SUPPORTING INFORMATION

The supporting information consists of 63 pages, including cover page, containing 11 figures, 37 tables, and 11 equations.

Life Cycle Assessment of Biodiesel Produced from Grease Trap Waste

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Supporting Information (SI)

RESEARCH SCOPE AND METHODS

System Boundary

The system boundary for A) GTW-Biodiesel, B) Current GTW Disposal, C) Soybean-Biodiesel, and D) Low-sulfur diesel are shown in Figure SI-S1. The soybean biodiesel and LSD processes were evaluated using GREET-2014 data[1, 2].

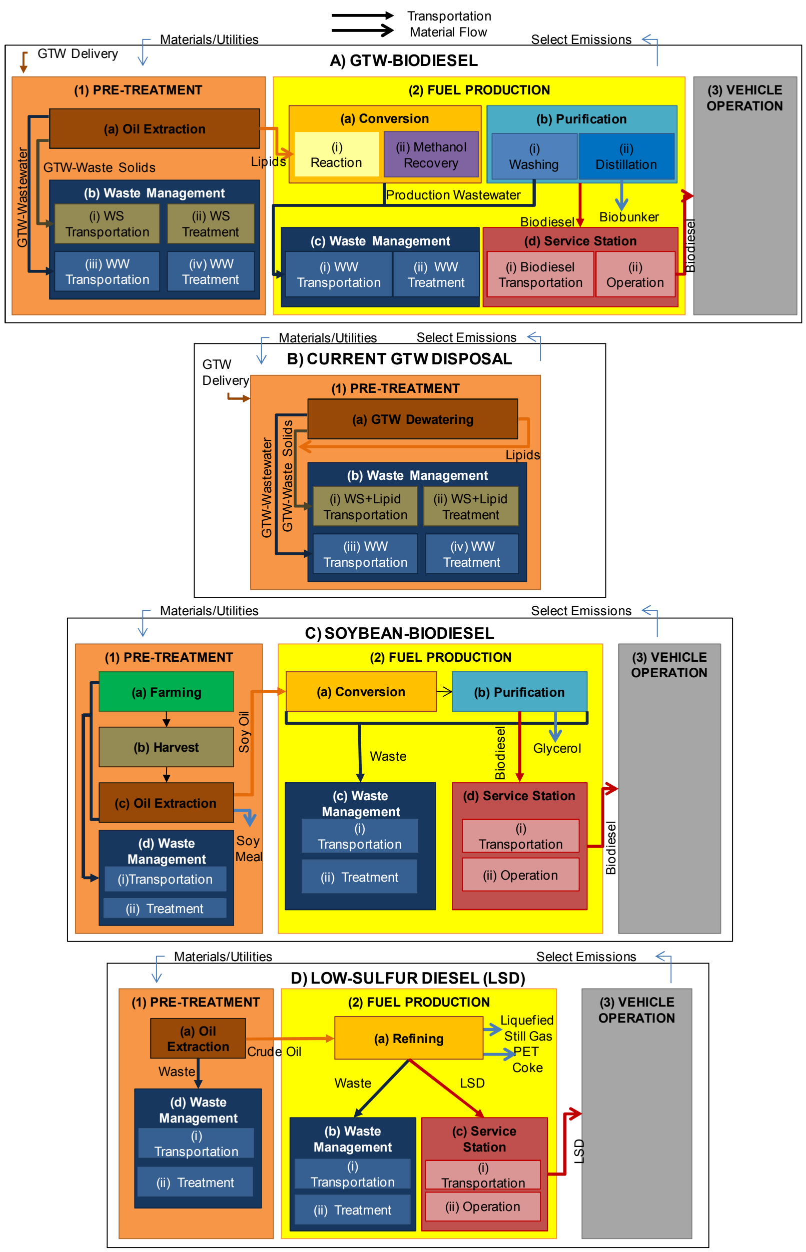


Figure SI-S1. System boundary for the production of A) GTW-biodiesel, B) Current GTW Disposal C) Soybean-biodiesel, D) LSD. The boxes indicate process stages; thin arrows represent transportation; and thick arrows are material flows. Each of the three main stages include the material and energy inputs and emission outputs for (1) Pre-treatment is represented by the orange box, (2) Fuel production is represented by the yellow box, and (3) Vehicle operation is represented by the gray box. Some process stages have a sub-stage marked with letters a-d and some sub-stages have individual steps marked i-iv.

For the soybean-biodiesel process, the pre-treatment included planting and harvesting of soybeans, soybean oil extraction, and transportation and treatment of waste. The fuel production stage included four sub-stages: conversion, purification, waste management, and the service station. Co-product soybean meal and glycerol were treated as mass and market allocations, respectively[1]. The final stage was vehicle operation.

For LSD, the pre-treatment included oil extraction and transportation and treatment of waste. The fuel production stage included three sub-stages: refining of LSD, waste management, and service station. The final stage was vehicle operation. In the model LSD, by-products such as liquefied still gas and petroleum (PET) coke were treated as internal products[2].

GTW-Biodiesel Process Description

GTW Transportation to Transfer Station

The average distance of the collection route was 286 based on data collected from a grease hauler during a longitudinal study[3]. Table SI-S1 shows the 13 different routes that were used to determine the average distance.

Table SI-S1. Transportation of GTW to transfer station

Sampling Date	Route, km
6/26/2014	140
7/3/2014	170
7/15/2014	192
7/25/2014	144

8/11/2014	364
12/8/2014	157
1/8/2015	272
2/3/2015	518
2/19/2015	223
3/10/2015	234
4/8/2015	407
4/17/2015	320
4/27/2015	373
5/11/2015	344
6/2/2015	459
6/23/2015	266
Average	286

The environmental impacts were determined using transportation emissions data in SimaPro8.

Process Flow Diagram

The process flow diagram (Figure SI-S2) shows the production of biodiesel from GTW including separation of lipids, reaction of lipids, methanol recovery, washing of crude FAME, and purification to ASTM grade biodiesel. The process model was developed using material and energy balances, process heuristics, and design projects.

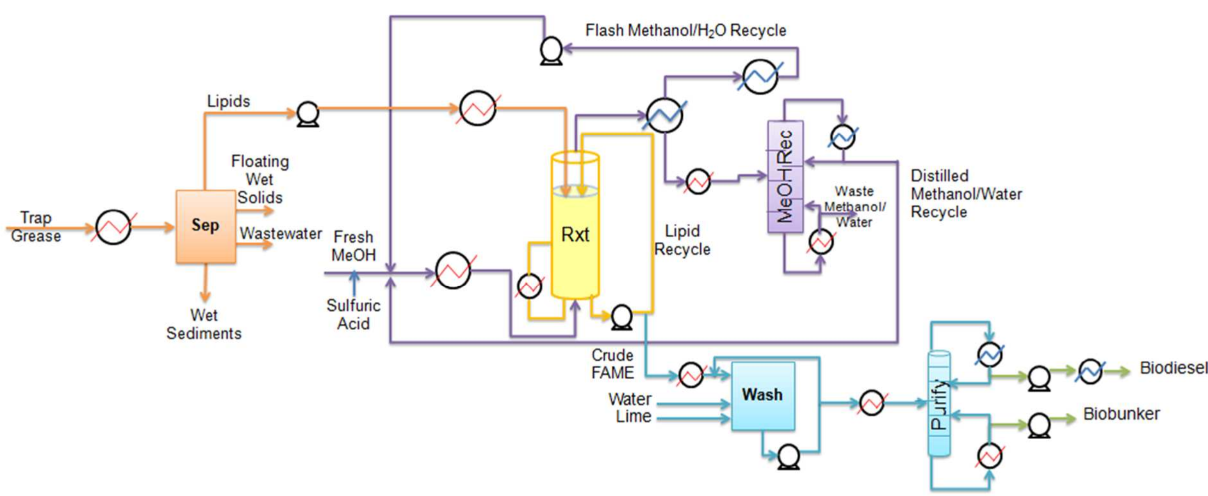


Figure SI-S2. Process flow diagram for the GTW-biodiesel production process. Process stages are represented: pre-treatment lipid separation (orange), biodiesel reaction (yellow), methanol recovery (purple), and washing/purification (blue).

Pre-treatment

Oil Extraction

The separation step extracted the brown grease lipids from the rest of the trap waste. The volumetric balance of the trap grease lipids was varied from 2% to 40% by volume. The floating solids and sediments were kept constant at 10% and 25%, respectively. The wastewater was the remaining portion of the overall grease trap waste. The lipids contained 97% FFA which was represented using oleic acid. Oleic acid (C18:1) is typically the highest percentage of substance present in the analysis of grease lipids. The GTW was heated to 60 ^{0}C for three hours with a heat loss of 50%. Process steam from the combustion of natural gas was used to heat the separator and electricity was used for a pump and vibrating screen.

Pre-treatment Waste Management

This section describes the method to determine GWP_{100} for emissions associated with flaring and co-generation of landfill gas. A diagram of landfill gas emissions and collection is shown in Figure SI-S3.

