Environmental Life Cycle Impacts of High Oleic Soybean Oil Used for Frying

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ABSTRACT

Life cycle assessment was used to quantify the environmental impacts and identify supply chain hotspots for high oleic soybean oil (HOSO), conventional soybean oil (CCO), hydrogenated soybean oil (HSO), high oleic canola oil (HOCO), and conventional canola oil (CCO) for use in US restaurant fryers. On a cradle-to-grave basis, environmental impacts for fryer oil are a function of oil use rate, manufacturing burdens, and restaurant management behavior. Results identify 30%-45% reductions of impacts for high oleic oils relative to their conventional counterparts for the relevant impact categories evaluated. Impacts are similar for HOSO and HSO based on similar use-phase performance. The LCA highlights the importance of oil performance in use, nitrogen fixation of soybeans, allocation assumptions, and waste disposal considerations of the oil after use. Using LCA demonstrates that HOSO not only offers nutritional and functional benefits but allows restaurants to improve the environmental footprint of their oil ingredients.

Keywords: Soybean Oil, High Oleic Soybean Oil, Canola Oil, High Oleic Canola Oil

1. Introduction

Many markets are experiencing a trend towards sustainability. The fryer market is no exception as consumers demand healthier options, causing restaurants to respond in kind, but without wanting to sacrifice cost, taste, or quality. For more than 50 years hydrogenated oils have been the main stay in the fryer oil market, providing increased stability, long fry life, and low cost relative to conventional oils (AHA, 2010). However, health concerns about trans-fats have caused regional bans on their use including bans in New York, Philadelphia, and California (Tavarnise, 2013). Top chefs and restaurant chains are looking for alternative oils that are just as stable and cost effective but without trans-fat and lower saturated fat content. Recently, the FDA announced a preliminary decision to remove partially hydrogenated oils from the 'Generally Recognized As Safe' (GRAS) list which will continue to boost the need for alternative highly stable oils. To stay in the market, oil suppliers are met with the task of supplying drop-in replacement products which can meet the nutritional demands without increasing costs. A switch to conventional oils may meet nutritional requirements, but they do so at the expense of fry-life. High oleic soybean oil is now available in the U.S. market which provides both the desired functionally (fry-life & taste) in addition to eliminating trans-fats and reducing saturated fat content. To complement the nutritional and performance benefits of high oleic frying oils, this study takes a holistic approach, using life cycle analysis, to quantify the environmental impacts of high oleic frying oils in restaurant fryer applications relative to those for conventional and hydrogenated oils. The goal of the study is three fold:

- Quantify the importance of functionality and oil performance in the use-phase
- Identify hotspots within the fryer oil supply chain;
- Understand the importance and sensitivity of the assumptions used in the LCA

2. Methods

Attributional life cycle methodology is used to evaluate the environmental impacts associated with frying oil use in restaurants for conventional soybean oil (CSO), high oleic soybean oil (HOSO), hydrogenated soybean oil (HSO), conventional canola oil (CCO), and high oleic canola oil (HOCO). The study focuses on U.S. restaurant fryer oil applications. Oil availability, consumer demands, restaurant practices, oil transportation, and, of course, seed agronomics may all vary with geography. No comparative assertions are intended. Comparisons among different seeds are made to highlight hotspots within the supply chains for the US market.

2.1. Functional Unit

The functional unit for this system is based on days of fryer oil use in a restaurant. As restaurants have many variations in terms of food throughput, the types of foods fried, and hours of operation, more than one scenario is required. A base case, Scenario 1, assumes two days of fryer use and a 4% loss rate of oil to the food per day. An alternate case, Scenario 2, assumes six days of fryer use and a 10% loss rate of oil to the food. Both cases follow fry-life test results where high oleic oils and hydrogenated oils have increased stability, allowing twice the fry-life of conventional oils based on polar compound generation rates (see Section 2.4.4). For each scenario, high oleic and hydrogenated oils are charged once, while conventional oils require two charges. Top-off is assumed to occur each day if the oil has not been changed. All cases assume four (4) 22.7 kg (50 lb) fryers are used at the restaurant. These two scenarios are not all-inclusive, but provide perception into the impacts of food absorption rates and fry-life. Extended fry-life increases the number of times oil must be topped-off while higher absorption rates increase the amount of top-off oil required. Since high-oleic and hydrogenated oils require half as many charges, one less day's top off quantity is required in each scenario for these oils relative to conventional oil. Table 1 summarizes the oil use rates and wash cycles for each type of oil for each scenario.

