Winter Safflower Biodiesel: A Green Biofuel for the Southern High Plains

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Abstract

Combustion of fossil fuels has added tremendous quantities of carbon dioxide to the atmosphere, and the increase will continue over the coming decades considering the increasing global population and standards of living. Biofuel cropping systems are believed to realize GHG emission reductions and the local environmental and societal benefits. However, they must be derived from feedstocks produced with much lower life-cycle GHG emissions than traditional fossil fuels and with little or no competition with food production. Winter safflower is considered a potential feedstock for biodiesel production that can be grown on the Texas High Plains. It requires fewer inputs in terms of irrigation and fertilizer, and could be grown on semi-arid or abandoned land. The purpose of this study is to assess and compare the life-cycle energy and greenhouse gas (GHG) emission impacts associated with winter safflower seed-derived biodiesel, and determine the suitability of safflower biodiesel as an energy crop on the Texas High Plains. In addition, this study identifies the parameters that have the greatest impact on GHG emissions and the likelihood that winter safflower would be adopted by farmers on the High Plains. Finally, in order to analyze farmers' planting decisions corresponding to different carbon policies, a production function of safflower and GHG emissions are developed, as well as a related profit function to evaluate possible incentives to change behaviors.

Key Words: Winter Safflower, Life-cycle Greenhouse Gas Emission, Biofuel, Suitability

Introduction

Combustion of fossil fuels has added tremendous quantities of carbon dioxide to the atmosphere, and the increase will continue over the coming decades considering the increasing global population and standards of living. Use and development of biofuels, such as winter safflower biodiesel is believed to realize greenhouse gas (GHG) emission reductions. In addition, it could also benefit agricultural economics by providing an important new source of income for farmers while lowering dependence on fossil fuel supplies. However, for biofuels to realize local environmental and societal benefits, they must be derived from feedstocks produced with much lower life-cycle GHG emissions than traditional fossil fuels and with little or no competition with food production (Tilman, et al. 2009).

Winter safflower is considered a potential feedstock for biodiesel production to grow on the Texas High Plains. It requires fewer inputs of irrigation and fertilizer, and could be grown on marginal or abandoned land. However, the production of winter safflower requires fossil-fuel inputs and emits non-CO_2 greenhouse gases. Thus, it is crucial to measure the greenhouse gas emissions over the entire life cycle of biodiesel production to assess the overall benefits on local environment. Generally, the less a biofuel depends on fossil energy, the more potential it has for diversifying our total fuel supply. On the other hand, the degree to which a biofuel relies on fossil energy for its production is one of many criteria that may be used by policymakers and others to evaluate and compare various biofuels.

In this report, we present a life-cycle assessment (LCA) of the energy inputs and GHG emission impacts of safflower biodiesel relative to those of petroleum diesel and gasoline. The life-cycle assessment (LCA) of safflower biodiesel is a cradle-to-grave analysis for the energy and environmental impacts of making a product, which provides a tool to quantify the total required energy from different sources and the overall energy efficiency of safflower biodiesel production processes. In this analysis, we estimate consumption of total energy, fossil energy, and petroleum oil and emissions of GHGs (CO_2, N_2O and CH_4). The LCA of safflower biodiesel in this analysis accounts for emissions in four stages of production:

(1) feedstock cultivation, including energy inputs to produce fertilizer and other chemicals, safflower farming and harvest;
(2) feedstock transportation from farms to processing plants;
(3) oil extraction and biodiesel conversion; and
(4) biodiesel distribution from plants to refueling stations.

The LCA assumes that a hexane extraction method is used to extract oil from safflower seeds, and transesterification is used to convert oil into biodiesel. Oil extraction and transesterification result in the production of two important coproducts, meal and crude glycerin, respectively, and a mass-based allocation method is used to account for the energy associated with co-products. This method is commonly used because it is easy to apply and provides very reasonable results (Vigon, et al. 1993).

