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Break-even price and carbon emissions of carinata-based sustainable aviation fuel production in the Southeastern United States

Asiful Alam | **Md Farhad Hossain Masum** | **Puneet Dwivedi**

Warnell School of Forestry and Natural Resources, University of Georgia, Athens, Georgia, USA

Correspondence
Puneet Dwivedi, Warnell School of Forestry and Natural Resources, University of Georgia, 180 E Green St Athens GA 30602, USA.
Email: puneetd@uga.edu

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Abstract

The production of biomass-based sustainable aviation fuel (SAF) is gaining traction to reduce the carbon footprint of the aviation sector. We performed a techno-economic analysis to estimate the break-even price and life cycle carbon emissions of the SAF derived from carinata (*Brassica carinata*) in the Southeastern United States. Carinata has the potential as a feedstock for SAF production in the selected region due to higher yield, low fertilizer use, co-product generation (animal feed, propane, and naphtha), and compatibility with current farming practices. The system boundary started at the farm and ended when the SAF is delivered to an airport. Without co-product credit or other subsidies such as Renewable Identification Number (RIN) credit, carinata-based SAF was more expensive (\$0.85 L^{-1} to \$1.28 L^{-1}) than conventional aviation fuel (\$0.50 L^{-1}). With co-product credit only, the break-even price ranged from \$0.34 L^{-1} to \$0.89 L^{-1}. With both co-product and RIN credits, the price ranged from -\$0.12 to -\$0.66 L^{-1}. The total carbon emission was 918.67 g CO_2e L^{-1} of carinata-based SAF. This estimate provides 65% relative carbon savings compared with conventional aviation fuel (2618 g CO_2e L^{-1}). Sensitivity analysis suggested a 95% probability that relative carbon savings can range from 61% to 68%. Our study indicates that carinata-based aviation fuel could significantly reduce carbon emissions of the aviation sector. However, current policy support mechanisms should be continued to support manufacturing and distribution in the Southeastern United States.

KEYWORDS
agriculture, aviation, bioenergy, economic analysis, life cycle assessment, sustainability

Abbreviations: \$, United States Dollar; CO_2, carbon dioxide; CO_2e, carbon dioxide equivalent; ha, hectare; kg, kilogram; km, kilometer; kWh, Kilowatt-hour; L, liter; MJ, mega joule; NPV, net present value; RIN, renewable identification number; SAF, sustainable aviation fuel; T, tonne.

1 | INTRODUCTION

Global warming, primarily induced by energy-related anthropogenic CO_2 emissions, can be mitigated by replacing fossil-based fuels with alternative renewable energy sources. One of the significant sources of CO_2 emissions is the aviation sector, as it was responsible for 2.5% of global emissions in 2018 (Ritchie, 2020). With an expected 5% increase in aviation activity in this decade and up to a 20% increase by 2050, it is quite likely that the carbon emissions of the sector will grow (Boeing, 2020; Ritchie, 2020). Therefore, the International Civil Aviation Organization (ICAO), a specialized agency of the United Nations for the aviation industry, adopted a goal of carbon-neutral growth of international aviation from 2020 (ICAO, 2015). Besides, the International Air Transport Association has set a goal of a 50% reduction in CO_2 emissions by 2050 (IATA, 2017). Emission reduction can be achieved in a number of ways, such as through improvements in the airframe, engine technologies, ground operations, and use of sustainable aviation fuel (SAF) derived from various biomass feedstocks (Cansino & Román, 2017; Graham et al., 2014; Linke et al., 2017; Schäfer et al., 2016).

In 2019, the United States consumed 101 billion L of conventional aviation fuel, that is, 18.1% of the global consumption (IEA, 2020). Replacing conventional aviation fuel with SAF can be an effective strategy to achieve the desired emission reduction goal in the United States. Existing literature suggests that the use of SAF derived from various feedstocks such as camelina, canola, and soybean can have 50% to 78% relative carbon savings compared with conventional aviation fuel (Agusdinata et al., 2011; De Jong et al., 2017; Elgowainy et al., 2012; Fortier et al., 2014; Ganguly et al., 2018; Lokesh et al., 2015; Moeller et al., 2017; Ukaew et al., 2016). However, much uncertainty exists on the carbon savings depending on various factors such as farm activities based on geographic location, yield, heating value parameters, refining technology, co-product allocation, and land-use change (Li & Mupondwa, 2014; Zemanek et al., 2020).

Along with the carbon saving criteria, analyzing the commercial viability or unit cost of producing SAF is also critical to increase the production and sustain supplies (Mawhood et al., 2016; Wang & Tao, 2016). Major challenges impeding investments in the SAF production are crude oil price, feedstock availability and cost, conversion technology yields and costs, environmental impacts, and government policies (Bittner et al., 2015). Whereas conventional aviation fuel costs \$0.55 L^{-1}, the cost of SAF could range between \$0.44 and \$8.45 L^{-1}, depending on the choice of feedstocks, yield varied by geographic location, and conversion technology (Baral et al., 2019; Klein-Marcuschamer et al., 2013; Mupondwa et al., 2016). Lower unit production costs were reported for SAF derived from oil-based feedstocks such as camelina and soybean, compared with lignocellulosic and microalgae-based SAF.