Table 1. Fryer Oil Use Scenarios; Scenario 1: Two Days Fryer Use, 4%/day Oil Loss Rate; Scenario 2: Six Days Fryer Use, 10%/day Oil Loss Rate

		Scenario 1		**Scenario 2**	
		Conventional	**High Oleic / Hydrogenated**	**Conventional**	**High Oleic / Hydrogenated**
Oil, Charged	kg	181.4	90.7	181.4	90.7
Oil, Top-off	kg	0	3.6	36.3	45.4
Oil, Total	kg	181.4	94.3	217.7	136.1
Oil, Spent	kg	174.2	87.1	163.3	81.6
Wash Cycles	-	2	1	2	1

2.2. System Boundaries

The system boundaries for this study are illustrated in Figure 1. They include agricultural inputs, farming operations, seed processing, soybean and canola oil refining (and hydrogenation when required), transport along the supply chain as well as transport for the refined oil to a warehouse local to the restaurant, oil use in the restaurant, washing of the fryers, and spent oil disposal. Key exclusions from the system boundary are as follows:

- Health impacts (Scope of the study is on environmental impacts)
- Electricity to operate the fryers at the restaurant (equivalent in all cases)
- Conversion of spent oil at EOL to alternative products such as biodiesel, animal feed, or boiler fuel (This study uses a restaurant perspective – see section 5)
- Transportation from the warehouse to the restaurant (deemed negligible)
- Oil packaging (would increase with increased total oil use – i.e. higher for conventional oils)
- Indirect effects such as indirect land use change (attributional modeling employed; would increase with increased total oil use – i.e. higher for conventional oils)
- Infrastructure
- Sequestered carbon in oil (Study assumes all biogenic carbon sequestered in the oil is released via digestion (absorbed oil), combustion (spent oil), or biodegradation (spent oil).)

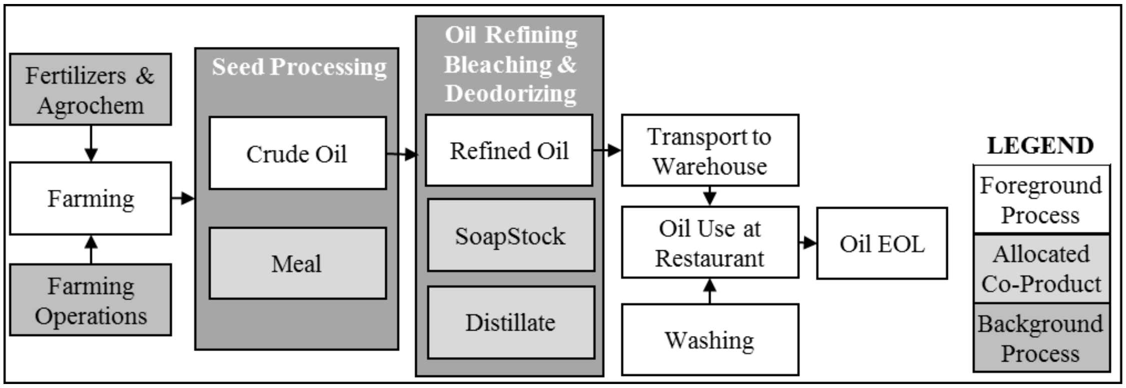

Figure 1. System Boundaries for Soybean Oil or Canola Oil.

2.3. Impact Categories

Based on the agricultural processes involved, the following impact categories were identified as relevant and included in this study: Climate Change Potential (CCP), Eutrophication Potential (EP), Acidification Potential (AP), Land Use, and Non-Renewable Energy Demand (NRE). The TRACI 2.0 impact assessment method is used for CCP, EP, and AP based on the U.S. focus for the study. NRE is calculated using the Cumulative Energy Demand (CED) Impact method. The CED model available in SimaPro™ software has been corrected to quantify all energy flows on a higher heating value (HHV) basis. Land Use is included and modeled using the impact category available in the ReCiPe Midpoint (Heuristic) model. Water use is both relevant and of interest, but is outside the scope of this study as this would require more regional information to provide meaningful results.

2.4. Process Models

2.4.1. Farming: U.S. Soybeans, Canadian Canola

U.S. soybean supply is virtually all domestically grown. A detailed life cycle analysis from the United Soybean Board (USB) is used as the basis for the soybean farming life cycle model (Omni-Tech, 2010). From 2007-2012, more than 65% of the canola oil supply to the US is imported, with most of that from Canada. A detailed life cycle assessment for the production of canola from the Canola Council of Canada (S&T2, 2010) is used which is deemed representative for the US supply chain and for US canola farming (S&T2, 2010; USDA, 2014). Ammonia air emissions and phosphorus and nitrate water emissions were adjusted or added such that both datasets used the same methodology for calculation (Nemecek & Kagi, 2007). Dinitrogen monoxide, a key field emissions contributing to CCP, has been updated since the original USB report from 0.35g N_2O per kg soybean based on DAYCENT modelling to 0.682 g N_2O per kg soybean based on actual field measurements in Minnesota. No carbon sequestration is included in either seed model as all carbon is assumed to be converted back to carbon dioxide at the end-of-life through digestion, combustion, or degradation.