The next step in this analysis is to determine the influence of individual parameters on the overall study results by sensitivity analyses. The four selected parameters are yield, fertilizer usage, irrigation levels and transportation distances. And each set of parameters is tested individually, while others are held at their base case values.

In response to governmental policies which aim to reduce GHG emissions, profit-maximizing famers will shift toward biofuel crops cultivation when profits from biofuel crops exceed profits from food production. This results from the fact that those kinds of instruments make energy sources with low greenhouse gas emissions, such as biofuels, increasingly profitable. Thus, the final step in this analysis was to analyze farmers' production decisions corresponding to different carbon policies. In order to do that, a production function of safflower and GHG emissions are developed, as well as a related profit function to evaluate possible incentives to change behaviors.

Energy Life-Cycle Analysis

This section describes the inventory and data used to construct the four stages of the biodiesel life cycle: feedstock cultivation, feedstock transportation, oil extraction with biodiesel conversion, and product distribution.

Feedstock Cultivation

According to Lai (2004), production, formulation, storage, distribution of carbon-based inputs and application with tractorized equipment lead to combustion of fossil fuel, and use of energy from alternate sources, which also emits CO_2 and other greenhouse gases (GHGs) into the atmosphere. Table 1 below lists all the possible sources of energy required (on a per-acre basis) and GHG and carbon emission equivalents associated with safflower production. The farm input data for safflower production were obtained through personal contact, which were the most recent data available at the time of this study. In addition, all energy inputs were converted to British thermal units (Btu) using low-energy heating values.

Crop systems emit $\mathrm{N_2O}$ directly, produced through nitrification and denitrification in the cropped soil, and also indirectly, when N is lost from the cropped soil as some form other than $\mathrm{N_2O}$ (NO_x, NH_3, NO_3) and later converted to $\mathrm{N_2O}$ off the farm (Adler, Del Grosso and Parton 2007). Thus, estimation of direct and indirect N_2O emissions from safflower farming requires two important parameters: (1) the amount of nitrogen from fertilizer application and (2) the amount of nitrogen in the aboveground biomass left in the field after harvest and in the belowground biomass (i.e., roots).

According to IPCC (2006) estimates, aboveground biomass for safflower is 91% of the yield (on a dry-matter basis). Aboveground biomass has a nitrogen content of 0.8%. Belowground biomass is about 19% of aboveground biomass, with a nitrogen content of 0.8%. The total amount of nitrogen in safflower biomass that is left in fields per acre of safflower harvested is calculated as shown in the following equation:

$$2000\ lb/acre * 85\%(dry\ matter\ content\ of\ safflower) * (0.91 * 0.8\% + 0.19 * 0.8\%) = 14.96\ \ lb\ N/acre.$$

IPCC (2006) sets the default value at 1% of *N* applied to soils for direct N_2O emissions from soil. On the other hand, to estimate indirect N_2O emissions, two additional emission factors are required: one associated with volatilized and re-deposited *N*, and the second associated with *N* lost through leaching/runoff. The IPCC (2006) estimate for the fractions of *N* that are lost through volatilization is 10%, with a range of 3-30%. The emission factor for N_2O emissions from atmospheric deposition of *N* on soils and water surfaces is 1%, with a range of 0.2-5%. And the fraction of N losses by leaching and runoff is estimated to be 30%, with a range of 10-80%. The other emission factor of leached and runoff nitrogen to N in N_2O emissions is 0.75%, with a range of 0.05–2.5%. Thus, the total N_2O emissions (direct and indirect) from managed soils are calculated as follows:

$$14.96\ lb\ N/acre * (1\% + 10\% * 1\% + 30\% * 0.75\%) * 44/28 = 0.31\ lb/acre.$$

In addition, adding urea to soils during fertilization leads to a loss of CO_2 that was fixed in the industrial production process, and it is estimated by:

$$50\ lbs/acre * 0.20 * 44/12 = 36.67\ lbs/acre,$$

where 0.20 represents an overall emission factor for urea (IPCC, 2006).