Carinata (*Brassica carinata*), also known as Ethiopian Mustard and Abyssinian Mustard, is an oil-based feedstock such as camelina and soybean and was suggested as a new potential feedstock for SAF production (Chu et al., 2017b; Gesch et al., 2015; Marillia et al., 2014). It was introduced in the Southeastern United States in 2010 through a joint research collaboration between the University of Florida Institute of Food and Agricultural Sciences (UF-IFAS) and Nuseed (Nuseed, 2020). About 1.4 million hectares of land were found suitable for carinata production in the Southeastern United States (Alam & Dwivedi, 2019). Carinata could be easily integrated into the current cropping systems in the Southeastern United States, as it grows well in winter months when agricultural land remains unused and, therefore, provides much-needed cover to otherwise exposed soils and reduces soil erosion (Seepaul et al., 2021; Seepaul et al., 2020). It was also reported to be agronomically superior and frost tolerant than other oilseed crops grown in the region as it has higher oil content (above 40%), larger seed size, and lower lodging and shattering rates (Seepaul et al., 2016). Unlike soybean and canola, there is no food-versus-fuel debate associated with carinata as it is not suitable for direct human consumption. Besides the carbon benefit of replacing conventional aviation fuel with carinata-based SAF, other economic benefits include the production of high-protein animal meal, propane, and naphtha as co-products and the profit share from these co-products (Wang et al., 2018). Growing a winter crop could provide additional income to the farmers, create local jobs, and boost the regional economy. However, as mentioned earlier, challenges remain in the economic feasibility of carinata-based SAF. The governments in many countries offer incentives to produce SAF based on the carbon benefits that it provides compared with conventional aviation fuel (Brown, 2013). Subsidies required for SAF could range from \$0.20 to \$0.61 L^{-1} (Chu et al., 2017a; Diniz et al., 2018; Winchester et al., 2015). The United States provides Renewable Identification Number (RIN) credits under the Renewable Fuel Standard (RFS) program. The RIN prices for carinata-based SAF can range from \$0.05 to \$2 per RIN generated, subject to changes in markets (US EPA, 2021).

Even though carinata shows potential for the Southeastern United States, a thorough investigation into the economic feasibility and carbon benefit is required before large investments are made to create supply chain infrastructures such as storage facilities, crushing mills, and biorefineries. Using agricultural input data suggested for the Southeastern United States, we estimated the break-even price of carinata-based SAF, contingent upon the variations in fixed costs, variable costs, co-product credits, and RIN credits. We also estimated the life cycle carbon emissions within the system boundary, starting from the production of carinata at an agricultural field to the transportation of manufactured SAF to an airport. We expect that this study would provide insights to policy-makers for facilitating informed decision-making about promoting the use of carinata-based SAF in the Southeastern United States and beyond.

2 | MATERIALS AND METHODS

2.1 | Data and system boundary

The life cycle of producing carinata-based SAF contains three major stages—farming, oil extraction, and refining (Figure 1). Our system boundary was comparable with the guidelines provided by Energy Systems Division, Argonne National Laboratory (Sieverding et al., 2016; Wang et al., 2018).

Field data collected from research plots (Boote et al., 2021) were used to determine the carbon emissions from carinata feedstock production (Table 1). The seed application rate was 5.58 kg ha^{-1}. The rate of fertilizers (N, P, K), pesticides, herbicides, and fungicides are standardized for the northeastern region of Florida (Seepaul et al., 2016). The yield of carinata seeds was 2.8 t ha^{-1} (Seepaul et al., 2016). In Q1, the quarter in which harvest occurs, seeds produced at the farmland would be directly transported to the crushing mill to produce crude oil. However, to meet the demand in the subsequent three quarters (Q2, Q3, and Q4), seeds would be stored. In the storage, seeds would decay at an assumed rate of 1%/quarter. Input parameters, reported in Table 2, required to extract crude oil from seeds and convert the same to the aviation fuel were obtained from GREET (Wang et al., 2018).

Crude oil would be transported to the refinery, where it would be transformed into SAF using hydro-processed esters and fatty acid (HEFA) process. Again, this pathway follows the guidelines of the Energy Systems Division, Argonne National Laboratory (Sieverding et al., 2016; Wang et al., 2018). During the HEFA process, triglycerides in vegetable oil is hydrogenated to saturate the double bonds and release the fatty acids by breaking their glycerin structure (Tao et al., 2017). According to GREET, the crude-oil-to-fuel ratio was about 72%. Co-products created during the HEFA process were propane and naphtha, about 8.8% and 6.2%, respectively (Wang et al., 2018). GREET reports propane and naphtha quantities in energy units. Alongside 1 kg of crude oil, 4.41 MJ propane and 2.78 MJ naphtha were produced. We estimated the mass percentage using propane's and naphtha's energy density, 50 MJ kg^{-1} and 45 MJ kg^{-1}, respectively (Engineering ToolBox, 2003; Pittam & Pilcher, 1972). It is important to mention here that the HEFA process described above is based on standard vegetable oil, that is, soybean oil fatty acid profile. Therefore, the composition described in Table