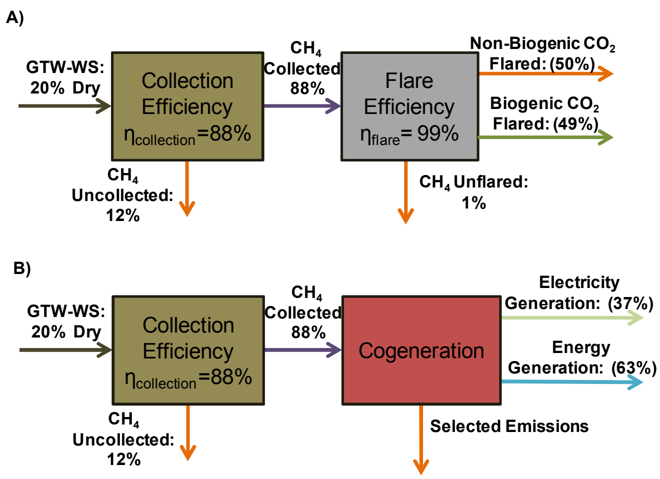


Figure SI-S3. Landfill emissions mass flow diagram for treatment of landfill gas by A) Flaring and B) Co-generation to produce electricity and heat.

GTW-WS were wet when separated; a moisture content of 80% was assumed based off laboratory tests to determine the dry mass. The waste in the landfill emits methane gas which assumed an average collection rate of 88%[4]. The flare landfill gas scenario included flaring with an efficiency of 99%[4]. Because 51% of the carbon content of food waste was biogenic[4], 51% of the carbon dioxide that was emitted through flaring did not contribute to the GWP_{100}. The co-generation scenario included the impacts of uncollected methane gas and the impacts associated with the co-generation. The co-generation was modeled from the Ecoinvent database for bioenergy[5] with an assumption of heat generation of 0.55 MJ/MJin and electricity generation of 0.32 MJ/MJin where MJin is the energy of the landfill gas that was collected. The electricity and heat produced from co-generation were treated as avoided products where the GWP_{100} associated with electricity and the energy of natural gas for steam production were treated as a negative value.

The landfill emissions were determined by a mass balance on the degradation food waste. The total amount of carbon dioxide equivalents emitted to the atmosphere through flaring of landfill gas is calculated using the following mass balance:

$$\frac{gCO_2eq}{\text{MJ-fuel}} = \{[300.7 * 0.2 * m_{GTW-WS,wet} * (1 - \eta_{collection})] + [300.7 * 0.2 * m_{GTW-WS,wet} * \eta_{collection} * (1 - \eta_{flare})]\} * 25 * \rho_{CH_4} + [(300.7 * 0.2 m_{GTW-WS,wet} * \eta_{collection} * \eta_{flare}) * \rho_{CH_4}] * \frac{44}{16} * \%_{NonbiogenicCO_2} \quad \text{(SI-S1)}$$

Where,

300.7 = methane yield for food waste (mL CH_4/g dry mass)[6]

0.2 = dry fraction of GTW-WS (80% moisture content based on lab tests)

$m_{GTW\text{-}WS,wet}$ = GTW-WS wet mass per MJ-fuel

25 = 100-year global warming potential of methane (g CO_2-eq)

ρ_{CH4} = methane density = 0.66 g/L

44/16 = ratio of molecular weights of carbon dioxide to methane

$\%_{NonbiogenicCO2}$ = percentage of non-biogenic carbon dioxide

η_i = efficiency at stage i: (1) methane collection = 88%[4] (2) methane flare = 99%

The simplified GWP_{100} for the co-generation of landfill gas can be represented by equation SI-S2:

$$\frac{gCO_2eq}{\text{MJ-fuel}} = [CH_4\text{uncollected}] + \{[\text{CogenerationGWP}_{100} + \text{LubricantGWP}_{100}]\} - \{[\text{AvoidedGWP}_{100}]\} \quad \text{(SI-S2)}$$

The GWP_{100} is determined by summing the GWP_{100} of the uncollected methane, the GWP_{100} for the lubricant use and disposal in co-generation and subtracting the impacts associated with the electricity and natural gas that are avoided because of the co-generation. The values for lubricant, co-generation greenhouse gases, electricity, and heat are defined by the life cycle inventory for bioenergy data as "per MJ" of methane gas into the process (Table SI-S2); therefore, these impacts need to be multiplied by the energy of methane gas collected.

The uncollected methane gas GWP_{100} is determined using the following equation:

$$CH_4\text{uncollected} = \frac{gCO_2eq}{\text{MJ-fuel}} = [300.7 * 0.2 * m_{GTW-WS,wet} * (1 - \eta_{collection})] * 25 * \rho_{CH_4} \quad \text{(SI-S3)}$$

The amount of landfill gas produced for the co-generation emissions were determined by truncating Equation SI-S1 before the flaring emissions and converting to energy using the lower heating value of 0.0359 MJ/L:

$$E_{CH4}\text{collected} = \frac{E_{CH4}}{\text{MJ}-\text{fuel}} = \{[300.7 * 0.2 * m_{GTW-WS,wet} * (\eta_{collection})]\} * 0.0359 \qquad \text{(SI-S4)}$$

The greenhouse gases associated with GWP_{100} and materials used for co-generation were determined using Table 13.12 in the life cycle inventories of bioenergy data[5] summarized below:

Table SI-S2. Summary of co-generation inventory based off of 1 MJ of energy in (landfill gas energy)

Item	Unit	Value
Generated Electricity	MJ/MJin	0.32
Generated Heat	MJ/MJin	0.55
Lubricating Oil	kg/MJin	3.00E-05
Disposal Mineral Oil	kg/MJin	3.00E-05
CH_4	kg/MJin	2.30E-05
N_2O	kg/MJin	2.50E-06

The GWP_{100} impacts associated with 1 kg of lubricant consumption and disposal is found in Table SI-S3. This table also includes the GWP_{100} of producing 1 MJ of electricity and 1 MJ of natural gas that are avoided depending on the amount of electricity and heat that is generated from the landfill gas. The lubricating oil and electricity impacts were determined using SimaPro8[7] while the natural gas impact was determined in GREET2014[8].

Table SI-S3. Environmental impacts associated with processing and avoided impacts in co-generation.

		Processing Impacts		Avoided Impacts	
	Unit	1 kg Lubricating Oil[7]	1 kg Disposal Mineral Oil[7]	1 MJ Electricity[7]	1 MJ Natural Gas[8]
GWP_{100}	g CO_2-eq	886	2850	201	86

The GWP_{100} for the co-generation greenhouse gases were determined using the following equation:

$$\text{CogenerationGWP}_{100} = \frac{gCO_2eq}{\text{MJ-fuel}} = [E_{CH4}\text{collected}] * \{[CH_4 * 25 + N_2O * 298] * 1000\} \quad \text{(SI-S5)}$$

The GWP_{100} associated with the lubricant were determined by multiplying the energy collected (equation SI-S4) by the amount of lubricating oil (table SI-S2) and GWP_{100} of lubricating oil (table SI-S3):

$$\text{LubricantGWP}_{100} = [E_{CH4}\text{collected}] * \{[\text{LubricatingOil} * GWP_{100}\text{LubricatingOil}] + [\text{DisposalMineralOil} * GWP_{100}\text{DisposalMineralOil}]\} \quad (SI-S6)$$

The avoided emissions were calculated using equation SI-S7:

$$\text{AvoidedGWP}_{100} = [E_{CH4}\text{collected}] * \{[\text{GeneratedElectricity} * GWP_{100}\text{Electricity}] + [\text{GeneratedHeat} * GWP_{100}\text{NaturalGas}]\} \quad (SI-S7)$$

Combining equations SI-S3 to SI-S7 and substituting into SI-S2 gives equation SI-S8 for the total GWP_{100} of landfill gas co-generation:

$$\text{TotalGWP}_{100} = \frac{gCO_2eq}{\text{MJ-fuel}} = \left[300.7 * 0.2 * m_{GTW-WS,wet} * (1 - \eta_{collection})\right] * 25 * \rho_{CH_4} + \left\{\left[300.7 * 0.2 * m_{GTW-WS,wet} * (\eta_{collection})\right]\right\} * 0.0359 * (\{[CH_4 * 25 + N_2O * 298] * 1000\} + \{[\text{LubricatingOil} * GWP_{100}\text{LubricatingOil}] + [\text{DisposalMineralOil} * GWP_{100}\text{DisposalMineralOil}]\} - \{[\text{GeneratedElectricity} * GWP_{100}\text{Electricity}] + [\text{GeneratedHeat} * GWP_{100}\text{NaturalGas}]\}) \quad \text{(SI-S8)}$$

Fuel Production

Conversion

The model uses a bubble column reactor that has been developed by researchers at Drexel University. This work was inspired by experiments done by Kocsisová et al. on the esterification of FFA at ambient pressure and high temperature (50-60 ^{0}C higher than the boiling point of methanol)[9]. The bubble column is effective at converting high-FFA lipid sources into FAME and the esterification of lipid at any FFA/TAG ratio[10]. The column is also robust at converting the FFA with a mixture of 80% methanol and 20% water which is beneficial when using recycled methanol[10].

The model uses the same conditions at which experimental data was collected with the bubble column reactor. The reactor was run at 125 ^{0}C for 3 hours with a heat loss of 50%. Fresh methanol and catalyst were also heated and pumped into the reactor. Another pump was used to re-circulate the oil. Pumping efficiencies were 60%. Process steam and cooling water were used for the reaction and electricity was used for the pumping.

Methanol Recovery

Methanol was recovered using a flash condenser and distillation column. The distillation column had a reflux ratio of 1.5 and a reboil ratio of 2 assuming pure methanol and water, respectively. A fractional recovery of water in the distillate was estimated to be 16.1%. Methanol was recovered 85% by mole in distillate during fractional distillation and 99% of methanol was recovered in the distillate of the distillation column. Natural gas combusted for process steam, cooling water, and electricity were used for heating/cooling and for powering pumps.