Feedstock Transportation

To estimate energy requirements and GHG emissions from the transport of safflower seeds from the field to biodiesel conversion facilities, we assume the average energy used for transporting is 1.13 MJ per kg of safflower seeds (Sheehan, et al. 1998). The estimation was based on the total distance of 320 miles, which includes the distance for trucking safflower seeds from the field to the nearest biodiesel conversion facilities located in Dallas, TX, and also the distance to get it to its final destination.

Biodiesel Production

The production of biodiesel from safflower seeds occurs in two stages: the safflower seeds are first treated to remove the oil, and then the safflower seed oil is converted into biodiesel. The first stage, the removal of the oil from the safflower seeds, is often called crushing, and the most common method used to convert the oil into biodiesel is a process known as transesterification.

1. Oil Extraction

Safflower seeds contain 28% oil by weight. Two main methods used for extraction of the safflower seed oil are identified as mechanical extraction and solvent extraction, and the latter is more commonly used. The standard solvent extraction process uses n-hexane that is produced from petroleum. Most of the n-hexane used in oil extraction is recovered and recycled, with some inevitable loss (Huo, et al. 2008). After extraction the oil is filtered through a filter press and is then ready for the conversion to bio-diesel.

Table 2 below presents the inputs required for the extraction of safflower seed oil using a continuous solvent extraction process. Due to a lack of availability of data on safflower seed-specific extraction processes, this study uses proxy data for the continuous solvent extraction of oil from multiple bio-feedstocks using hexane as the solvent (Whitaker 2009). And it is assumed that the oil is extracted via solvent extraction with an efficiency of 95%.

2. Transesterification

Transesterification is the process used to make biodiesel fuel, which is the reaction of a fat or oil with an alcohol to form esters and glycerol in the presence of a catalyst. Methanol and ethanol are used most frequently among all alcohols that can be used in the transesterification process, especially methanol because of its low cost and its physical and chemical advantages (Ma and Hanna 1999). After biodiesel is derived, the remaining material is then distilled to recover the methanol and most of the water, which are reused to avoid waste and reduce input costs. The glycerin is also refined to be used in the production of various other products (Pradhan, et al. 2009).

Natural gas and electricity are required as energy inputs during the transesterification process, and the data used in this study is based on a comprehensive survey by the National Biodiesel Board (NBB) of its 230 member companies from biodiesel production in the U.S. (National Biodiesel Board 2009), since no published data was found for the methanol-based biodiesel transesterification safflower seed oil. The data provided by the survey represent the most accurate depiction of the energy used to produce biodiesel, and are intended to replace all data currently in use for the modeling of the life cycle GHG and energy impacts of biodiesel production in the U.S. The survey returned one data set that represents the industry average for transesterification of all biodiesel feedstocks used in the survey results, the inputs required for the conversion of the safflower seed oil into biodiesel, the recovery of the excess methanol, and treatment of the glycerin are listed in Table 3.

Calculating Co-product Credits for Biodiesel

The energy used to produce the meal portion and the crude glycerin that is produced during the transesterification stage must be excluded from the life-cycle assessment. A mass-based allocation method was used in this study because it is easy to apply and provides reasonable results, which simply allocates energy to the various co-products by their relative weights, as illustrated in figure 1. Thus, the energy used to produce biodiesel can be calculated in the following way:

$$\text{Energy input allocation for biodiesel} = E_1 f_1 + E_2 f_2 + E_3 \qquad (1)$$

where E_1 is energy input for agriculture, safflower seeds transport and crushing, f_1 is the mass fraction of safflower seeds oil used to produce biodiesel; E_2 is the energy used during transesterification, and f_2 is mass fraction of the transesterified oil used to produce biodiesel. E_3 is energy input for biodiesel transport.