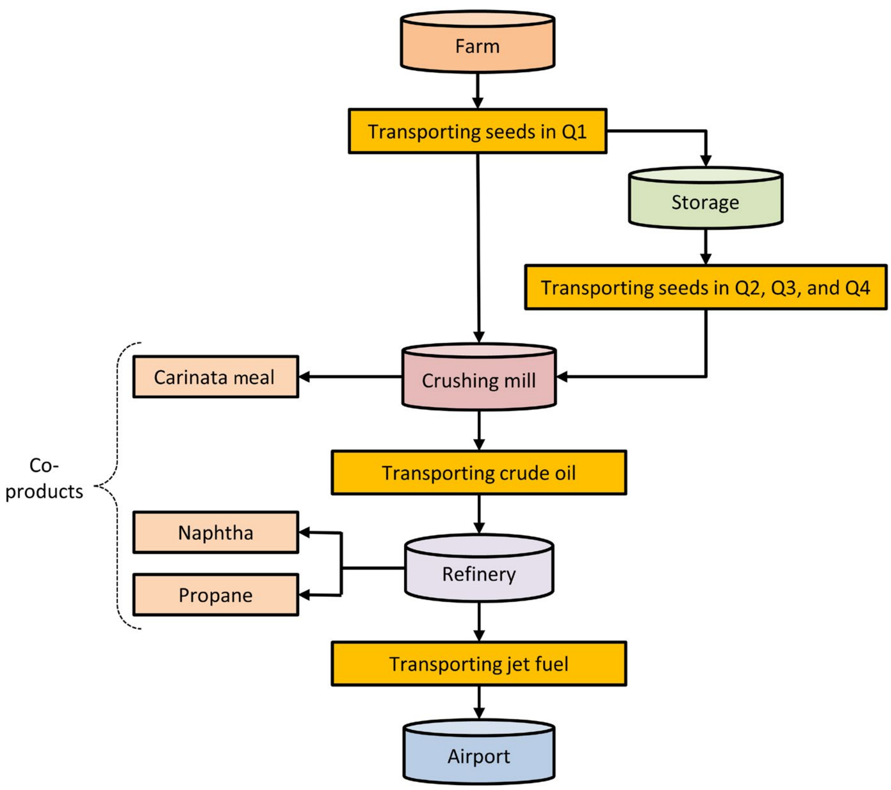

FIGURE 1 System boundary of the life cycle of carinata-based sustainable aviation fuel

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TABLE 1 Inputs for producing carinata-based sustainable aviation fuel in the Southeastern United States

Stages	Inputs	Amount	Unit	Source
Farming	N fertilizer	88.92	kg ha^{-1}	IFAS, UF
	P fertilizer	44.46	kg ha^{-1}	
	K fertilizer	88.92	kg ha^{-1}	
	Herbicide	6.37	kg ha^{-1}	
	Fungicide	0.93	kg ha^{-1}	
	Insecticide	0.69	kg ha^{-1}	
	Diesel	40.13	L ha^{-1}	
	Electricity	382.85	kWh ha^{-1}	
Storage	Loading/ unloading	4	\$ t^{-1} of seed	
	Holding	8	\$ t^{-1} of seed per quarter	
Oil extraction	Natural gas	2.14	MJ L^{-1} of oil	Wang et al. (2018)
	Hexane	0.09	MJ L^{-1} of oil	
	Electricity	0.40	kWh L^{-1} of oil	
Sustainable aviation fuel production	Hydrogen	6.09	MJ L^{-1} of SAF	
	Natural gas	7.09	MJ L^{-1} of SAF	
	Electricity	0.20	kWh L^{-1} of SAF	

TABLE 2 Composition of carinata seeds and oil per unit mass

Input	Output	Composition	References
Carinata seeds	Carinata oil	44% of seed	Sieverding et al. (2016)
	Carinata meal	56% of seed	
Carinata oil	HEFA SAF	71.98% of oil	Han et al. (2013); Stratton et al. (2010); Wang et al. (2018)
	Propane	8.82% of oil	
	Naphtha	6.2% of oil	
	Water	12.62% of oil	

Abbreviations: HEFA, hydro-processed esters and fatty acid; SAF, sustainable aviation fuel.

2 is an approximation rather than an exact match. We used a factor of 1087 L t^{-1} when mass and volume needed to be reconciled (de La Salles et al., 2010). The remaining 12.6% of the mass was released as water by the hydrodeoxygenation process, which refers to the removal of oxygen from free fatty acids by supplying hydrogen (Han et al., 2013; Stratton et al., 2010). Produced SAF was transported to the airport, which was the last stage of our system boundary. Distance from farm to storage or farm to crushing mill was calculated on the size of the biorefinery capacity and sourcing radius for that biorefinery (discussed in Section 2.2.2). The distances from the storage to the crushing mill, the crushing mill to the refinery, and the refinery to the airport were taken as 100 kms. This study was an attributional LCA, in which we observed the cost and carbon emissions within our chosen spatial window. The temporal window was 20 years. The functional unit of this study was 1 liter of SAF delivered at the airport.

We did not include nonbiogenic emissions from burning SAF during aircraft operation in this analysis due to a lack of proper validation with HEFA combustion in aircraft operations. The boundary of the life cycle assessment also excludes crop rotations, soil organic carbon sequestration, carbon emissions from storage facilities, and direct and indirect land-use change (if any) mostly due to the lack of information. The current GREET model has a limitation with the nonfood feedstock carbon sequestration process; therefore, the land-use change model is not included in our system boundary. Additionally, in our model, there was no variation between the costs of transporting seeds, crude oil, and manufactured SAF.

2.2 | Cost

The cost of carinata-based SAF depends on the variation in fixed costs, variable costs, co-product credits, and RIN credits. All costs were discounted with a real interest rate of 6%.

2.2.1 | Fixed costs

Fixed costs include project capital expenditure, production operating expenditure, and labor costs. Fixed costs are, by definition, constant and independent of production levels. The capital cost attributed to a liter of SAF was calculated using equation (1)

$$\text{Capital cost}\,(\$\,\text{L}^{-1}) = \frac{\text{CAPEX} + \text{Fixed OPEX} + \text{Labor cost}}{\text{Total SAF produced over 20 years}} \quad (1)$$

where, CAPEX was the present value of capital expenditure ($411.3 million) and fixed OPEX was the fixed operating expenditure (7.2% of the CAPEX), respectively (Chu et al., 2017a; Diniz et al., 2018). Fixed OPEX included costs related to overhead, maintenance, insurance, and tax. Labor cost was assumed to be $72000 month^{-1} in the lower category and $80000 month^{-1} in the upper category. The annual SAF production capacity was 398 million L (Chu et al., 2017a).

2.2.2 | Variable costs

The UF-IFAS provided information on the cost parameters for seed production from the Quincy, FL trial research plot (Table 3). Studies mentioned for the cost parameters used Aspen simulation for bio-refinery size, production profiles, and project finance structure.