2.4.2. Seed & Oil Processing

Data from the USB is used to model the burdens associated with soybean processing (Omni-Tech, 2010). Specific canola processing data is not available in the Canola Council of Canada LCA. Detailed and consistent data for a European rapeseed mill is available in the literature (Jungbluth, N., et. al., 2007; Schmidt, 2007). For this study, canola mill yields, solvent use, and energy consumption are taken from the thesis by Schmidt.

Since mill processing results in both oil and meal co-products allocation is required. This study uses economic allocation of the oil and meal for both soybeans and canola. For soybeans, average price and production data of US meal and oil from 2007-2011 per the USDA NASS oil crops yearbook (USDA, 2014) is used. For canola, price and production data are taken from Statistics Canada(StatCan, 2014). Sensitivity analysis for allocation methods is included in this study.

For high oleic oil allocation purposes, pricing for crude high oleic soybean and canola oil is assumed to be \$0.132/kg (i.e. \$0.06/lb) higher than conventional oil. No price differences are included for meal.

Refining, bleaching and deodorizing are required for both soybean oil and canola oil food applications. Both are modeled using the same oil refining process data (Schmidt, 2007). In addition to refined oil (98.7% by mass), soap stock and a distillate co-product are produced. Spot pricing for the co-products is used for economic allocation. The refined oil receives roughly 97% of the allocation.

Hydrogenation was modeled by accounting for energy (100 kg steam, 13 kWh electricity), Hydrogen (72 m3 at STP), refined soybean oil (1010 kg), and nickel catalyst (0.3 kg) required per tonne of hydrogenated soybean oil (Chakrabarty, 2009). Allocation for HSO is not affected by its higher price since hydrogenation occurs after both the milling and refining steps.

2.4.3. Transport: Refined Oil to Warehouse

The transport for refined oil to the restaurant is simplified to capture just the main portion of travel from the refinery to the warehouse local to the restaurant. As a base case, the restaurant is assumed to be in New York City, NY, requiring 900 miles of transport for soybean oil (i.e. distance from Rock Island, IL) and 2200 miles for canola Oil (from Prince Albert, Saskatchewan). Local transport from warehouse to the restaurant and backhaul is ignored. Sensitivity analysis on transport assumptions is included.

2.4.4. Use-Phase: Fry-Life and Washing

DuPont internal fry-life tests were performed for high oleic soybean oil relative to conventional soybean oil. For HOSO, oil stability, as measured by the composition of polar compounds in the oil reaching 25% during prolonged time at frying temperature, was at least twice that of conventional soybean oil. Actual fry-life is a function of restaurant cooking demand and restaurant behavior. This study assumes that the restaurant cooking demand results in either 2 or 6 days of fry life for HOSO and, half of that, 1 or 3 days, for conventional soybean oil. HOCO and CCO fry-life performance is estimated to be consistent with HOSO, and CSO, respectively. HSO is estimated to have the same fry-life as the high oleic oils (Pambau, et.al, 2010).

The washing procedure used in this study is based on Stratas Foods Fryer Tips (Stratus, 2009). Two fryer volumes of water are used for washing including 1 cup of vinegar per five gallons of water. The energy associated with the washing step is based on heating the water from 50°F to 200°F with electric heat. The same washing procedure is assumed for all oils. Washing is assumed to be done every time the oil is changed.

2.4.5. Spent Oil

Spent oil has several potential end-of-life scenarios after use in the restaurant. For instance, the spent oil may be used for animal feed, may be processed and used as fuel in a boiler, or may be processed to yellow grease and used as a feedstock to biodiesel generation. However, the restaurant typically does not control the end use for the oil. As it leaves the restaurant, the spent oil has free fatty acids generated during use and contains water and animal fats as well as other impurities. In the past, restaurants would need to pay for spent oil waste removal. Currently, many restaurants are having the oil collected without charge or credit, while some may receive a small credit. From the restaurant's perspective, an appropriate method to model the spent oil is via economic substitution. For the base case, we assume no burdens and no credits for the spent oil, so no adjustments, additions, or credits to the model are required to address the end-of-life (EOL) for the spent oil. Sensitivity analysis is included for modeling of spent oil.