According to personal contact information, 28 percent of the total energy used for safflower agriculture, transport, and crushing is allocated to the oil used to make biodiesel, and 72 percent is allocated to the meal. Following transesterification, 90.6 percent of the total energy used to convert safflower seed oil into biodiesel is allocated to biodiesel and 9.4 percent is allocated to glycerin. In addition, the coproduct energy value of glycerin must be deducted from safflower agriculture, crushing, and transport, so that f_1 in equation $(1) = 0.254 = (0.28 * 0.906)$, and $f_2 = 0.906$. All the energy used to transport biodiesel is allocated to biodiesel.

Results

The results for safflower seed-derived biodiesel are compared to the baseline fuel, conventional petroleum diesel, based on three metrics: net changes in life cycle GHG emissions, net energy value (NEV), and the net energy ratio (NER).

Net Energy Value and Net Energy Ratio

Two widely used types of energy efficiency are reported here. NEV is simply the difference between the energy output of the final biodiesel product and the fossil energy required to produce the biodiesel. A positive NEV indicates that this biofuel has a positive energy balance. NER is defined simply as the ratio of the final fuel product energy to the amount of fossil energy required to make the fuel, which tells us something about the degree to which a given fuel is or is not renewable. The base case energy requirements for safflower seed-derived biodiesel are presented in Table 4 below. After allocating energy by co-products, the total energy required to produce a gallon of biodiesel is 18,410 Btu. The net energy value is about 99,886 Btu per gallon. The estimated net energy ratio is 6.4.

From a policy perspective, these are important considerations. Policy makers want to understand the extent to which a fuel increases the renewability of our energy supply. Another implication of the NER is the question of climate change. Higher fossil energy ratios imply lower net CO_2 emissions (Sheehan, et al. 1998).

GHG Emissions

Table 5 presents CO_2-equivalents of GHGs (including CO_2, CH_4, and N_2O) involved in the production of safflower seed-derived biodiesel. To clearly show the GHG reduction benefit of safflower biodiesel, Table 6 presents the changes in GHG emissions of the biodiesel relative to the petroleum diesel, and it is found that safflower seed-derived biodiesel production and use reduces net life cycle greenhouse gas emissions by approximately 78% in the U.S. compared with conventional diesel. As indicated by the results, base case LCA calculations indicate that biodiesel produced from safflower seeds will lead to reduction of greenhouse gas and petroleum consumption compared with petroleum diesel.

Sensitivity analyses

Sensitivity analyses are also conducted to determine the influence of individual parameters on the overall study results. The base case scenario focuses on existing agricultural technology and transportation distance of winter safflower within a short-term time horizon. However, sensitivity analysis allows us to consider the potential for near-term improvements. The four selected parameters are yield, fertilizer usage, irrigation levels and transportation distances. And each set of parameters is tested individually, while others are held at their base case values. The results identify which input parameters have the greatest impact on the net life cycle GHG emissions.

According to Whitaker and Heath (2009), the normalized local sensitivity coefficient can be interpreted as the fractional change in model output resulting from a 100% change in model input. Equation 2 represents the calculation of the normalized local sensitivity coefficient (dimensionless):

$$\frac{\partial C_j / C_j}{\partial \lambda_i / \lambda_i} = \frac{\lambda_i}{C_j} \frac{\partial C_j}{\partial \lambda_i} \tag{2}$$

where C is the set of model output, *j* representing a specific output, and λ is the set of model input parameters, with *i* representing a specific input parameter. The influence of an individual parameter on model results is indicated by the absolute magnitude of the coefficient. Coefficients with absolute magnitudes of greater than one indicate that a 100% change in the input parameters will lead to a greater than 100% change in the model output. Coefficients less than one indicate parameters with a lesser direct impact on overall model results. As LCAs are typically linear models, the normalized local sensitivity coefficient is expected to remain consistent throughout the likely range of input parameter values (Whitaker and Heath 2009).