Seed sourcing radius or required transportation distance between farmland to storage or farmland to crushing mill depended on biorefinery size, seed yield, and nonproductive land ratio. We calculated the seed transportation distance with equation (2)

$$\text{Seed transportation distance (km)} = \sqrt{\frac{BC \times LTT}{C1 \times C2 \times Yield \times \pi}} \times 0.01 \times \text{ALR} \quad (2)$$

where, BC was the biorefinery capacity, 398 million L; LTT was the conversion factor from liter to tonne for SAF, 0.00092 t L^{-1} (de La Salles et al., 2010); C1 was the seed to oil conversion factor, 0.44 (Sieverding et al., 2016); C2 was the oil to aviation fuel conversion factor reported in GREET database, 0.7198 (Argonne, 2020); Yield was the seed yield, 2.8 t ha^{-1}; 0.01 was the conversion factor for the area from ha to km^2; and ALR was the conversion factor for agricultural land ratio, 8.95, a ratio of the agricultural land area in corn, cotton, and peanut in the three bottom USDA Crop Reporting Districts (CRDs) in Georgia, US - CRD70, CRD80, CRD90 over the total area in these CRDs. The total area in selected CRDs was approximately 5.9 million hectares, and the total agricultural land area was approximately 0.66 million hectares (NASS, 2021).

2.2.3 | Co-product credit

We estimated the co-product credit using equation (3)

$$\text{Coproduct credit}\,(\$\,\text{L}^{-1}) = \frac{\text{Revenue from coproduct}}{\text{L}} \quad (3)$$

where revenue from co-product was the present value of revenue earned in 20 years, and L was the total SAF produced within the same time frame. The price range of the co-products is listed in Table 4. Because there is no market, carinata meal price was assumed to be similar to canola meal (Chu et al., 2017a). However, we added a lower range and upper range based on the suggestions provided by the SPARC (Southeastern Partnership for Advanced Renewables from Carinata) team at the UF-IFAS.

2.2.4 | RIN credit

We estimated the co-product credit using equation (4)

$$\text{RIN credit}\,\left(\$\,\text{L}^{-1}\right) = \frac{\text{RCR}}{\text{RCC}} \times \frac{\text{EC}}{\text{ECC}} \times \text{RIN price} \quad (4)$$

where RCR was the renewable content ratio, assumed to 1 or 100%; RCC was the renewable conversion constant, 0.972; EC was the energy content of aviation fuel, 39.74 MJ L^{-1} (Wang et al., 2016); and ECC was the energy conversion constant for 1 MJ of energy, 81.23. Using this formula, 0.42 RINs were generated per liter of SAF. RIN price can range between $0.05 to $2 per RIN generated (US EPA, 2021).

2.3 | Carbon intensity

We estimated the carbon intensity for inputs and activities performed within the system boundary and compared it with the carbon intensity of conventional aviation fuel, 2618 g CO_2e L^{-1} (US EPA, 2018a).

TABLE 3 Variable cost parameters across selected stages of the life cycle

	Items	Lower range	Upper range	Unit	Source
Farming	Land preparation	37.07	49.42	\$/ha	UF-IFAS
	Seed	49.42	74.13	\$/ha	
	Fertilizer application	247.11	345.95	\$/ha	
	Irrigation	0.00	74.13	\$/ha	
	Crop protection	12.36	86.49	\$/ha	
	Nonroad diesel fuel	9.88	17.30	\$/ha	
	Harvesting	98.84	123.55	\$/ha	
	Delivery	0.00	24.71	\$/ha	
	Crop insurance	37.07	61.78	\$/ha	
	Electricity	0.114	0.120	\$/kWh	Shell (2019)
Storage	Holding	8		\$/t/quarter	Personal communication*
	Loading/unloading	4		\$/t	
Oil extraction	Natural gas	0.003	0.005	\$/MJ	US EIA (2018b)
	Hexane	1	3	\$/MJ	Chu et al. (2017a)
	Water	0.002	0.002	\$/L	US EIA (2018a)
	Electricity	0.114	0.12	\$/kWh	US EIA (2018a)
Sustainable aviation fuel production	Hydrogen	1.1	2	\$/kg	Diniz et al. (2018); US EIA (2018a)
	Natural gas	0.003	0.005	\$/MJ	US EIA (2018b)
	Water	0.002	0.002	\$/L	US EIA (2018a)
	Electricity	0.114	0.120	\$/kWh	US EIA (2018a)
Transportation**		0.75	0.84	\$/t/km	Shell (2019)

*Butch Cobb, grain accounting supervisor and hedge manager, Agrowstar, Davisboro, Georgia, US.; **Between farmland and storage, farmland and crushing mill, storage and crushing mill, crushing mill and biorefinery, and biorefinery and airport.

TABLE 4 Price of co-products generated during the production of sustainable aviation fuel

Co-product	Lower range	Upper range	Reference
Carinata meal	320	430	Assumed
Propane	497	625	US EIA (2021)
Naphtha	1043	1245	Statista (2021)

2.3.1 | Mass allocation

We estimated the emissions from SAF attributed to seed production, C_{SEED}, with equation (5)

$$C_{SEED}\ (\mathrm{kg\,CO_2e\,L^{-1}}) = \frac{C_{FERT} + C_{CHEM} + C_{DIESEL} + C_{ELEC} + C_{SEEDTRANS}}{\mathrm{L\,ha^{-1}}} \tag{5}$$

where C_{FERT} was the emissions related to the production and use of N, P, and K fertilizers (Table 5); C_{CHEM} was the emissions related to the production and use of herbicide, insecticide, and fungicide; C_{DIESEL} was the emissions related to the usage of diesel to operate tractors; C_{ELEC} was the emissions related to the use of electricity; $C_{SEEDTRANS}$ was the emissions related to transporting seeds (t ha^{-1}) directly from farmland to the crushing mill in Q1 or via storage in the other quarters, at a rate of 0.104 kg CO_2e t^{-1} km^{-1} (US EPA, 2018b).