Of note, no carbon sequestration is assumed in the production of soybeans or canola, so no carbon emissions associated with the spent oil need to be addressed at end-of-life. All carbon in the oil is assumed to return to the atmosphere as carbon dioxide via digestion, combustion, or decomposition.

2.5. Auxiliary Models

Throughout the process models, several background LCA models are required for electricity and fuel supply, minor chemical, fertilizers, farming operations, etc. In general, US-EI 2.0 database models are used. These models are based mainly from ecoinvent 2.2, where all electricity flows have been replaced with a US average electricity mix. Foreground models use region specific electricity.

3. Results

For each impact assessment, the burdens associated with different steps of the supply chain were segregated to identify their contribution to the total burden. The term ‘Farming’ includes the production, transportation, and application of fertilizers, soil emissions, and the on-farm energy. ‘Milling/ Refining’ includes all processing energy and impacts allocated to the oil including milling, solvent extraction, degumming, neutralization, bleaching, and deodorizing. For HSO, impacts associated with the hydrogenation are included as well. ‘Transportation’ refers only to burdens of transporting the refined oil to a warehouse local to the restaurant. ‘Washing’ refers to cleaning the fryers at the restaurant each time the oil is changed. For each oil type, Figures 2a-2e show the breakdown of impacts by these process areas.

The results presented are based on several assumptions and methodologies. Sensitivity analyses are required to understand the importance of these assumptions and to test the robustness of the magnitude of the impacts and the trends identified in the results. These are presented for fry-life and oil absorption, oil transportation from the warehouse, allocation methods, and spent oil allocation.

3.1. Scenario 1; 2 Days Fryer Use, 4% Oil Loss Rate

In general, under the assumptions in this study, environmental impacts follow the functionality of the oil. The increased oil stability due to the high oleic content or hydrogenation uses less oil, results in lower transport requirements and requires fewer washes. HOSO and HOCO achieve these savings at the expense of slightly higher allocation at the mill stage due to a higher valued oil product. HSO requires additional processing following the refining steps. Figures 2a-2e show the impacts broken down by process step for CCP, NRE, AP, EP, and Land Use, respectively. Across all impact categories, the increased oil stability provided by the high oleic oils and HSO result in roughly a 42%-47% reduction in impact relative to conventional oils.

3.1.1. Climate Change Potential

As shown for Scenario 1 in Figure 2a, CCP is dominated by the farming step for each oil type. For soybean oils in scenario 1 (2 days frying, 4% oil loss rate), farming contributes 53%-57% of the total impacts. Field N_2O emissions account for half of the soybean farming CCP burden, while emissions during quicklime production account for 24%, and emissions from fuel consumption at the farm account for 16%. Milling adds another 28%-31% to the overall CCP. HSO has slightly lower climate change impacts than HOSO. For CCP, the increased impacts from economic allocation for the higher priced HOSO are marginally higher than the burdens from hydrogenation for HSO. Although the overall CCP impacts for canola oil are higher than those for soybean oil, two-thirds of the difference is due to oil transport to the warehouse. Canola oil has higher CCP from farming due mainly to increased fertilizer use (particularly N-based fertilizers). Canola oil has 40% lower impacts in the milling process per kg oil relative to soybean oils.

3.1.2. Non-Renewable Energy Demand

Figure 2b shows the NRE impacts for Scenario 1. For soybean oils, milling and refining impacts account for 44%-50% of the total NRE impacts, while farming only accounts for 26-29%. Washing impacts are more important for NRE than for CCP, accounting for 18%-21% of the total NRE. Roughly 50% of the soybean farming NRE comes from on farm energy requirements. The impacts from HSO are 3% higher than those for HOSO. For canola, fuel use at the farm accounts for 45%, while the production of N-based fertilizers accounts for 44% of canola farming NRE impacts. Differences between soybean and canola oils are more pronounced for NRE as compared to CCP, mainly due to the higher fertilizer inputs for canola.