Purification

The crude biodiesel was first neutralized with sodium hydroxide, washed with water, and dried at 80 ^{0}C. A short-path evaporator was then used for further purification. Short-path evaporation operates similarly to a distillation column; however, it operates under vacuum to lower the boiling point of the crude material. The evaporator was run at 0.1 bar and 260 ^{0}C. Process steam, cooling water, and electricity were used for the heating/cooling and for pumping. The model has a rough estimate of conditions for the short-path evaporator and more research is being performed to optimize the conditions for purifying biodiesel.

Life Cycle Inventory

The material and energy balances based on the process flow diagram, heuristics, and design projects were used to calculate a process inventory.

Table SI-S4. Life cycle inventory by component and database used in the LCA

	Name in Database	Database	Program
INPUTS			
Materials			
Sulfuric acid	Sulphuric acid, liquid, at plant/RER U	Ecoinvent	SimaPro8
Methanol	Methanol, at regional storage/CH U	Ecoinvent	SimaPro8
Wash water	Water, deionised, at plant/CH U	Ecoinvent	SimaPro8
Sodium hydroxide	Sodium hydroxide, production mix, at plant/kg/RNA	USLCI	SimaPro8
Utilities			
Natural gas for steam production			GREET2014
Electricity	Electricity, medium voltage, at grid/US U	Ecoinvent	SimaPro8
Cooling water	Water, decarbonised, at plant/RER U	Ecoinvent	SimaPro8
OUTPUTS			
Materials			
Production wastewater	Waste water – untreated, slightly organic contaminated EU-27 S	ELCD	SimaPro8
GTW wastewater	Waste water – untreated, EU-27 S	ELCD	SimaPro8
GTW waste solids: methane gas production	Food Waste	Landfill Literature	Calculation
GTW waste solids: co-generation		EcoInvent	Calculation
Transportation			

Biodiesel	Transport, lorry >16t, fleet average/RER U	EcoInvent	SimaPro8
Production wastewater	Transport, lorry >16t, fleet average/RER U	EcoInvent	SimaPro8
GTW wastewater	Transport, lorry >16t, fleet average/RER U	EcoInvent	SimaPro8
GTW waste solids	Transport, lorry >16t, fleet average/RER U	EcoInvent	SimaPro8

The full inventory for 2-40% lipid content is shown in Table SI-S5. Most of the materials and utilities are independent of lipid content with the exception of rows 5, 15, 17, 19, 21 which are part of the pre-treatment process.

Table SI-S5. Life Cycle Inventory for GTW-biodiesel production with lipid contents of 2-40%

	Lipid Content	**2%**	**3%**	**4%**	**5%**	**7%**	**10%**	**20%**	**30%**	**40%**
	INPUTS/MJ biodiesel									
	Materials									
1	Sulfuric acid, kg [a]	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
2	Methanol, kg [a]	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029
3	Wash water, kg [a]	0.0295	0.0295	0.0295	0.0295	0.0295	0.0295	0.0295	0.0295	0.0295
4	Sodium hydroxide, kg [a]	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	Utilities									
	Oil Extraction									
5	Natural gas for steam production, m^3 [b]	0.0115	0.0076	0.0057	0.0045	0.0032	0.0022	0.0011	0.0007	0.0005
6	Electricity, kWh [a]	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
	Conversion									
7	Natural gas for steam production, m^3 [b]	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020
8	Electricity, kWh [a]	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
9	Cooling water, kg [a]	0.7255	0.7255	0.7255	0.7255	0.7255	0.7255	0.7255	0.7255	0.7255
	Purification									

10	Natural gas for steam production, m^3 [b]	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017
11	Electricity, kWh [a]	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
12	Cooling water, kg [a]	0.9982	0.9982	0.9982	0.9982	0.9982	0.9982	0.9982	0.9982	0.9982
	OUTPUTS/MJ Biodiesel									
	Materials									
13	GTW biodiesel, kg	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265
14	Biobunker, kg	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
15	GTW wastewater, kg [a]	0.9084	0.5960	0.4398	0.3460	0.2389	0.1586	0.0649	0.0336	0.0180
16	Production wastewater, kg [a]	0.0323	0.0323	0.0323	0.0323	0.0323	0.0323	0.0323	0.0323	0.0323
17	GTW waste solids, kg [c]	0.5046	0.3364	0.2523	0.2019	0.1442	0.1009	0.0505	0.0336	0.0252
	Transportation									
18	Biodiesel, tkm* [a]	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026
19	GTW wastewater, tkm* [a]	0.0454	0.0298	0.0220	0.0173	0.0119	0.0079	0.0032	0.0017	0.0009
20	Production wastewater, tkm* [a]	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016
21	GTW waste solids, tkm* [a]	0.0252	0.0168	0.0126	0.0101	0.0072	0.0050	0.0025	0.0017	0.0013

*metric ton times kilometers traveled
[a] SimaPro8[7]
[b] GREET2014[11]
[c] Landfill Literature[4, 6]/EcoInvent database[5]

To produce 1 MJ of biodiesel, the amount of GTW entering the process increases as lipid content decreases; unlike the constant GTW input studied by Tu and McDonnell where biodiesel production was varied. In this scenario, many of the inputs do not change with lipid content because they are proportional to the amount of biodiesel produced. When lipid content decreases, the pre-treatment requires more energy and produces more GTW-WW and GTW-WS that need to be transported and treated for disposal.

Uncertainty/Model Fitting

A model was developed to analyze and test trends in the environmental impacts of producing biodiesel from GTW with varying lipid contents. The total impact normalized by the amount of biodiesel produced is expressed as a sum of the flowrates into each stage (Figure SI-S1-A) multiplied by the impact intensity from each of the process stages in Equation SI-S9:

$$\frac{I_{Total}}{E_{Biodiesel}} = \frac{\dot{M}_{GTW}\hat{I}_{PT} + \dot{M}_{Lipids}\hat{I}_{FP} + \dot{M}_{Biodiesel}\hat{I}_{VO}}{\dot{M}_{Biodiesel}\Delta\hat{H}_c} \quad \text{(SI-S9)}$$

Where,

$\hat{I}_i$ = environmental impact intensity of process stage i per unit mass of input (PT = pre-treatment, FP = fuel production, and VO = vehicle operation: combustion emissions)

$\dot{M}_j$ = mass flowrate of j entering into the process stage

$\Delta\hat{H}_C$ = heat of combustion of biodiesel (lower heating value)

$E_{Biodiesel}$ = energy content of biodiesel produced

The impact intensity factors $\hat{I}_i$ approximate the environmental impacts per unit of feedstock entering each stage (GTW enters the pre-treatment stage, GTW lipids enter fuel production stage, and biodiesel enters the vehicle operation stage). The relationship between the feedstock flowrates can be estimated using the lipid content of GTW as x and the yield of the fuel production process as ϕ:

$$\dot{M}_{Biodiesel} = \phi\dot{M}_{Lipids} = \phi x\dot{M}_{GTW} \quad \text{(SI-S10)}$$

Combining Equations 2 and 3 produces a relationship between the total impacts and GTW lipid content that is useful for analyzing the LCA results shown in Equation SI-S11.

$$\frac{I_{Total}}{E_{Biodiesel}} = \left(\frac{\hat{I}_{PT}}{\phi\Delta\hat{H}_c}\right)\frac{1}{x} + \left(\frac{\hat{I}_{FP}}{\phi\Delta\hat{H}_c} + \frac{\hat{I}_{VO}}{\Delta\hat{H}_c}\right) \quad \text{(SI-S11)}$$

Equation SI-S11 predicts that the total environmental impacts are proportional to the reciprocal of the GTW lipid content, *1/x*. The reciprocal of the lipid content is a measure of the amount of GTW that must be processed to produce a given amount of biodiesel. In the LCA model, more lipid contents were used in the low-range lipid contents (2%, 3%, 4%, and 5%) to best represent the hyperbolic rise. Linear regression of Equation SI-S11 to the theoretical environmental impacts versus *1/x* was used to estimate slope and intercept.

For the model fitting, the lipid content by volume was inverted to get $1/x$. Multiplying by the density of the GTW (1.1 kg/L) the lipid content gives the lipid content by mass.

RESULTS AND DISCUSSION

100-year Global Warming Potential Consequential LCA

The table below lists the data for the GWP_{100} for the consequential analysis in Figure 2 of the article.

Table SI-S6. GWP_{100} Consequential LCA for Flare Scenario. The colored cells indicate the corresponding bars in Figure 2.