The results of normalized local sensitivity coefficients displayed in Table 7 identify yield as the parameter with the greatest influence on lifecycle GHG emissions, followed by irrigation level. However, absolute values of all these coefficients are less than one, indicating that model outputs are less sensitive to these parameters. Safflower yield has a negative normalized local sensitivity coefficient which indicates a negative relationship between yield and lifecycle GHG emissions. Thus, if safflower yield per acre increases from the base case value, lifecycle GHG emissions of safflower-based biodiesel will decrease. In contrast, an increase in irrigation level will lead to an increase in lifecycle GHG emissions as indicated by the positive local sensitivity coefficient. Results of normalized local sensitivity coefficients indicate that fertilizer and transport distance have relatively minimal impacts on GHG emissions with coefficients of less than 0.1.

Producer Profit Analysis

Since the American Clean Energy and Security Act (ACES) passed the House of Representatives recently, it is expected that a cap and trade system and new markets for agriculture will be created. Under ACES, capped entities could purchase offsets to meet compliance obligations; in total, domestic and international offsets would be allowed up to a total of 2 billion metric tons of GHG emissions annually (Larsen 2009). This creates opportunities for farmers to participate in a new market and generate increased revenue as the legislation looks to the agricultural community to serve as offset providers. Consequently, biofuel crops cultivation is considered as one of cost-effective manners for providing offsets and also increasing profits. Thus, the purpose of the last part of this study is to analyze the costs and revenue from safflower production, as well as farmers' planting decisions under a cap and trade market to provide useful implications. In order to do that, a production function of safflower is estimated as a function of fertilizer and water; production functions of GHG emissions from fertilizer application and irrigation process are also developed. Finally, a related profit function is developed to evaluate possible incentives to change behaviors.

The data used to estimate safflower production function is based on Engel and Bergman's study in 1997. Although safflower yield is determined by numerous factors, our analysis focuses on two crucial input factors: fertilizer and irrigation water. A cubic functional form (Equation 3) was used to better describe the increasing and decreasing returns to scale as exhibited in the data:

$$Y = \alpha_0 + \alpha_1 w + \alpha_2 f + \alpha_3 w^2 + \alpha_4 f + \alpha_5 w^3 + \alpha_6 f^3 + \alpha_7 wf + \alpha_8 w^2 f + \alpha_9 wf^2 \quad (3)$$

where Y denotes safflower yield per area, f the amount of fertilizer applied, and w irrigation water applied. Three interaction terms, wf, w^2f and wf^2, were included to capture the relationship between two input factors, but were ruled out by a joint significance test. The results of the production function estimation are presented in Table 8. The adjusted R-squared value of 0.83 indicates the estimated production function properly captured the underlying relationship between the two input factors, and t-values of coefficients are also acceptable.

Emission factors used to derive GHG emissions from fertilizer application and irrigation process were obtained from U.S. Environmental Protection Agency (EPA). Finally, the profit function of safflower is simply the difference between the revenue from production and total costs. Specifically, it can be expressed as follows:

$$\pi = p * Y - p_c * Y - p_c * c(w) - \left(p_w * w + p_f * f + fixed\ costs\right) \tag{4}$$

where π denotes profit, p safflower price, p_c carbon price, p_w irrigation water price and p_f fertilizer price. By assuming prices of safflower, fertilizer and irrigation water are exogenously determined, our analysis shows that there is a positive relationship between water irrigated and carbon price. That is to say, if the carbon price increases, farmers will decrease water usage to decrease GHG emissions to remain profitable. On the other hand, it also indicates that farmers could benefit from selling emission offset credits to industries required to reduce their emission levels if they can decrease their GHG emissions during production.