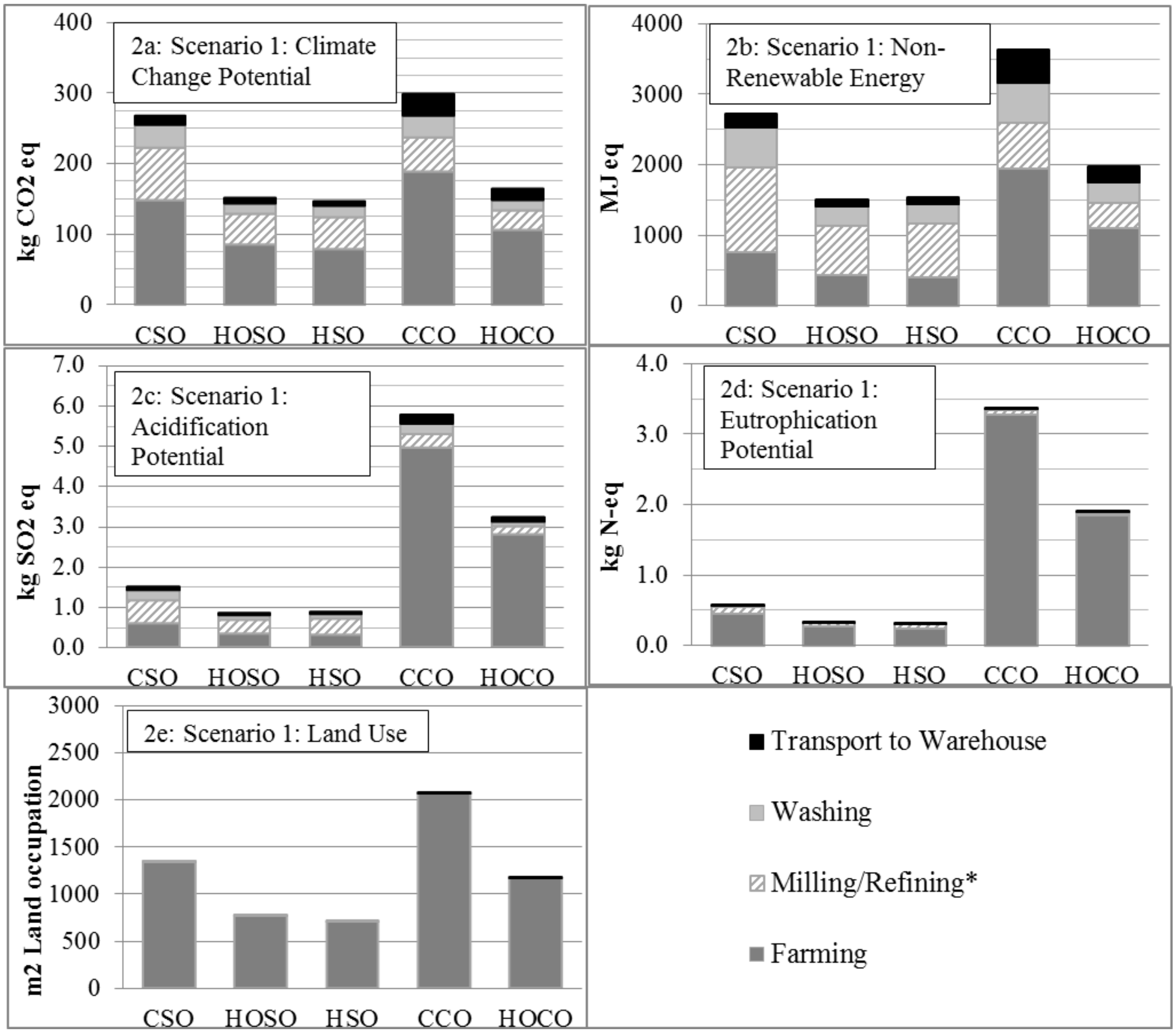

Figure 2a-2e: Impacts by Process Step and Oil type for Scenario 1. Impacts evaluated include Climate Change Potential, Non-Renewable Energy Use, Acidification Potential, and Eutrophication Potential, and Land Use.

3.1.3. Acidification Potential

Ammonia, nitrogen oxide, and sulfur dioxide are the three main emissions affecting acidification. In the frying use supply chain, these are released as field emissions, from fuel combustion throughout the supply chain, and from production of some N-based fertilizers. For soybean oils, where N-fertilizer demand is low because of the N-fixation properties of the legume, the fuel combustion pathway dominates. As shown in Figure 2c for Scenario 1, farming impacts are 38% of the total AP impact for soybean oils, with less than 12% from direct field emissions. For canola oils, field emissions of ammonia drive the AP impacts since fertilizer use is much higher, leading to much higher AP impacts than soybean oils. More than 85% of the AP impacts for canola oils come from farming with over 66% from direct field emissions.

3.1.4. Eutrophication Potential

Eutrophication is driven mainly by releases of nitrates, ammonia, phosphates, and phosphorus in this supply chain. Both soybean and canola farming play the major role for their respective oil co-products. As shown in Figure 2d, for soybean oil, farming accounts for 78%-80% of the total impacts, with nearly 30% from field emissions. The impacts from canola fertilizer requirements are even more pronounced for EP than seen above for AP, as farming accounts for more than 97% of the total EP potential with 72% from direct field emissions.