Lipid Content	2%	3%	4%	5%	7%	10%	20%	30%	40%
Proposed GTW-Biodiesel Process									
Delivery to Transfer Station	44	29	22	18	13	9	4	3	2
Pre-treatment WM	131	87	65	52	37	25	12	8	6
GTW-Biodiesel Rest of Process	50	40	35	31	28	25	22	21	20
Total GTW-Biodiesel Process	***226***	***156***	***122***	***101***	***77***	***59***	***39***	***32***	***28***
Current GTW Process									
Delivery to Transfer Station	44	29	22	18	13	9	4	3	2
Current GTW Disposal	139	95	73	60	45	33	20	16	13
Low Sulfur Diesel	93	93	93	93	93	93	93	93	93
Total Displaced Current GTW Process	***276***	***217***	***188***	***170***	***150***	***135***	***117***	***111***	***108***
Total GTW-Biodiesel - Total Current GTW Disposal	**-50**	**-61**	**-66**	**-69**	**-73**	**-75**	**-78**	**-80**	**-80**

Table SI-S7. GWP_{100} Consequential LCA for Co-Generation Scenario

Lipid Content	**2%**	**3%**	**4%**	**5%**	**7%**	**10%**	**20%**	**30%**	**40%**
Proposed GTW-Biodiesel Process									
Delivery to Transfer Station	44	29	22	18	13	9	4	3	2
Pre-treatment WM	175	116	87	69	49	34	17	11	8
Biodiesel Co-Gen Avoided Utilities	-107	-71	-54	-43	-31	-21	-11	-7	-5
GTW-Biodiesel Rest of Process	50	40	35	31	28	25	22	21	20
Total GTW-Biodiesel Process	***162***	***114***	***90***	***76***	***59***	***47***	***32***	***27***	***25***
Current GTW Process									
Delivery to Transfer Station	44	29	22	18	13	9	4	3	2
Current GTW Disposal	185	126	97	79	59	44	26	21	18
Current GTW Co-Gen Avoided Utilities	-112	-77	-59	-48	-36	-27	-16	-13	-11
Low Sulfur Diesel	93	93	93	93	93	93	93	93	93
Total Displaced Current GTW Process	***209***	***171***	***153***	***141***	***128***	***119***	***107***	***104***	***102***
Total GTW-Biodiesel - Total Current GTW Disposal	**-47**	**-57**	**-63**	**-66**	**-69**	**-72**	**-75**	**-76**	**-77**

Attributional LCA

The two tables below represent are the results of GREET2014 for soybean-biodiesel and LSD.

Table SI-S8. Soybean biodiesel data

	GWP_{100}	CED_{Fossil}	Carbon Monoxid e	Particulat e Matter	Mono-nitrogen Oxides	Sulfur Oxides
Unit	g-CO_2-eq/MJ-fuel	MJ/MJ-fuel	g-CO/MJ-fuel	g-PM/MJ-fuel	g-NOx/MJ-fuel	g-SOx/MJ-fuel
Soybean Production	5.663	0.049	0.010	0.002	0.018	0.017
Soy Oil Extraction	4.241	0.056	0.003	0.001	0.006	0.010
Soy oil Transportation	0.721	0.009	0.002	0.000	0.007	0.001
Pre-Treatment	**10.625**	**0.113**	**0.014**	**0.003**	**0.032**	**0.028**

Total						
Soy oil Conversion	9.117	0.138	0.004	0.001	0.008	0.008
Biodiesel Transportation	0.510	0.006	0.001	0.000	0.004	0.001
Biodiesel Storage	0.000	0.000	0.000	0.000	0.000	0.000
Fuel Production Total	**9.627**	**0.144**	**0.004**	**0.002**	**0.011**	**0.009**
Vehicle Operation	4.794	0.000	0.066	0.001	0.037	0.000
Total	**25.046**	**0.257**	**0.085**	**0.006**	**0.080**	**0.037**

Table SI-S9. LSD data

	GWP_{100}	CED_{Fossil}	Carbon Monoxide	Particulate Matter	Mono-nitrogen Oxides	Sulfur Oxides
	g-CO_2-eq/MJ-fuel	MJ/MJ-fuel	g-CO/MJ-fuel	g-PM/MJ-fuel	g-NOx/MJ-fuel	g-SOx/MJ-fuel
Heavy Butane from Crude Oil	0.001	0.000	0.000	0.000	0.000	0.000
Crude Recovery for U.S. Refineries	8.744	0.079	0.008	0.002	0.025	0.013
Well/Pre-treatment Total	**8.744**	**0.079**	**0.008**	**0.002**	**0.025**	**0.013**
LSD Refining	7.890	0.123	0.005	0.002	0.010	0.008
Processing LSD	0.463	0.005	0.001	0.000	0.003	0.001
LSD Storage	0.000	0.000	0.000	0.000	0.000	0.000
Fuel Production/ Processing Total	**8.353**	**0.128**	**0.005**	**0.002**	**0.013**	**0.009**
Vehicle Operation	**75.717**	**1.000**	**0.128**	**0.002**	**0.033**	**0.001**
LSD Total	**92.814**	**1.207**	**0.141**	**0.006**	**0.071**	**0.022**

Presented below are the results for all environmental impacts for GTW-biodiesel for scenarios with landfill gas flaring, landfill gas co-generation of heat and electricity, and a scenario without GTW waste management (omits impacts associated with delivery of GTW to the transfer station and GTW wastewater and waste solids disposal. These results are compared to soybean-biodiesel and LSD. Note that the values of soybean-biodiesel and LSD do not change with each GTW scenario.

The GWP_{100} was determined for the GTW-biodiesel process from 2-40% lipid content and compared to the soybean-biodiesel process and LSD process shown in Figure SI-S4.

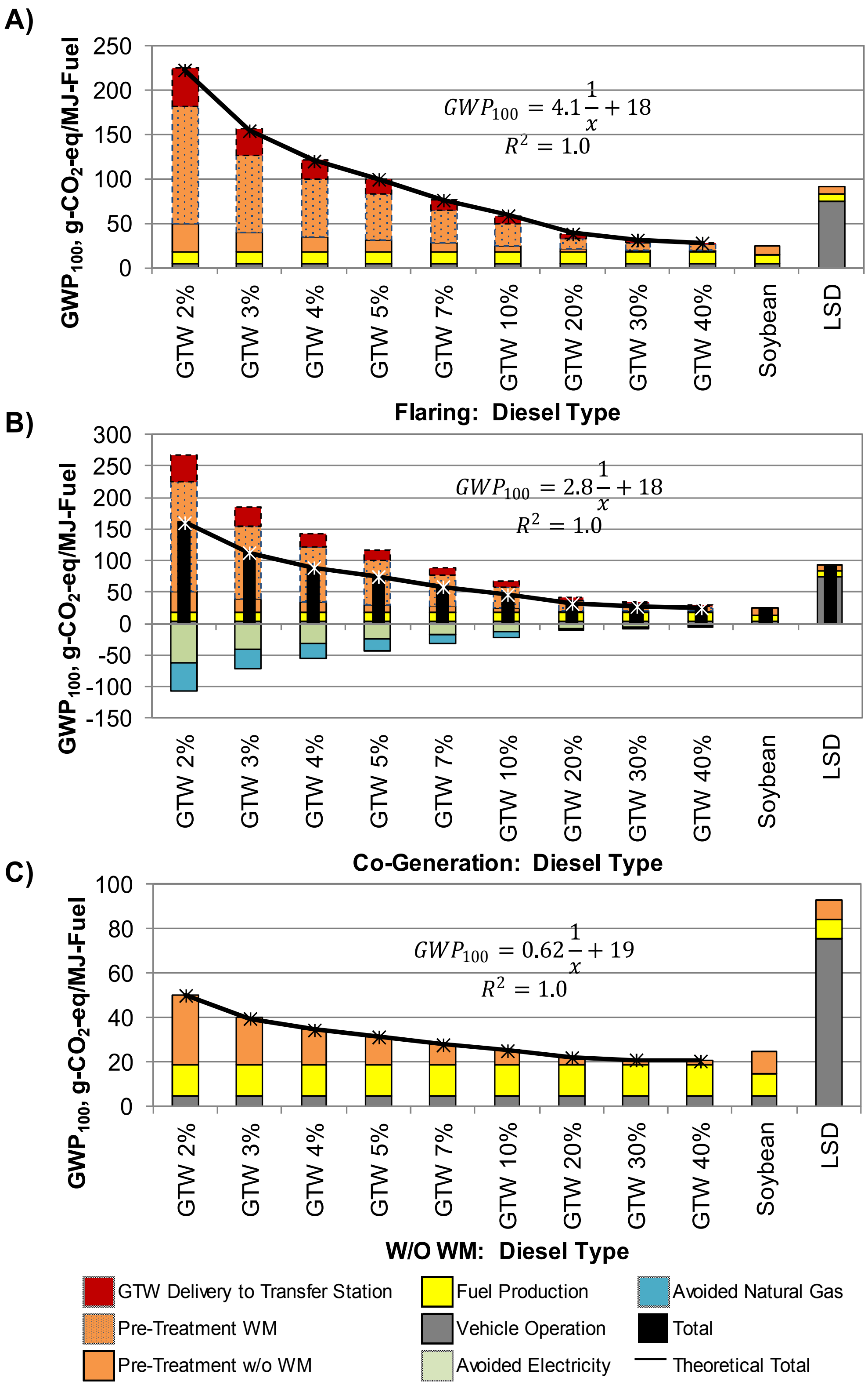


Figure SI-S4. 100-y Global Warming Potential Complete Parametric Study of GTW-Biodiesel Compared to Soybean-biodiesel and LSD for A) Flaring landfill gas, B) Co-generation of landfill gas, and C) without GTW waste management. The stacked bars represent GTW-biodiesel stages: delivery of GTW to transfer station (red), pre-treatment WM (orange with blue dots), pre-treatment without WM (orange), fuel production (yellow), vehicle operation (gray), avoided electricity production from co-generation (light green), and avoided natural gas from co-generation (teal). The total GWP_{100} (black bar) and modeled curve (black line) are also shown.

The following tables show the GWP_{100} value by process stage, the percent contribution of each process stage, and the percent reduction compared to soybean-biodiesel and LSD for each of the waste scenarios.

