emissions. Approximately 4% of all emissions were offset by the sequestered carbon in the soil. Seber et al. 2014 [71] reported a range of 76% to 81% relative GHG savings for SAF produced from waste oils and tallow via CHJ. However, that study was not a supply chain analysis, and waste oil and tallow do not require farming or incur any associated emissions. Sieverding et al. 2016 [25] reported about 1.37 kg CO_2e L^{-1} of GHG emissions from carinata-based SAF using HEFA technology. Li, Mupondwa, and Tabil [68] reported a range of 0.12 to 1.2 kg CO_2e L^{-1} of GHG emissions from camelina-based SAF using HEFA technology, based on variations in yield, nitrogen fertilizer use, and refining technique. Our estimate closely resembled those estimates and varied primarily because of the difference in conversion technology, feedstock choice, and system boundary. With our estimates, it would require approximately \$206 tCO_2e^{-1} of marginal abatement cost of carbon to make SAF price competitive with CAF. The recently signed Inflation Reduction Act signed by the Biden administration provided tax credits between \$0.33 and \$0.46 L^{-1} of SAF purchased by the airlines, which would make SAF fully competitive with CAF [72].

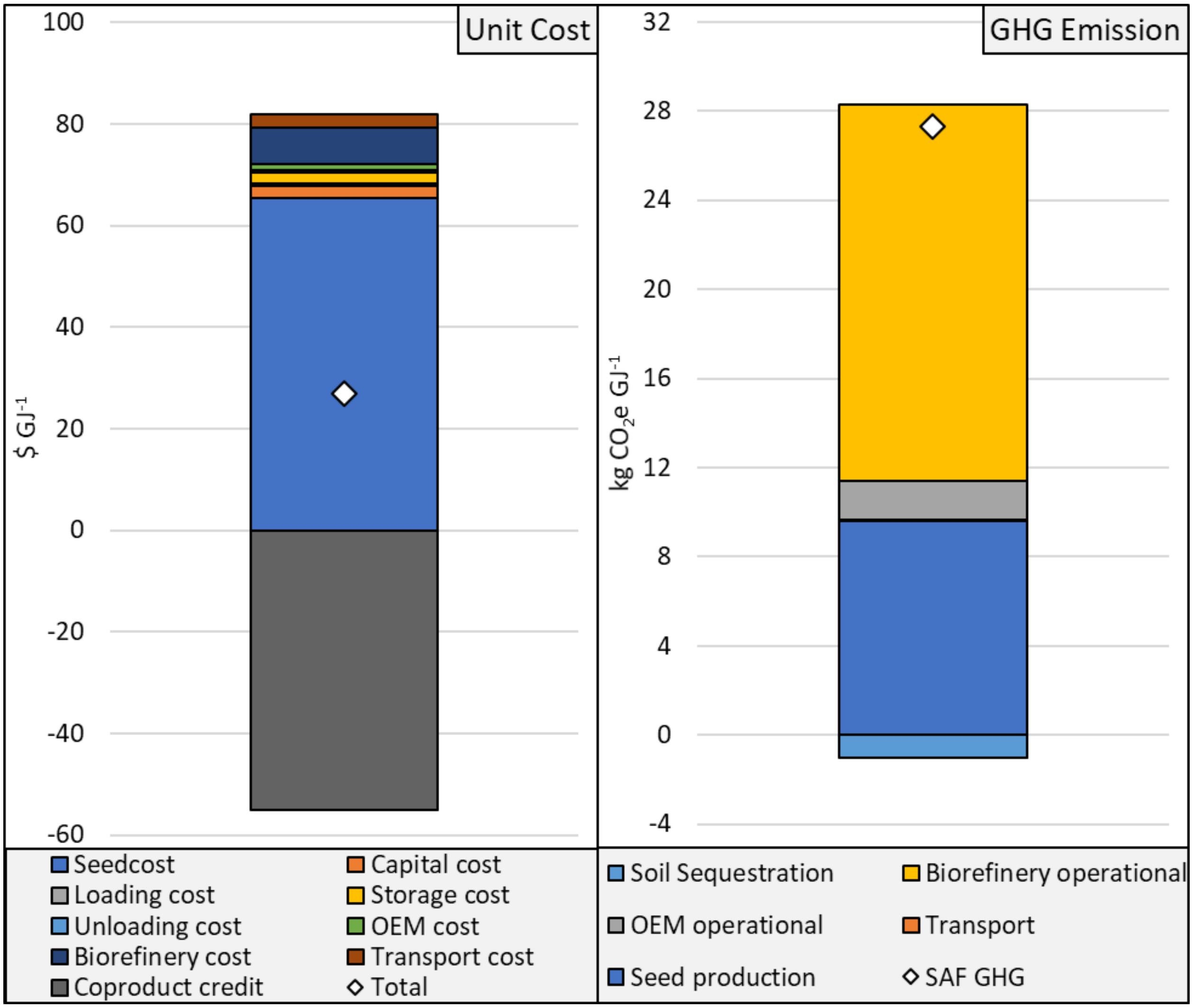

Figure 06: Unit cost and GHG emissions of SAF throughout the supply chain. CAF price and GHG emissions were \$14.98 GJ^{-1} and 84.55 kg CO_2e GJ^{-1}, respectively.

3.5. Sensitivity Analysis

When yield estimates were higher, the average yield was 3.62 t ha^{-1}. With a high yield and high demand scenario, the net cost was \$6.15 billion for twenty years of operation, which included \$18.94 billion of expenditure and \$12.79 billion of co-product credit. Except for the capital cost, all costs and co-product credits were approximately 25% higher. Since the number of required oil extraction mills and biorefineries did not change, the only change in capital cost was due to the number of storage facilities required. A total of 1673 storage facilities were created, which increased the capital cost by 9%. Oil extraction mill and biorefinery, one of each, were created in Georgia—Turner and Crisp County, respectively. The unit cost of SAF production remained comparable to the base case, only 1% lower ($26.51 GJ^{-1}).