We estimated the per liter emissions attributed to oil production at the crushing mill, C_{OIL}, with equation (6)

$$C_{OIL}\,(\mathrm{kg\,CO_2e\,L^{-1}}) = C_{FUEL} + C_{HEXANE} + C_{ELECTRICITY} + C_{OILTRANS} \tag{6}$$

where C_{FUEL}, C_{HEXANE}, and $C_{ELECTRICITY}$ were the emissions related to the use of natural gas, hexane, and electricity, respectively (Table 5). $C_{OILTRANS}$ was the emissions related to transport oil (t ha^{-1}) to the refinery at a rate of 0.104 kg CO_2e t^{-1} km^{-1} with an assumed distance up to 100 km (US EPA, 2018b).

We estimated the carbon emissions at the biorefinery, $C_{REFINERY}$ with equation (7)

TABLE 5 Carbon-related parameters for inputs throughout the life cycle

Inputs	Emission	Unit	Source
N fertilizer	4.77	kg CO_2e kg^{-1}	Lal (2004)
P fertilizer	0.73	kg CO_2e kg^{-1}	
K fertilizer	0.55	kg CO_2e kg^{-1}	
Herbicide	23.1	kg CO_2e kg^{-1}	
Insecticide	18.7	kg CO_2e kg^{-1}	
Fungicide	14.3	kg CO_2e kg^{-1}	
Electricity	0.42	kg CO_2e kWh^{-1}	US EIA (2020)
Diesel	2.726	kg CO_2e L^{-1}	US EPA (2018b)
Natural gas	0.0503	kg CO_2e MJ^{-1}	
Hexane	0.0725	kg CO_2e MJ^{-1}	
Hydrogen	0.0503	kg CO_2e MJ^{-1}	

$$C_{REFINERY}\,(\text{kg}\,CO_2\text{e}\,L^{-1}) = C_{FUEL} + C_{HYDROGEN} + C_{ELECTRICITY} \quad (7)$$

where $C_{HYDROGEN}$ was the emissions related to the use of hydrogen to remove excess oxygen. We assumed that emissions for hydrogen use is the same as from natural gas since hydrogen is commonly produced from natural gas reforming (Dincer & Acar, 2014).

Finally, we estimated the carbon emissions of carinata-based SAF with equation (8)

$$C\,(\text{kg}\,CO_2\text{e}\,L^{-1}) = (C_{SEED} + C_{OIL}) \times C1 \times C2 + C_{REFINERY} \times C2 + C_{SAFTRANS} \quad (8)$$

where $C_{SAFTRANS}$ was the emissions related to transported SAF to the airport at a similar rate to $C_{OILTRANS}$ (US EPA, 2018b). Since the operations performed in C_{SEED} and C_{OIL} estimation dealt with seed, those emissions were multiplied with both seed to oil and oil to fuel conversion factor. Because the operations performed for $C_{REFINERY}$ dealt with oil, those emissions were multiplied with oil to SAF ratio.

2.3.2 | Market and energy allocation

For market and energy allocation, we used the allocation ratio reported in GREET (Argonne, 2020). For market allocation, SAF and co-product allocations were 62.49% and 37.51%, respectively. For the energy allocation, these estimates were 51.4% and 48.6%, respectively.

2.4 | Sensitivity analysis

In the presence of low co-product credit and no RIN credit, we performed a sensitivity analysis of break-even price induced by the variation in yields and transportation distances. For this analysis, both high and low costs are considered for fixed and variable costs. To see the impact on carbon emissions, we used @Risk software (https://www.palisade.com) to perform an uncertainty analysis. We used triangular distribution for fertilizers, herbicides, fungicides, and insecticide inputs. Maximum and minimum values for the triangular distribution functions are reported by Lal (2004). For other inputs mentioned in Table 5, we assumed a normal distribution with a standard deviation of 10% of the original values. Using the Latin Hypercube sampling method, we ran the simulation with 100,000 iterations. We reported the results for the range of carbon emissions per unit volume (g CO_2e L^{-1}) and standardized regression coefficients for carbon emissions with respect to inputs' carbon intensity.

3 | RESULTS AND DISCUSSIONS

From 2.8 t ha^{-1} of carinata seeds, 1.21 t ha^{-1} crude oil, and 1.55 t ha^{-1} of animal feed were produced. These quantities were lower than seed to oil and seed to meal ratio, respectively, due to the decay of seeds in storage. The quantity of SAF produced annually from a hectare of farmland was 0.87 t, while 0.11 t and 0.08 t of propane and naphtha were produced as co-products. The estimated harvested area was 419,202 ha, while the area with NPL was approximately 3.75 million ha. The required sourcing radius was 109.29 km. In Q1 of every year, approximately 289,032 t and 884,732 t of seed were transported to the crushing mill and storage facility. However, after decay, 867,097 t of seed was carried to the crushing mill in Q2, Q3, and Q4 combined. Total cost estimates in various stages of the life cycle are reported in the supporting information (Table S1).

3.1 | Break-even price

The price of SAF from carinata feedstock ranged from -\$0.66 to \$1.28 L^{-1} depending on the variation in variable cost, co-product credit, and RIN credit (Figure 2). With low variable cost and no credits, the break-even price was \$0.85 L^{-1}, which was \$0.35 L^{-1} higher than conventional aviation fuel (IATA, 2021). With high variable cost, the same estimate was \$1.28 L^{-1}. When co-product credit was applied, break-even price ranged from \$0.34 L^{-1} to \$0.89 L^{-1}, depending on whether credit and/or variable cost were lower or higher.