Table SI-S10. Landfill Gas Flaring Scenario for 100-y Global Warming Potential

Diesel Type	**GTW 2%**	**GTW 3%**	**GTW 4%**	**GTW 5%**	**GTW 7%**	**GTW 10%**	**GTW 20%**	**GTW 30%**	**GTW 40%**	**Soy-bean**	**LSD**
GWP_{100}, g-CO_2-eq/MJ-fuel											
Delivery to Transfer Station	44	29	22	18	13	8	4	3	2	N/A	N/A
Pre-Treatment WM	131	87	65	52	37	25	12	8	6	N/A	N/A
Pre-Treatment w/o WM	31	21	16	13	9	6	3	2	1	11	9
Fuel Production	14	14	14	14	14	14	14	14	14	10	8
Vehicle Operation	5	5	5	5	5	5	5	5	5	5	5
Total	226	156	122	101	77	59	39	32	28	25	93
Percent Contribution, %											
Delivery to Transfer Station	20	19	18	17	16	15	11	9	7	N/A	N/A
Pre-Treatment WM	58	56	54	51	48	43	32	25	20	N/A	N/A
Pre-Treatment w/o WM	14	13	13	12	12	10	8	6	5	42	9
Fuel Production	6	9	12	14	18	24	37	45	50	38	9
Vehicle Operation	2	3	4	5	6	8	12	15	17	19	82
Reduction, %											
Compared to Soybean	802	525	386	303	208	137	54	26	13	0	271
Compared to LSD	143	69	31	9	-17	-36	-58	-66	-70	-73	0

Table SI-S11. Landfill Gas with Co-Generation Scenario for 100-y Global Warming Potential

Diesel Type	GTW 2%	GTW 3%	GTW 4%	GTW 5%	GTW 7%	GTW 10%	GTW 20%	GTW 30%	GTW 40%	Soy-bean	LSD
GWP_{100}, g-CO_2-eq/MJ-fuel											
Delivery to Transfer Station	44	29	22	18	13	9	4	3	2	N/A	N/A
Pre-treatment WM	175	116	87	69	49	34	17	11	8	N/A	N/A
Pre-treatment w/o WM	31	21	16	13	9	6	3	2	1	11	9
Fuel Production	14	14	14	14	14	14	14	14	14	10	8
Vehicle Operation	5	5	5	5	5	5	5	5	5	5	78
Avoided Electricity	-62	-41	-31	-25	-18	-12	-6	-4	-3	N/A	N/A
Avoided Natural Gas	-45	-30	-23	-18	-13	-9	-5	-3	-2	N/A	N/A
Total	162	114	90	76	59	57	32	27	25	25	93
Percent Contribution, %											
Delivery to Transfer Station	27	26	24	23	21	19	13	10	8	N/A	N/A
Pre-treatment w/o WM	19	18	17	17	15	13	9	7	6	42	9
Fuel Production	9	12	16	19	24	30	44	52	57	38	9
Vehicle Operation	3	4	5	6	8	10	15	17	19	19	82
Avoided Electricity	-38	-36	-34	-33	-30	-26	-19	-15	-12	N/A	N/A
Avoided Natural Gas	-28	-27	-25	-24	-22	-19	-14	-11	-9	N/A	N/A
Reduction, %											
Compared to Soybean	547	355	259	201	136	86	29	9	0	0	271
Compared to LSD	75	23	-3	-19	-36	-50	-65	-70	-73	-73	0

Table SI-S12. Without GTW Waste Management Scenario for 100-y Global Warming Potential

Diesel Type	**GTW 2%**	**GTW 3%**	**GTW 4%**	**GTW 5%**	**GTW 7%**	**GTW 10%**	**GTW 20%**	**GTW 30%**	**GTW 40%**	**Soy-bean**	**LSD**
GWP_{100}, g-CO_2-eq/MJ-fuel											
Pre-treatment	31	21	16	13	9	6	3	2	2	11	9
Fuel Production	14	14	14	14	14	14	14	14	14	10	8
Vehicle Operation	5	5	5	5	5	5	5	5	5	5	76
Total	50	40	35	32	28	25	22	21	20	25	93
Percent Contribution, %											
Pre-treatment	62	52	45	40	32	25	14	9	7	42	9
Fuel Production	28	36	41	45	51	56	64	68	69	38	9
Vehicle Operation	10	12	14	15	17	19	22	23	23	19	82
Reduction, %											
Compared to Soybean	101	59	38	26	11	1	-12	-16	-18	0	271
Compared to LSD	-46	-57	-63	-66	-70	-73	-76	-77	-78	-73	0

Fossil Cumulative Energy Demand (Fossil CED)

The fossil cumulative energy demand (fossil CED) was determined for the GTW-biodiesel process from 2-40% lipid content and compared to the soybean-biodiesel process and LSD process shown in Figure SI-S5.

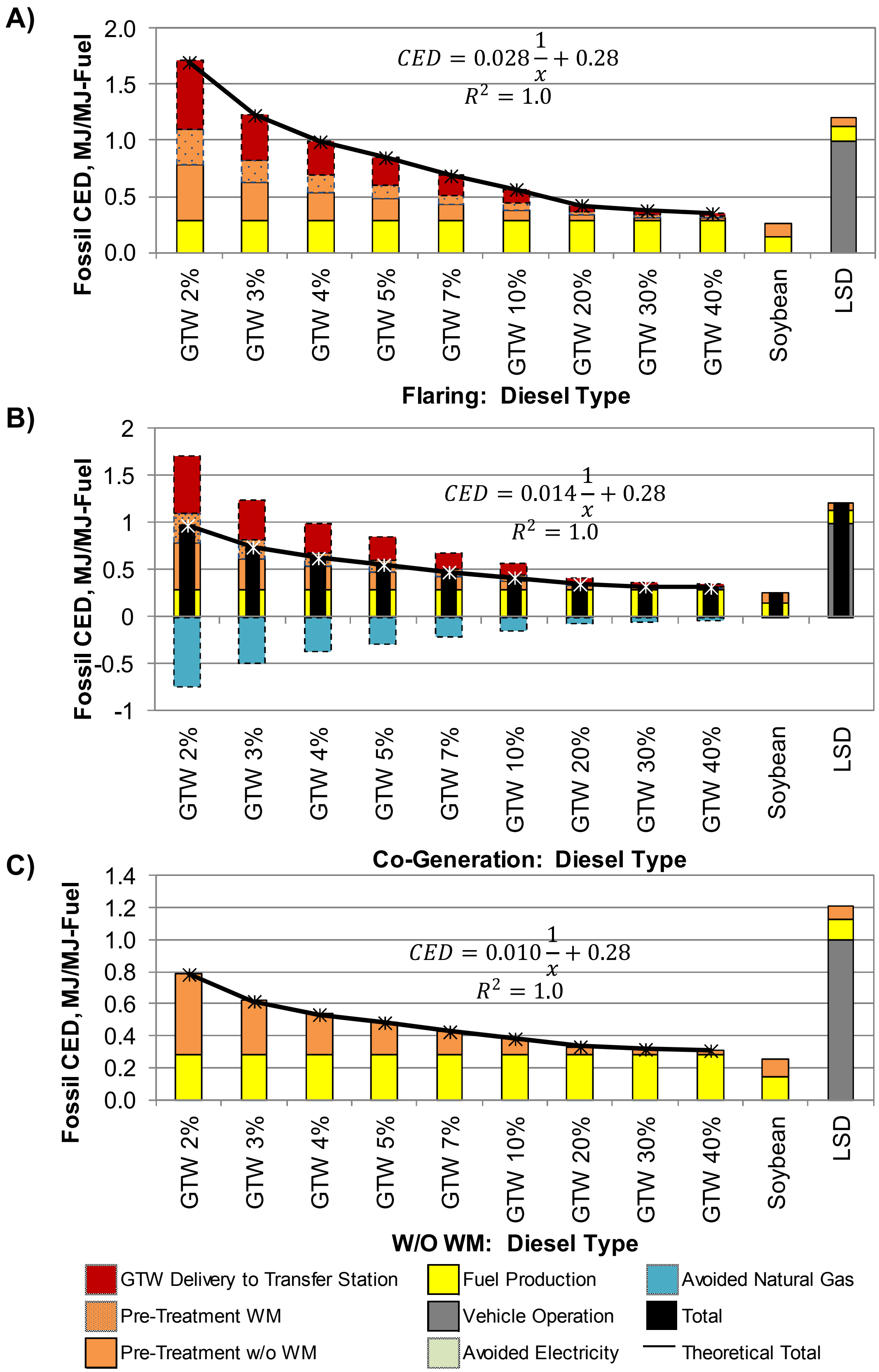

A)
Fossil CED, MJ/MJ-Fuel
2.0
1.5
1.0
0.5
0.0
$CED = 0.028\frac{1}{x} + 0.28$
$R^2 = 1.0$
GTW 2%
GTW 3%
GTW 4%
GTW 5%
GTW 7%
GTW 10%
GTW 20%
GTW 30%
GTW 40%
Soybean
LSD
Flaring: Diesel Type
B)
Fossil CED, MJ/MJ-Fuel
2
1.5
1
0.5
0
-0.5
-1
$CED = 0.014\frac{1}{x} + 0.28$
$R^2 = 1.0$
GTW 2%
GTW 3%
GTW 4%
GTW 5%
GTW 7%
GTW 10%
GTW 20%
GTW 30%
GTW 40%
Soybean
LSD
Co-Generation: Diesel Type
C)
Fossil CED, MJ/MJ-Fuel
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$CED = 0.010\frac{1}{x} + 0.28$
$R^2 = 1.0$
GTW 2%
GTW 3%
GTW 4%
GTW 5%
GTW 7%
GTW 10%
GTW 20%
GTW 30%
GTW 40%
Soybean
LSD
W/O WM: Diesel Type
GTW Delivery to Transfer Station
Pre-Treatment WM
Pre-Treatment w/o WM
Fuel Production
Vehicle Operation
Avoided Electricity
Avoided Natural Gas
Total
Theoretical Total

Figure SI-S5. Fossil Cumulative Energy Demand Complete Parametric Study of GTW-Biodiesel Compared to Soybean-biodiesel and LSD for A) Flaring landfill gas, B) Co-generation of landfill gas, and C) without GTW waste management. The stacked bars represent GTW-biodiesel stages: delivery of GTW to transfer station (red), pre-treatment WM (orange with blue dots), pre-treatment without WM (orange), fuel production (yellow), vehicle operation (gray), avoided electricity production from co-generation (light green), and avoided natural gas from co-generation (teal). The total CED_{Fossil} (black bar) and modeled curve (black line) are also shown.