3.1.5. Land Use

Not surprisingly, agricultural land use is governed by farm yields, oil content, and the amount of soybeans or canola allocated to the respective oils. For CSO, at a yield of 2768 kg soybeans / ha, an oil content of 19.5%, and an economic allocation factor of 39.42%, 1368 kg crude soybean oil are produced per hectare. For CCO, at a yield of 1550 kg canola/ha, 42.6% oil content, and a 75.01% economic allocation factor, 880 kg crude canola oil are produced per hectare. Due to use of economic allocation for the base case, where high oleic oils are priced $0.132/kg higher than conventional oils, a higher allocation rate of seed is applied to HOSO and HOCO per kg of oil used. Therefore, for Scenario 1, although oil use rate drops by 48% due to high oleic oil stability, land use decreases only 43%. Based on economic allocation, canola oils require over 50% more land per 2-day fryer use in Scenario 1. Figure 2e shows the land occupation for each oil type for Scenario 1.

3.2. Sensitivity Analysis: Scenario 2; 6 Days Fryer Use, 10% Oil loss rate

In general, Scenario 2 impacts are higher than those from scenario 1, but with less differentiation between conventional and high oleic oils due to higher oil adsorption rates to the food. The benefits of additional oil stability are not realized for the oil that is absorbed. The importance of washing is diminished for Scenario 2 since washing burdens don't change compared to Scenario 1, but oil use rate increases. For a given oil type, the other relative impacts of farming, milling, refining, and transport are similar to Scenario 1. Impacts for conventional oils increase roughly 17-19% compared to Scenario 1while high oleic impacts increase 40%-42%. HSO impacts increase 37%, slightly less than high oleic oils due to economic allocation.

3.3. Sensitivity Analysis: Transportation Assumptions

Transportation of the oil is clearly a function of location. Selecting cities closer to the refinery would reduce the magnitude of the oil transport to the warehouse. Selecting different cities may also change the relative impacts of canola based oils versus soybean based oils, but would not affect the relative impacts of high oleic and conventional oils. In the base case, transport had the highest impacts on CCP and NRE, but still only account for 5-13% of the total impacts. Impacts for transportation for three other U.S. cities are presented to show the change in magnitude of impact due to distance and the relative impact across seed types. Table 3 shows the CCP impacts for both transportation and for the functional system for Scenario 1 for each city. The relative impacts from transport range from 1%-10% for soybean oils and 5% to 13% for canola oils. For Seattle, where the transport distance is greater for soybean oil than canola, the overall CCP burdens from Scenario 1 for the different seed types become equivalent instead of favoring soybean oil. For NRE, Scenario 1 transport impacts range from 1%-14% for soybean oils and 7%-15% for canola Oils depending on restaurant location. Unlike for CCP, the Seattle location still favors soybean oils over canola oils, but the relative difference is decreased from 30% to 15%. Transport has much less impact for AP, EP, and Land Use and does not result in any significant changes in relative impacts among oil types for any restaurant location evaluated.

Table 3. Transportation Sensitivity: Transportation and Total Impacts for Scenario 1, CCP, at various U.S. Cities

Restaurant Location	**Distance, km**			**CCP, kg CO2 eq.**				
	Soybean	**Canola**		**CSO**	**HOSO**	**HSO**	**CCO**	**HOCO**
New York City, NY	1450	3540	Transport	13.1	6.8	6.8	32.1	16.7
			Total	**268**	**151**	**146**	**300**	**165**
Seattle, WA	3080	1820	Transport	27.9	14.5	14.5	16.5	8.6
			Total	**283**	**159**	**154**	**285**	**157**
Los Angeles, CA	2990	4410	Transport	27.1	14.1	14.1	40.0	20.8
			Total	**282**	**158**	**154**	**308**	**169**
Chicago, IL	270	2210	Transport	2.4	1.3	1.3	20.0	10.4
			Total	**257**	**146**	**141**	**288**	**159**

3.4. Allocation Methods

Central to LCA methodology is how to address the burdens associated with co-products. Allocation choices affect both the magnitude of impacts for all oil types and the relative impacts between soybean oils and canola oils since soybeans and canola have significantly different oil and meal compositions. The referenced USB LCA study for soybeans used mass allocation of soybean oil and soybean meal at the mill. However, the two co-products have significantly different value. Further, soybean meal is actually valued on its meal protein content, not just its overall mass since it may be sold with and without the hulls. This study has used economic allocation as the base case to address the difference in value of the two co-products. This prevents favoring soybean oils relative to canola oil based on the higher meal content in soybeans. A downside to economic allocation is price fluctuation. Since oil and meal serve different markets, they do not necessarily vary in the same manner. However, these fluctuations are dampened by averaging across multiple years of production.