About 0.5 RINs L^{-1} of SAF were generated, which provided \$0.03 to \$1.01 L^{-1} of RIN credit. In the most optimistic scenario—low variable cost, high co-product credit, and high RIN credit—SAF break-even price was -\$0.66 L^{-1},

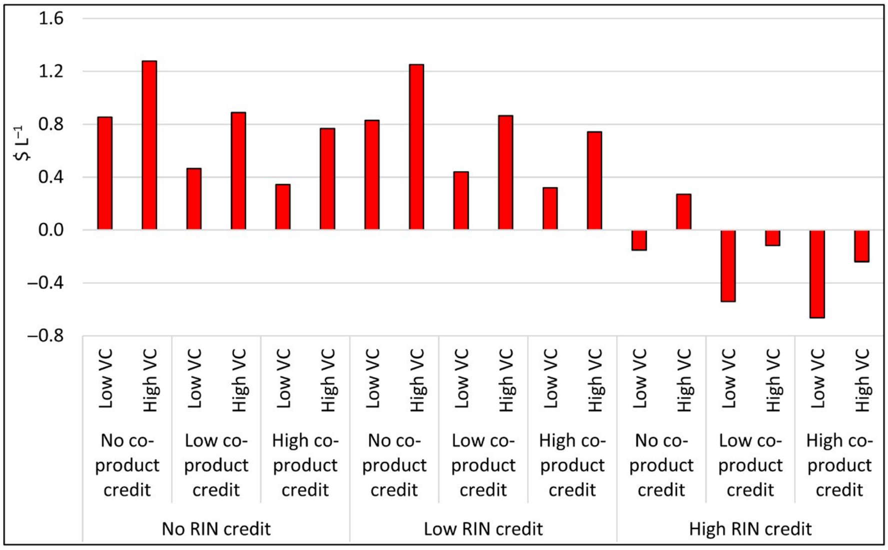

FIGURE 2 Break-even cost of carinata-based sustainable aviation fuel

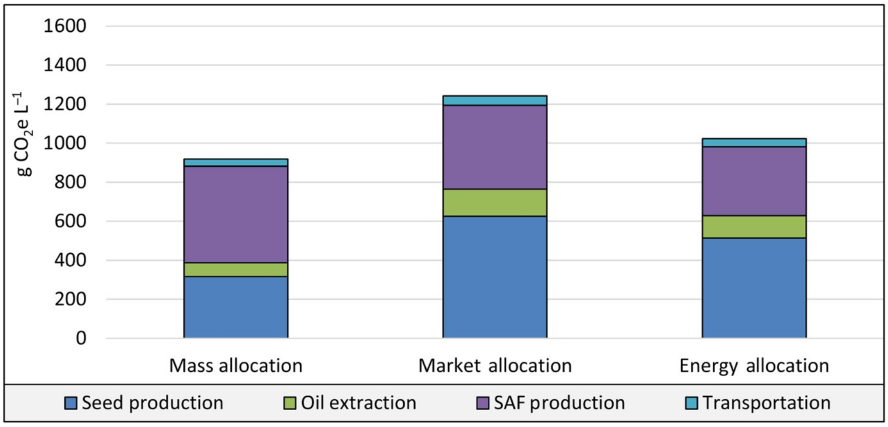

FIGURE 3 Carbon emission during the life cycle of producing SAF from carinata seeds

which suggests profits for the overall supply chain. Under the same scenario but with low RIN credit, the price estimate was \$0.32 L^{-1}. Even with high variable costs, price estimates could be negative (-\$0.24 L^{-1}) if co-product credit and RIN credits were high. Cost estimates from Chu et al. (2017a) were \$0.75 L^{-1} of SAF from carinata, which was \$0.10 L^{-1} lower than our estimates with no credits and low variable cost. Li et al. (2018) reported \$0.8 L^{-1} of SAF from camelina, which was \$0.06 L^{-1} lower than what we consider to be the most likely scenario—low co-product credit, low RIN credit, and high variable cost. Wang (2019) reported that the minimum selling price could range from \$0.91 L^{-1} to \$2.74 L^{-1} (Wang, 2019). Our estimates with high variable costs with no co-product credit fall within that range, both with no and low RIN credit.

3.2 | Carbon emissions

Based on mass allocation, the total carbon emissions for carinata-based SAF was 918.67 g CO_2e L^{-1} of SAF (Figure 3). Relative carbon savings was 65% compared with the carbon emissions from conventional aviation fuel (US EPA, 2016b). This estimate assumes the energy value of conventional aviation fuel reported by Wang et al. (2016). Using the energy value of conventional aviation fuel reported by EIA, 33.49 MJ L^{-1}, relative carbon savings reduce to 58% (US EIA, 2018a). Based on market and energy allocation, carbon emissions allocated to SAF were 1243 and 1023 g CO_2e L^{-1}, respectively. Higher emissions from market and energy allocation compared with the mass allocation is not uncommon in life cycle estimates (Alvarez-Gaitan et al., 2014; Taylor et al., 2017), especially in our case where the mass of the main product (SAF) is only 32% of the seed it's coming from.