The following tables show the CED_{Fossil} value by process stage, the percent contribution of each process stage, and the percent reduction compared to soybean-biodiesel and LSD for each of the waste scenarios.

Table SI-S13. Landfill Gas with Flaring Scenario for Fossil Cumulative Energy Demand

Diesel Type	GTW 2%	GTW 3%	GTW 4%	GTW 5%	GTW 7%	GTW 10%	GTW 20%	GTW 30%	GTW 40%	Soy-bean	LSD
Fossil CED, MJ/MJ-Fuel											
Delivery to Transfer Station	0.62	0.41	0.31	0.25	0.18	0.12	0.06	0.04	0.03	N/A	N/A
Pre-Treatment WM	0.31	0.20	0.15	0.12	0.08	0.06	0.03	0.02	0.01	N/A	N/A
Pre-Treatment w/o WM	0.51	0.34	0.25	0.20	0.14	0.10	0.05	0.03	0.02	0.11	0.08
Fuel Production	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.14	0.13
Vehicle Operation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Total	1.72	1.24	1.00	0.85	0.69	0.56	0.42	0.37	0.35	0.26	1.21
Percent Contribution, %											
Delivery to Transfer Station	36	33	31	29	26	22	14	11	9	N/A	N/A
Pre-Treatment WM	18	16	15	14	12	10	6	4	3	N/A	N/A
Pre-Treatment w/o WM	29	27	25	24	21	18	12	8	7	44	7
Fuel Production	17	23	29	33	41	50	68	76	82	56	11
Vehicle Operation	0	0	0	0	0	0	0	0	0	0	83
Reduction, %											
Compared to Soybean	568	381	287	231	167	119	63	45	35	0	370
Compared to LSD	42	2	-18	-29	-43	-53	-65	-69	-71	-79	0

Table SI-S14. Landfill Gas with Co-Generation Scenario for Fossil Cumulative Energy Demand

Diesel Type	GTW 2%	GTW 3%	GTW 4%	GTW 5%	GTW 7%	GTW 10%	GTW 20%	GTW 30%	GTW 40%	Soy-bean	LSD
Fossil CED, MJ/MJ-fuel											
Delivery to Transfer Station	0.62	0.41	0.31	0.25	0.18	0.12	0.06	0.04	0.03	N/A	N/A
Pre-treatment WM	0.31	0.20	0.15	0.12	0.08	0.06	0.03	0.02	0.01	N/A	N/A
Pre-treatment w/o WM	0.51	0.34	0.25	0.20	0.14	0.10	0.05	0.03	0.02	0.11	0.08
Fuel Production	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.14	0.13
Vehicle Operation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Avoided Electricity	-0.01	-0.004	-0.003	-0.003	-0.002	-0.001	-0.001	<-0.001	<-0.001	N/A	N/A
Avoided Natural Gas	-0.73	-0.49	-0.37	-0.29	-0.21	-0.15	-0.07	-0.05	-0.04	N/A	N/A
Total	0.98	0.74	0.63	0.56	0.48	0.42	0.35	0.32	0.31	0.26	1.21
Percent Contribution, %											
Delivery to Transfer Station	63	55	49	44	37	30	18	12	10	N/A	N/A
Pre-treatment WM	31	27	24	22	18	14	8	5	4	N/A	N/A
Pre-treatment w/o WM	52	45	40	36	30	24	14	10	7	44	7
Fuel Production	29	38	45	51	60	68	82	88	91	56	11
Vehicle Operation	0	0	0	0	0	0	0	0	0	0	83
Avoided Electricity	-1	-1	-1	-1	<-1	<-1	<-1	<-1	<-1	N/A	N/A
Avoided Natural Gas	-75	65	58	53	-44	-35	-21	-15	-12	N/A	N/A
Reduction, %											
Compared to Soybean	281	190	144	117	85	62	35	25	21	0	370
Compared to LSD	-19	-38	-48	-54	-61	-66	-71	-73	-74	-79	0

Table SI-S15. Without GTW Waste Management Scenario for Fossil Cumulative Energy

Lipid Content	GTW 2%	GTW 3%	GTW 4%	GTW 5%	GTW 7%	GTW 10%	GTW 20%	GTW 30%	GTW 40%	Soy-bean	LSD
Fossil CED, MJ/MJ-fuel											
Pre-treatment	0.51	0.34	0.25	0.20	0.14	0.10	0.05	0.03	0.02	0.11	0.08
Fuel Production	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.14	0.13
Vehicle Operation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Total	0.79	0.62	0.54	0.48	0.43	0.38	0.33	0.32	0.31	0.26	1.21
Percent Contribution, %											
Pre-treatment	64	54	47	41	33	26	15	10	7	44	7
Fuel Production	36	46	53	59	67	74	85	90	93	56	11
Vehicle Operation	0	0	0	0	0	0	0	0	0	0	83
Reduction, %											
Compared to Soybean	207	141	108	89	66	49	29	23	19	0	370
Compared to LSD	-35	-49	-56	-60	-65	-68	-72	-74	-75	-79	0

Carbon Monoxide

The carbon monoxide (CO) emissions were determined for the GTW-biodiesel process from 2-40% lipid content and compared to the soybean-biodiesel process and LSD process shown in Figure SI-S6.