For comparison to the base case economic allocation method (ECON), two additional allocation techniques are investigated, including mass allocation (MASS) as used in the USB report, and mass allocation between the meal protein content and the oil content in the seed (MASS-MP). The MASS-MP basis combines the simplicity of mass allocation with the valued aspects of the two co-products. Process subdivision was not credible for the mill stages due to both processing and energy integration.

Meal protein concentrations for soybeans from the United Soybean board and have been averaged across the 2007-2010 time horizon at 44.2% of soybean meal (USB, 2010). Meal protein content for canola meal is reported at 36% (S&T2, 2010). Results for CCP based on scenario 1are shown for each oil type and each allocation method in Figure 3 along with the mill allocation factors for each allocation method. Mass allocation results are 32%-45% lower than economic allocation for CCP. Reductions are higher for soybeans where more meal is produced relative to oil and for high oleic oils where the oil has higher value. While still lower, the MASS-MP results are much closer to economic allocation results since meal is priced on protein content. For each impact category evaluated, using mass allocation or MASS-MP allocation generally reduces the overall impact for fryer oil use, increases the differentiation between soybean oil and canola oil, and results in HSO being consistently higher than HOSO due to the impacts from hydrogenation

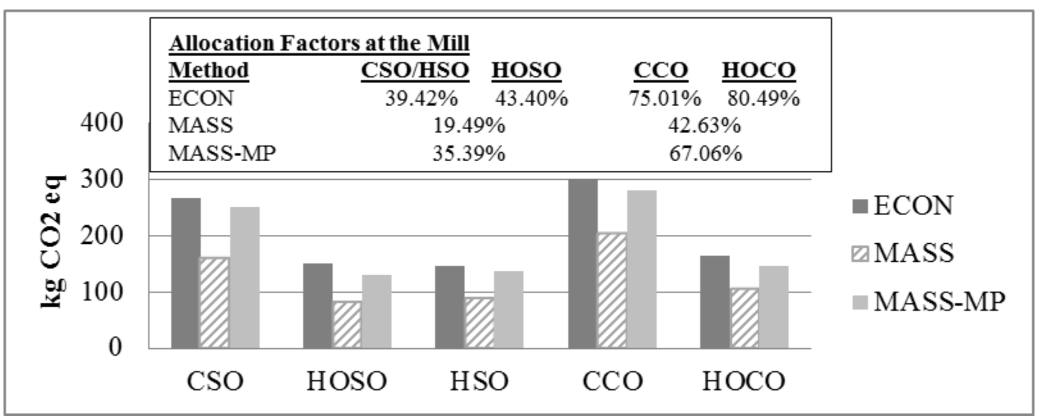

Figure 3: Allocation Sensitivity: CCP Impacts for Scenario 1 using Economic, Mass (Meal/Oil), and Mass-MP (Meal Protein/Oil) Allocation Methods. Allocation factors at the mill are included for reference.

3.5. Spent Oil Sensitivity

As demand for biodiesel increases, the potential outlets for spent oil for the restaurant owner may become more plentiful and profitable. While the current scenario assumes no burdens or credits for the spent oil, this sensitivity analysis assumes the restaurant receives \$0.11/kg (i.e. \$0.05/lb) for the spent oil on a dry basis. It is modelled as an economically equivalent quantity of crude (i.e. extracted) conventional oil that is avoided from the overall burden of the fryer system. In other words, roughly 0.1 kg crude soybean oil is avoided per 1 kg spent soybean oil produced. No packaging materials are considered with respect to spent oil collection.

For scenario 1, overall impacts are reduced 6%-10% for conventional oils depending on the impact category, and 5.5%-8.1% for high oleic oils, with the reduction being 15% more for conventional oils than for high oleic oils for any specific impact category. For scenario 2, overall impacts are reduced 4.5%-5.9% for conventional oils but only 1.7%-2.5% for high oleic and hydrogenated oils. Figure 4 highlights the CCP impacts with and without the spent oil credit for conventional and high oleic soybean oil.