This result is especially meaningful for safflower producers considering recent emerging cap and trade market. Under a carbon market, it is estimated that carbon offsets could be valued at \$15 - \$30 per metric ton with prices increasing at 5% a year depending on market demand (EPA, 2009). In addition, if offset providers earned market carbon prices starting at \$15 per metric ton of carbon dioxide sequestered with prices rising at 5% annually, analysis indicates that the domestic offset market could grow to \$4.5 billion or higher per year by 2020 (Sands, Harper and Brodnax 2009). Our analysis shows that safflower production is profitable for producers to grow as an energy crop.

Conclusions

Base case analysis results indicate that biodiesel produced from winter safflower achieves a significant reduction in net life cycle GHG emissions of 78% compared with conventional petroleum diesel. With a positive NEV of 99,886 Btu per gallon and NER of significantly greater than one, the safflower-derived biodiesel system yield more useful energy out than is required during production, processing, and transport. These results suggest that the safflower-based biodiesel system under consideration could potentially achieve the identified sustainability goals of reducing net GHG emissions, displacing conventional petroleum diesel consumption, and improving the net energy ratio. In addition, through the use of sensitivity analyses, this study also identified yield and irrigation level as critical parameters that influence the study's overall GHG emissions.

Finally, the profit function analysis reveals that, under a cap and trade market, producers could gain additional profits by cultivating winter safflower as a low-carbon biofuel. Thus, winter safflower is considered as a pofitable feedstock for biodiesel production to grow on the Texas High Plains.

Note that this study does not consider potential land use changes. Increased CO_2 emissions from potential land use changes are an important factor, but it is not included in the current analysis since reliable data on potential land use changes induced by safflower seed-based biodiesel production are not available. However, safflower is grown on abandoned or marginal land. It is anticipated that there will be a neutral to positive net carbon change as the areas are changed from lacking vegetation to hosting large-scale safflower plants.

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Table 1. Annual Energy Requirements, GHG and Carbon Emissions Equivalent for Safflower Agriculturare Inputs before Allocating Coproduct Credits

Inputs	Usage	Energy Required (Btu/gal)
Urea	50.00(Lbs/acre)	878.12
Diesel	3.84 (Gal/acre)	7250.15
Electricity	130.84(kWh/acre)	6508.75
Herbicides	1.50(Lbs/acre)	2504.81
Total		17141.83

Table 2. Fossil Energy Requirements for Safflower Seed Oil Extraction before Allocating Coproduct Credits, per Tonne of Input

Inputs	Equivalent Energy Required	Units
Electricity	55	kWh
Hexane	4	kg
Steam	280	kg
Water	12	m^3

Table 3. Base Case Data Inputs for Methanol-based Biosiesel Transesterification via Safflower Seed Oil, per Tonne of Biodiesel

Inputs	Equivalent Energy Required	Units
Safflower Seed Oil	1060	kg
Electricity	57	kWh
Natural Gas	1.12	MJ
Methanol	98	kg
Sodium Methylate	25	kg
Sodium Hydroxide	0.99	kg
Potassium Hydroxide	0.068	kg
Hydrochloric Acid	28	kg
Sulfuric Acid	0.14	kg
Citric Acid	0.37	kg
Glycerin Output	124	kg