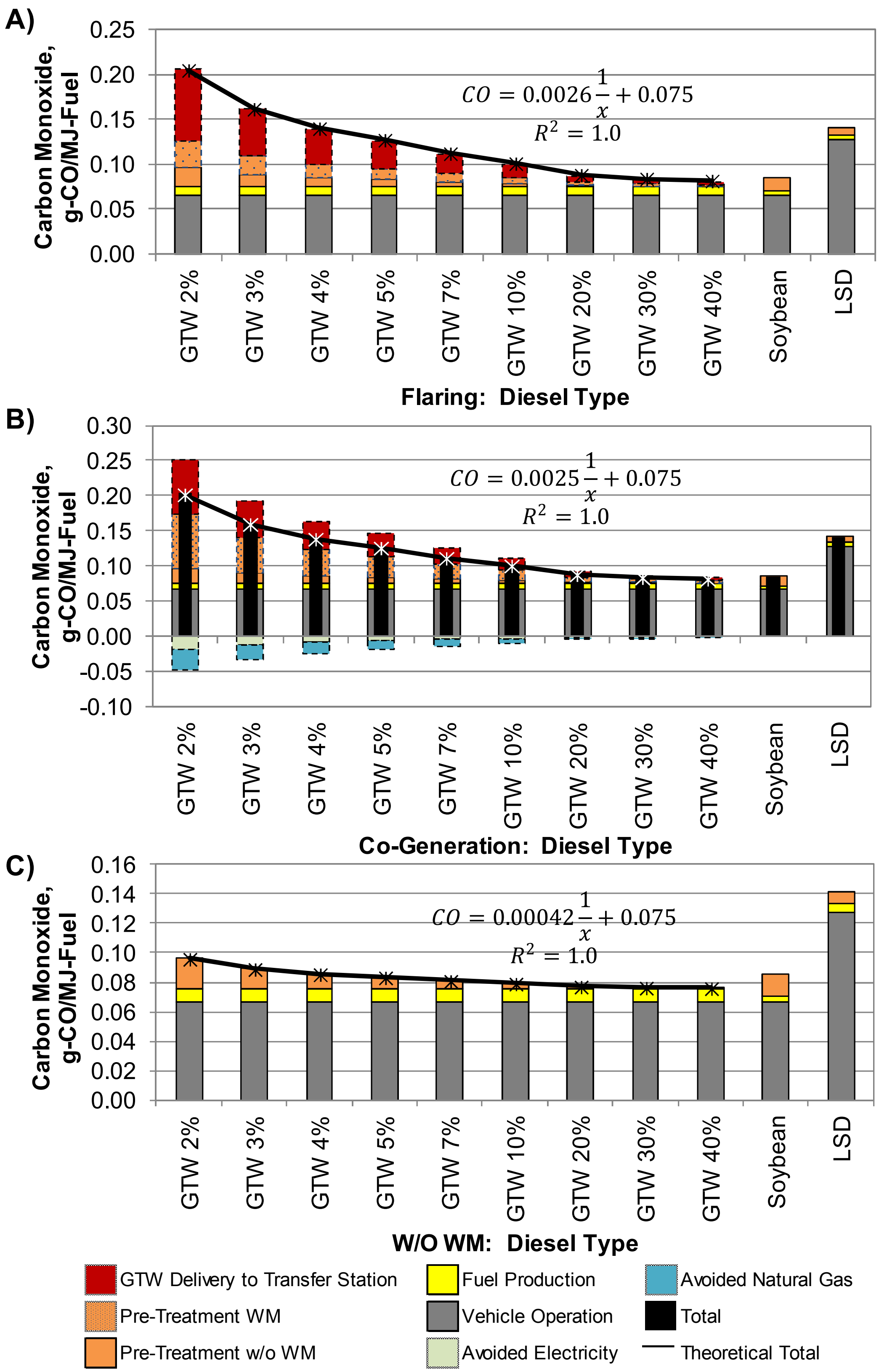

A)
Carbon Monoxide, g-CO/MJ-Fuel
0.25
0.20
0.15
0.10
0.05
0.00
$CO = 0.0026\frac{1}{x} + 0.075$
$R^2 = 1.0$
GTW 2%
GTW 3%
GTW 4%
GTW 5%
GTW 7%
GTW 10%
GTW 20%
GTW 30%
GTW 40%
Soybean
LSD
Flaring: Diesel Type
B)
Carbon Monoxide, g-CO/MJ-Fuel
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
$CO = 0.0025\frac{1}{x} + 0.075$
$R^2 = 1.0$
GTW 2%
GTW 3%
GTW 4%
GTW 5%
GTW 7%
GTW 10%
GTW 20%
GTW 30%
GTW 40%
Soybean
LSD
Co-Generation: Diesel Type
C)
Carbon Monoxide, g-CO/MJ-Fuel
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
$CO = 0.00042\frac{1}{x} + 0.075$
$R^2 = 1.0$
GTW 2%
GTW 3%
GTW 4%
GTW 5%
GTW 7%
GTW 10%
GTW 20%
GTW 30%
GTW 40%
Soybean
LSD
W/O WM: Diesel Type
GTW Delivery to Transfer Station
Pre-Treatment WM
Pre-Treatment w/o WM
Fuel Production
Vehicle Operation
Avoided Electricity
Avoided Natural Gas
Total
Theoretical Total

Figure SI-S6. Carbon Monoxide Complete Emissions Parametric Study of GTW-Biodiesel Compared to Soybean-biodiesel and LSD A) Flaring landfill gas, B) Co-generation of landfill gas, and C) without GTW waste management. The stacked bars represent GTW-biodiesel stages: delivery of GTW to transfer station (red), pre-treatment WM (orange with blue dots), pre-treatment without WM (orange), fuel production (yellow), vehicle operation (gray), avoided electricity production from co-generation (light green), and avoided natural gas from co-generation (teal). The total CO (black bar) and modeled curve (black line) are also shown.

The following tables show the CO emissions by process stage, the percent contribution of each process stage, and the percent reduction compared to soybean-biodiesel and LSD for each of the waste scenarios.

Table SI-S16. Landfill Gas Flaring Scenario for Carbon Monoxide Emissions

Diesel Type	GTW 2%	GTW 3%	GTW 4%	GTW 5%	GTW 7%	GTW 10%	GTW 20%	GTW 30%	GTW 40%	Soy-bean	LSD
Carbon Monoxide, g-CO/MJ-Fuel											
Delivery to Transfer Station	0.079	0.053	0.039	0.032	0.022	0.016	0.008	0.005	0.004	N/A	N/A
Pre-treatment WM	0.030	0.020	0.015	0.012	0.009	0.006	0.003	0.002	0.001	N/A	N/A
Pre-treatment w/o WM	0.021	0.014	0.011	0.008	0.006	0.004	0.002	0.001	0.001	0.014	0.008
Fuel Production	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.004	0.005
Vehicle Operation	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.128
Total	0.206	0.162	0.140	0.127	0.112	0.101	0.088	0.083	0.081	0.085	0.141
Percent Contribution, %											
Delivery to Transfer Station	38	33	28	25	20	16	9	6	5	N/A	N/A
Pre-treatment WM	10	9	8	7	5	4	2	2	1	N/A	N/A
Pre-treatment w/o WM	15	12	11	9	8	6	3	2	1	17	6
Fuel Production	4	5	6	7	8	9	10	11	11	5	4
Vehicle Operation	32	41	47	52	59	66	76	80	82	78	90
Reduction, %											
Compared to Soybean	142	90	65	49	32	18	3	-2	-5	0	66
Compared to LSD	46	15	-1	-10	-21	-29	-38	-41	-43	-40	0

Table SI-S17. Landfill Gas Co-Generation Scenario for Carbon Monoxide Emissions

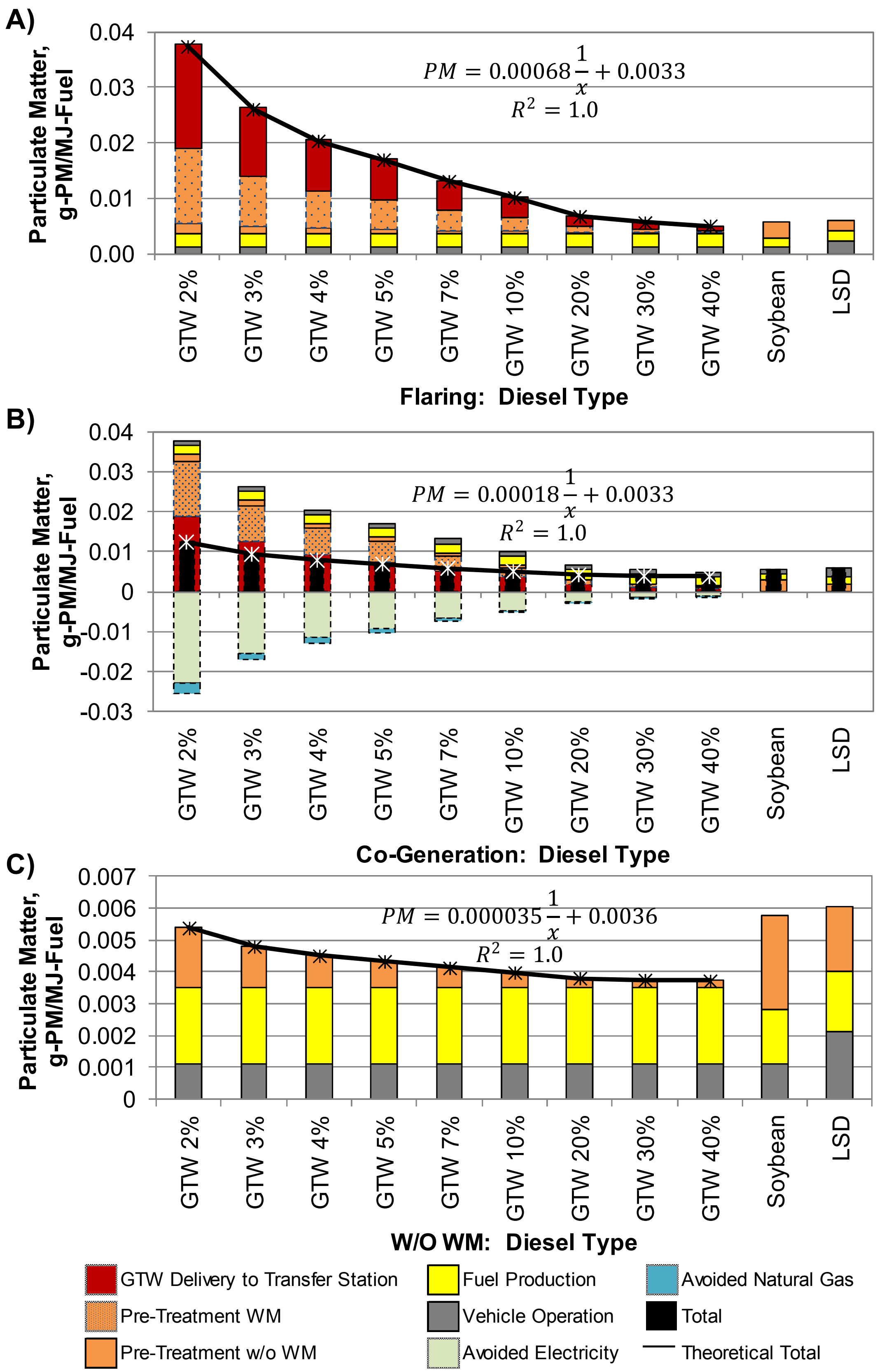
Diesel Type	**GTW 2%**	**GTW 3%**	**GTW 4%**	**GTW 5%**	**GTW 7%**	**GTW 10%**	**GTW 20%**	**GTW 30%**	**GTW 40%**	**Soy-bean**	**LSD**
Carbon Monoxide, g-CO/MJ-fuel											
Delivery to Transfer Station	0.079	0.053	0.039	0.032	0.022	0.016	0.008	0.005	0.004	N/A	N/A
Pre-treatment WM	0.076	0.051	0.038	0.030	0.022	0.015	0.007	0.005	0.004	N/A	N/A
Pre-treatment w/o WM	0.021	0.014	0.011	0.008	0.006	0.004	0.002	0.001	0.001	0.014	0.008
Fuel Production	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.004	0.005
Vehicle Operation	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.128
Avoided Electricity	-0.018	-0.012	-0.009	-0.007	-0.005	-0.004	-0.002	-0.001	-0.001	N/A	N/A
Avoided Natural Gas	-0.031	-0.020	-0.015	-0.012	-0.009	-0.006	-0.003	-0.002	-0.002	N/A	N/A
Total	0.203	0.160	0.139	0.126	0.111	0.100	0.087	0.083	0.081	0.085	0.141
Percent Contribution, %											
Delivery to Transfer Station	39	33	28	25	20	16	9	6	5	N/A	N/A
Pre-treatment WM	38	32	27	24	19	15	8	6	4	N/A	N/A
Pre-treatment w/o WM	10	9	8	7	5	4	2	2	1	17	6
Fuel Production	4	5	6	7	8	9	10	11	11	5	4
Vehicle Operation	33	41	48	53	60	66	76	80	82	78	90
Avoided Electricity	-9	-8	-7	-6	-5	-4	-2	-1	-1	N/A	N/A
Avoided Natural Gas	-15	-13	-11	-10	-8	-6	-4	-2	-2	N/A	N/A
Reduction, %											
Compared to Soybean	139	88	63	48	31	18	3	-2	-5	0	66
Compared to LSD	44	13	-2	-11	-21	-29	-38	-41	-43	-40	0