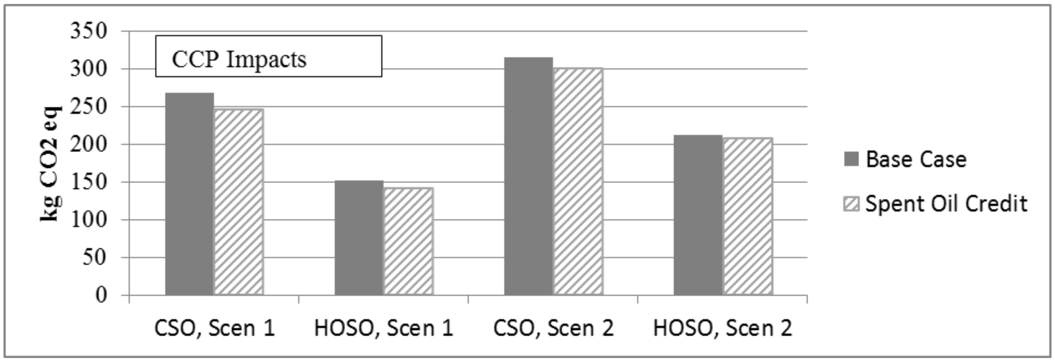

Figure 4: Spent Oil Sensitivity: CCP impacts for CSO and HOSO for both Scenarios 1 and 2 for the base case and assuming a $0.11/kg spent oil credit.

4. Discussion

When comparing among the environmental impacts evaluated in this study of the three soybean oil options, oil performance and restaurant behavior account for the majority of the differences in impacts, while mill co-product allocation, spent oil allocation, and oil processing have more subtle impacts. The increased stability of both the high oleic and the hydrogenated oils allows for lower oil use rates and fewer washes at the restaurant. The amount of food cooked during the day will affect the oil absorption rate, with increased absorption dampening the environmental benefits of the HOSO and HSO since the benefits of increased stability are not realized for absorbed oil. Impacts can be reduced as much as 48% based on the increased stability compared to CSO. As absorption rates increase from 4% to10% the differentiation among CSO and HSO environmental impacts is reduced by 20%. The allocation methodology can have significant impacts to the overall environmental burdens of the soybean oil options. Mass allocation results in impacts as much as 40% lower than economic allocation, but has less importance when differentiating among the oils types. For instance, CCP for HOSO is 44% lower than CSO using economic allocation and 48% lower using mass allocation. The environmental impacts of increased processing required for hydrogenation for HSO counterbalances the higher economic allocation impacts of HOSO, resulting in 4% to 6% lower impacts than HOSO for CCP and EP, but 3%-4% higher impacts for NRE and AP. For MASS and MASS-MP allocation methods, HSO consistently has higher impacts than HOSO. Soybean yields, farming practices, electricity mix assumptions, and oil transport distance do not serve to differentiate among these options since they are the same for each. Similar conclusions can be made when comparing CCO to HOCO.

However, when comparing different types of oils, such as CSO to CCO, or HOSO to HOCO, other facets of the oil supply chain become important. Farming fertilizer use is significantly higher for canola, leading to increased impacts for canola oil, particularly for AP and EP. As legumes, soybeans have N-fixating capabilities which significantly reduce the amount of N-based fertilizer required. This, in turn, reduces CCP, AP, and EP due to reduced fertilizer production impacts and field emissions. Crop yield favors soybeans as canola is shown to require as much as 50% more land under Scenario 1 assumptions. Although modeled with similar emissions per hectare, nitrous oxide field emissions have a substantial impact on the overall climate change and the relative impacts for soybean and canola oils. These emissions will likely differ by region for each crop, local field conditions, farming practice, etc., and have perhaps more than 100% uncertainty based on the USB report where N_2O emissions increased two-fold as they moved from calculated emissions to a site specific measurement (Omni-Tech, 2010). Finally, transport of the oil becomes more important. Although only 1%-13% of the total CCP impact for the cities evaluated, the transport model assumptions can represents more than 60% of the relative difference between soybean and canola oils for CCP. Transport accounts for roughly 30% of the difference between soybean oil and canola oil for NRE with little to no impact on AP, EP, and Land Use.

5. Conclusion

Overall, oil functionality was shown to be a key driver and a new handle on reducing environmental impacts for frying oil applications. Improvements to oil stability facilitated by high oleic seeds reduces oil use requirements and restaurant washing requirements. Increases in economic allocation factors for the high oleic oils do not dampen the impact reductions significantly. Restaurant behavior in terms of food throughput and oil replacement frequency as well as the food's oil absorption rate may significantly influence the extent of benefit. Similar environmental impacts are seen for HSO in comparison to HOSO as they both provide similar increased oil stability, but the hydrogenated oil alternative is compromised with trans-fats and higher saturated fat content. While yield, allocation methodology, transportation assumptions, and spent oil allocation all have the potential to affect the overall magnitude of frying oil environmental impacts, and may influence comparison across oils from different seeds, they have limited impact when comparing high oleic and conventional oils from the same feedstock. In addition to having nutritional benefits, high oleic soybean oil has been shown to reduce all environmental impacts evaluated in this study relative to conventional soybean oil for fryer use in the U.S.

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