Figure 1. Weight-based Energy Allocation for Biodiesel Co-products

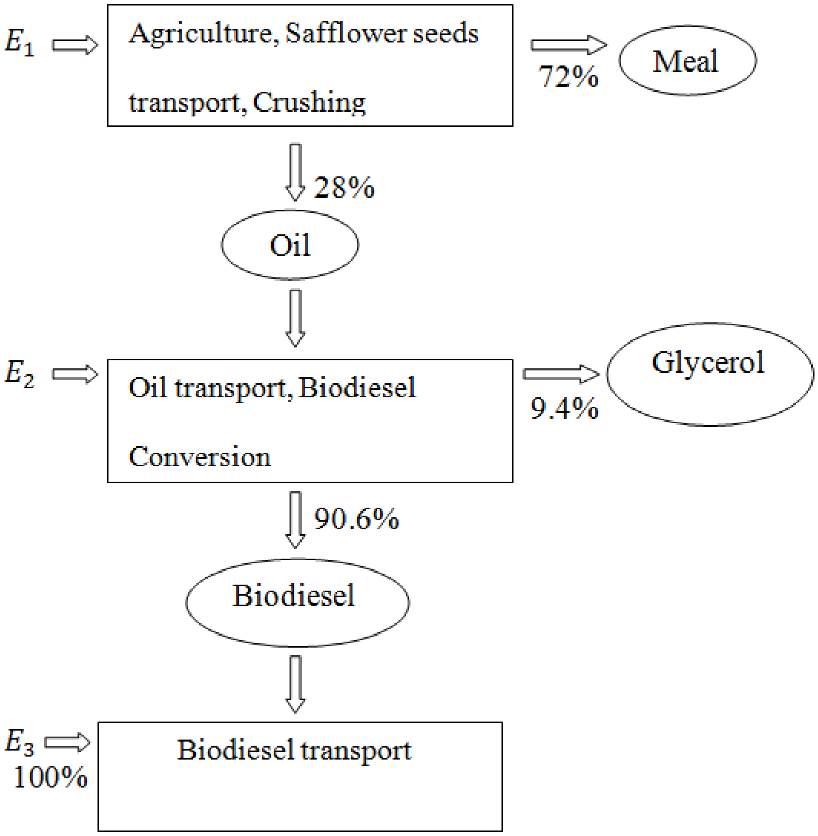

Table 4. Base Case Energy Use for Biodiesel and adjusted by Energy Efficiency Factors

Life-Cycle Inventory	**Fossil Energy Use (Btu/gal of Biodiesel)**	
	Total	**Biodiesel Fraction**
Feedstock Cultivation	17142	4,800
Safflower Seeds Transport and Biodiesel Distribution	8,507	2,382
Safflower Seeds Oil Extraction	26,534	7,430
Biodiesel Conversion	4,192	3,798
Total Energy Input for Biodiesel Adjusted for Co-products		18,410
Biodiesel Total Energy Content		118,296
Net Energy Value (Btu Out – Btu In)		99,886
Net Energy Ratio (Btu Out/Btu In)		6.4

Table 5. CO_2-equivalents of GHG Emissions for Biodiesel and adjusted by Energy Efficiency Factors

Activities	**CO_2 Emissions (kg CO_2/mmBTU)**
Feedstock Cultivation	6.66
Safflower Seeds Transport and Biodiesel Distribution	1.12
Oil Extraction and Biodiesel Conversion	13.87
Total	21.65

Table 6. Lifecycle GHG Emissions for Safflower-based Biodiesel and Petroleum Diesel

Fuel	**CO_2 Emissions (kg CO_2/mmBTU)**	**Percent Change from Diesel**
Diesel	97	----
Safflower-based Biodiesel	21.65	-78%

The data on lifecycle GHG emissions for diesel were obtained from Federal Register, Canola Biodiesel (2010).

Table 7. Normalized Local Sensitivity Coefficients for Lifecycle GHG Emissions for Safflower-based Biodiesel

Parameter	**Sensitivity Scenario**		**Normalized Local Sensitivity Coefficient**
Yield	High seed yield	Set to high end of reported range.	-0.20
Irrigation	Less irrigation	Set to low end of reported range.	0.15
Fertilizer	Low fertilizer level	Set to low end of reported range.	0.03
Transport	Reduced distance	Reduced distance of travel of 100 miles.	0.05

Table 8. Estimated Results of the Safflower Production Function

	intercept	**w**	**f**	**w^2**	**f^2**	**w^3**	**w^3**
Coefficients	4405	-1090	-8.68	86.43	0.12	-1.91	$-4.56 * 10^{-4}$
t-values		-1.71	-1.28	1.85	1.21	-1.74	-1.11
Adjusted Rsq							0.83