In mass allocation, the highest (52%) emissions occurred in the biorefinery, followed by the seed production stage at the farm (34%). Based on market and energy allocations, seed production was the most carbon intensive, approximately 50%. Our carbon savings estimate for mass allocation was comparable with the other studies

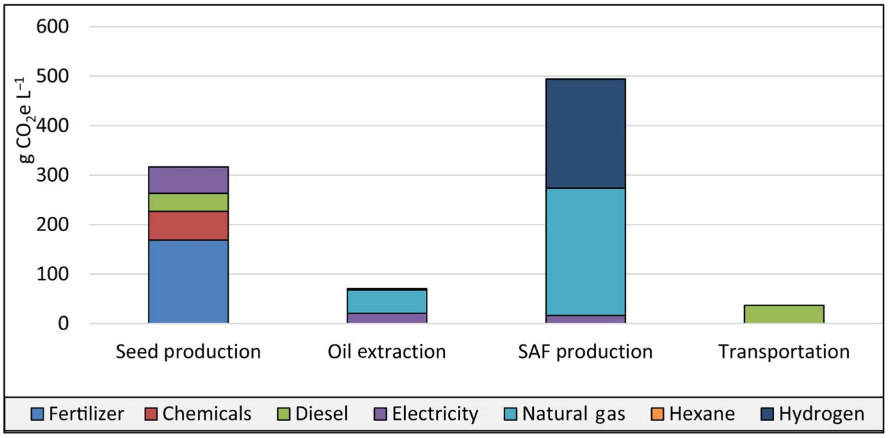

FIGURE 4 Carbon emissions during various stages of life cycle based on mass allocation

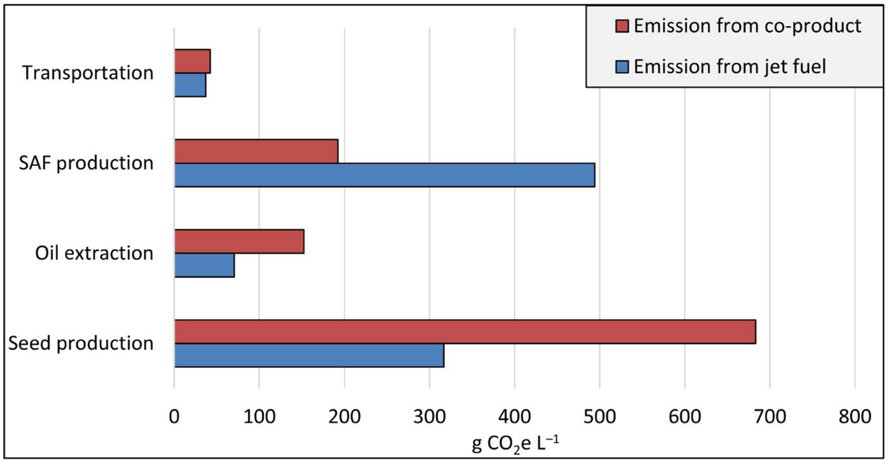

FIGURE 5 Emission from SAF and co-products based on mass allocation

that analyzed HEFA-based SAF from similar oilseed crops such as camelina and canola (Chen et al., 2018; Dangol et al., 2017; US EPA, 2016a; 2016b; Zemanek et al., 2020).

The maximum carbon emissions occurred because of the usage of natural gas, about 304 g $CO_2e\ L^{-1}$, based on mass allocations (Figure 4). Natural gas was needed both in oil extraction (47 g $CO_2e\ L^{-1}$) and SAF production stages (257 g $CO_2e\ L^{-1}$). Natural gas was followed by hydrogen in carbon emission, 221 g $CO_2e\ L^{-1}$. During the seed production stage, fertilizer was the most carbon-intensive input, which emitted about 160 g $CO_2e\ L^{-1}$.

Emissions allocated to the co-products, 1070 g $CO_2e\ L^{-1}$, were about 17% higher compared with the emissions allocated to the SAF (Figure 5). Unlike SAF, the most carbon intensive stage for the co-products was the seed production stage, 683 g $CO_2e\ L^{-1}$. It makes sense as 68% of the seeds were co-products, for example, animal feed, propane, naphtha. Because only 44% of the seeds were oil and the remaining 56% was animal feed, carbon emissions in the oil extraction stage (152 g $CO_2e\ L^{-1}$) were higher for co-products as well.

3.3 | Sensitivity analysis

With low co-product credit and no RIN credit, our sensitivity analysis for sourcing radius, variable cost, and yield suggested that break-even price can range from \$0.28 L^{-1} \$1.26 L^{-1} (Table 6). With the baseline yield, the break-even price ranged from \$0.37 L^{-1} to \$0.99 L^{-1}. When variable cost was low, price ranged from \$0.28 L^{-1} to \$0.72 L^{-1}, while price with high variable cost ranged from \$0.64 L^{-1} to \$1.26 L^{-1}. It is important to reiterate the presence of low co-product credit in these price estimates as these prices would be \$0.40 L^{-1} higher without it.

There was a 95% probability that the carbon emissions of carinata-based SAF would range between 841 and 1014 g $CO_2e\ L^{-1}$, whereas the distribution mean was 927 g $CO_2e\ L^{-1}$ (Figure 6). Based on that range, relative carbon savings compared with conventional aviation fuel were 68% and 61%, respectively. The maximum and minimum carbon emission was 1117 and 751 g $CO_2e\ L^{-1}$, respectively, which suggests 57% and 71% relative carbon savings. With a 90% confidence interval, the estimates ranged 927$\pm$0.23 g $CO_2e\ L^{-1}$.

TABLE 6 Sensitivity analysis of break-even price of sustainable aviation fuel varied by transportation distances*, fixed and variable cost, and yield**

Distance (km)	Variable cost	Yield (sourcing radius, km) 30% lower (131) $/L	20% lower (122)	10% lower (115)	Baseline (109)	10% higher (104)	20% higher (100)	30% higher (96)
50	Low	0.54	0.47	0.41	0.37	0.34	0.31	0.28
75		0.58	0.52	0.46	0.42	0.38	0.35	0.33
100		0.63	0.56	0.51	0.47	0.43	0.40	0.37
125		0.68	0.61	0.56	0.51	0.48	0.45	0.42
150		0.72	0.66	0.60	0.56	0.52	0.49	0.47
50	High	1.05	0.94	0.85	0.78	0.73	0.68	0.64
75		1.10	0.99	0.91	0.84	0.78	0.73	0.69
100		1.15	1.04	0.96	0.89	0.83	0.78	0.74
125		1.21	1.10	1.01	0.94	0.88	0.84	0.80
150		1.26	0.15	1.06	0.99	0.94	0.89	0.85

*Transportation distances between storage and crushing mill, crushing mill and biorefinery, and biorefinery to airport.; **Variation in yield causes sourcing radius to change. Baseline yield was 2.8 t ha^{-1}.