When yield estimates were higher, the average yield was 2.17 t ha^{-1}. With a low yield and low demand scenario, the net cost was $3.8 billion, where $11.5 billion was total expenditure, and the co-product credit was $7.7 billion. Similar to the high yield and high demand scenario, the cost difference was 25% in all costs and credits compared to the base case except for the capital cost, where the difference was 9%. Not surprisingly, these estimates were lower than the base case. A total of 1013 storage facilities were created in this scenario. Oil extraction mill and biorefinery, one of each, were created in Georgia—Crisp and Dooly County, respectively. The unit cost of SAF production was $27.27 GJ^{-1}, 2% higher than the base case.

4. Conclusion

Reducing the consumption of CAF and replacing it with SAF could be an effective strategy to make the aviation sector less GHG-intensive. In this study, we analyzed the logistics of achieving that objective using SAF from carinata. We showed the optimum location of storage, oil extraction mills, and biorefineries. We also determined the optimal carinata cultivation locations and the optimum supply quantity to offset 2.4% of CAF demand from major airports in the region. Using a realistic system boundary, we estimated the unit cost and GHG emissions from SAF. We found that SAF from carinata is more expensive but less GHG intensive compared to CAF. Based on the GHG benefits achieved from carinata SAF, there is justification for subsidies such as RIN (Renewable Identification Number) credit that can make SAF competitive with CAF.

Due to data limitations, we did not include emissions from storage facilities in our study. Another limitation of the study is to assume linear distances between the county centers. Therefore, this study can be enhanced by including a transportation network analysis. This study can also be extended by comparing different conversion processes in the refinery, such as HEFA and CHJ. Despite these limitations, this study illustrates a clear picture of SAF sustainability in this region. This study broadens the horizon of our understanding related to the competitiveness of SAF with CAF from both cost and GHG perspectives. Even though this study was performed for carinata seeds in the Southeast United States, it can be extrapolated to the broader region. We expect that our findings will interest farmers in the Southeast United States, supply-chain facility managers, investors, and other stakeholders related to the aviation industry.

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