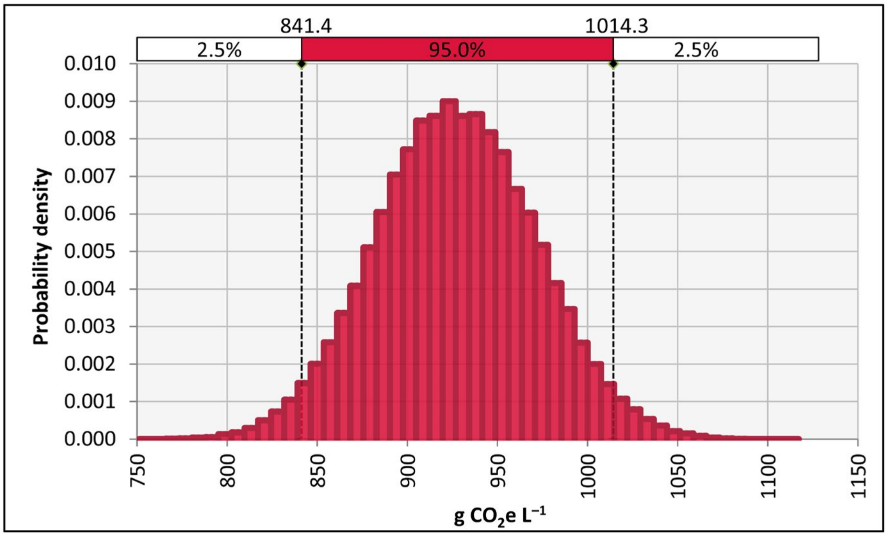

FIGURE 6 Uncertainty analysis of carbon emissions of producing carinata-based sustainable aviation fuel

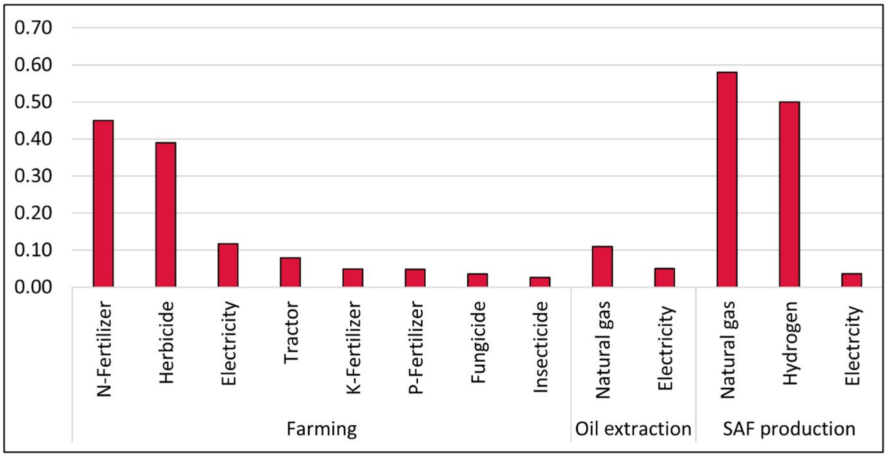

FIGURE 7 Standardized regression coefficients for carbon emissions for carinata-based sustainable aviation fuel

Natural gas usage in the biorefinery had the highest impact on the carbon emission estimates, followed by hydrogen use in biorefinery (Figure 7). It emphasizes technological improvement required in the biorefineries to further reduce carbon emissions of SAF. During the seed production stage, nitrogen fertilizer adjustments could have the highest impact on carbon emissions, followed by herbicide adjustments.

4 | CONCLUSION

The use of SAF in place of conventional aviation fuel can reduce dependence on fossil fuel and reduce harmful carbon emissions from the aviation sector. With that objective in mind, we created a methodology to systematically estimate carbon intensity of carinata-based SAF. We showed that the produced SAF provides about 65% relative carbon savings compared with conventional aviation fuel. We also calculated the break-even price of carinata-based SAF, considering variations in multiple parameters such as fixed cost, the variable cost, co-product credit, RIN credit, yield, and transportation distance. SAF from carinata is more expensive than conventional aviation fuel without co-product or the RIN credits. Even with a low fixed cost and in the presence of low co-product credit, the production of SAF from carinata requires subsidies, especially if the variable cost is high.

Despite the limitations described in the system boundary (Section 2.1), we provided a background on which further techno-economic analysis can be performed. This study can be extended by comparing unit production cost and carbon emissions from other pathways, such as the catalytic hydrothermolysis process. There also exists a need for incorporating soil carbon sequestration over time for refining the carbon intensity of carinata-based SAF in the Southeastern United States. We expect this study to help reduce the knowledge gap regarding the feasibility of SAF using new and promising feedstocks. This study will expand the repository of ongoing studies related to the economic feasibility and carbon reduction potential of SAF. We expect our results will inform stakeholders such as farmers, policymakers, and investors with crucial information necessary before large investments are made in the SAF industry.

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AUTHORS' CONTRIBUTION

AA and MFHM collected the data, developed the model, performed the analysis, and co-wrote the initial draft of the manuscript. PD arranged the funding support, supervised the overall research, and edited and finalized the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Asiful Alam https://orcid.org/0000-0001-9024-1681
Md Farhad Hossain Masum https://orcid.org/0000-0002-6279-5545
Puneet Dwivedi https://orcid.org/0000-0001-6272-7473

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