Table SI-S18. Without GTW Waste Management Scenario for Carbon Monoxide Emissions

Diesel Type	**GTW 2%**	**GTW 3%**	**GTW 4%**	**GTW 5%**	**GTW 7%**	**GTW 10%**	**GTW 20%**	**GTW 30%**	**GTW 40%**	**Soy-bean**	**LSD**
Carbon Monoxide, g-CO/MJ-fuel											
Pre-treatment	0.021	0.014	0.011	0.008	0.006	0.004	0.002	0.001	0.001	0.014	0.008
Fuel Production	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.004	0.005
Vehicle Operation	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.128
Total	0.096	0.089	0.086	0.083	0.081	0.079	0.077	0.076	0.076	0.085	0.141
Percent Contribution, %											
Pre-treatment	22	16	12	10	7	5	3	2	1	17	6
Fuel Production	9	10	10	10	11	11	11	11	12	5	4
Vehicle Operation	69	74	77	79	82	84	86	87	87	78	90
Reduction, %											
Compared to Soybean	13	5	1	-2	-5	-7	-9	-10	-11	0	66
Compared to LSD	-32	-37	-39	-41	-43	-44	-45	-46	-46	-40	0

Particulate matter

The particulate matter (PM) emissions were determined for the GTW-biodiesel process from 2-40% lipid content and compared to the soybean-biodiesel process and LSD process shown in Figure SI-S7.


A)
Particulate Matter, g-PM/MJ-Fuel
0.04
0.03
0.02
0.01
0.00
$PM = 0.00068\frac{1}{x} + 0.0033$
$R^2 = 1.0$
GTW 2%
GTW 3%
GTW 4%
GTW 5%
GTW 7%
GTW 10%
GTW 20%
GTW 30%
GTW 40%
Soybean
LSD
Flaring: Diesel Type
B)
Particulate Matter, g-PM/MJ-Fuel
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
$PM = 0.00018\frac{1}{x} + 0.0033$
$R^2 = 1.0$
GTW 2%
GTW 3%
GTW 4%
GTW 5%
GTW 7%
GTW 10%
GTW 20%
GTW 30%
GTW 40%
Soybean
LSD
Co-Generation: Diesel Type
C)
Particulate Matter, g-PM/MJ-Fuel
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
$PM = 0.000035\frac{1}{x} + 0.0036$
$R^2 = 1.0$
GTW 2%
GTW 3%
GTW 4%
GTW 5%
GTW 7%
GTW 10%
GTW 20%
GTW 30%
GTW 40%
Soybean
LSD
W/O WM: Diesel Type
GTW Delivery to Transfer Station
Pre-Treatment WM
Pre-Treatment w/o WM
Fuel Production
Vehicle Operation
Avoided Electricity
Avoided Natural Gas
Total
Theoretical Total

314

Figure SI-S7. Particulate Matter Complete Parametric Study of GTW-Biodiesel Compared to Soybean-biodiesel and LSD for A) Flaring landfill gas, B) Co-generation of landfill gas, and C) without GTW waste management. The stacked bars represent GTW-biodiesel stages: delivery of GTW to transfer station (red), pre-treatment WM (orange with blue dots), pre-treatment without WM (orange), fuel production (yellow), vehicle operation (gray), avoided electricity production from co-generation (light green), and avoided natural gas from co-generation (teal). The total PM (black bar) and modeled curve (black line) are also shown.

The following tables show the PM emissions by process stage, the percent contribution of each process stage, and the percent reduction compared to soybean-biodiesel and LSD for each of the waste scenarios.

Table SI-S19. Landfill Gas Flaring Scenario for Particulate Matter Emissions

Diesel Types	GTW 2%	GTW 3%	GTW 4%	GTW 5%	GTW 7%	GTW 10%	GTW 20%	GTW 30%	GTW 40%	Soy-bean	LSD
Particulate Matter, g-PM/MJ-Fuel											
Delivery to Transfer Station	0.019	0.012	0.009	0.007	0.005	0.004	0.002	0.001	0.001	N/A	N/A
Pre-treatment WM	0.014	0.009	0.007	0.005	0.004	0.002	0.001	0.001	0.000	N/A	N/A
Pre-treatment w/o WM	0.002	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.003	0.001
Fuel Production	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Vehicle Operation	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002
Total	0.038	0.026	0.021	0.017	0.013	0.010	0.007	0.006	0.005	0.006	0.006
Percent Contribution, %											
Delivery to Transfer Station	50	48	46	44	40	37	27	22	18	N/A	N/A
Pre-Treatment WM	36	34	32	31	28	24	16	11	7	N/A	N/A
Pre-Treatment w/o WM	5	5	5	5	5	5	4	4	4	52	33
Fuel Production	6	9	12	14	18	23	36	43	48	29	31
Vehicle Operation	3	4	5	7	9	11	17	20	23	19	35
Reduction, %											
Compared to Soybean	553	354	254	195	128	76	16	-4	-14	0	5
Compared to LSD	523	334	238	181	117	68	11	-8	-18	-5	0

Table SI-S20. Landfill Gas Co-Generation Scenario for Particulate Matter Emissions

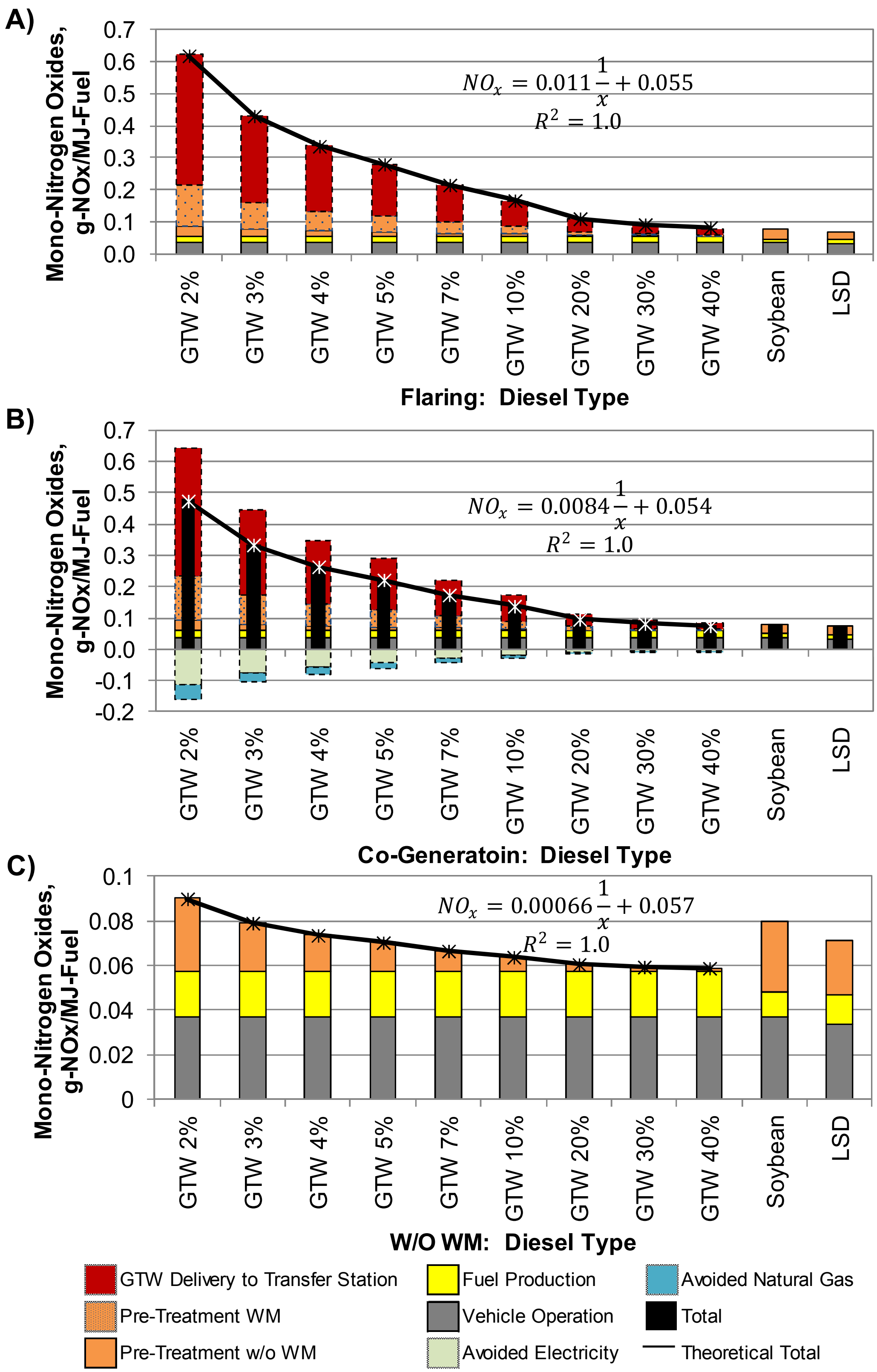
Lipid Content	**GTW 2%**	**GTW 3%**	**GTW 4%**	**GTW 5%**	**GTW 7%**	**GTW 10%**	**GTW 20%**	**GTW 30%**	**GTW 40%**	**Soy-bean**	**LSD**
Carbon Monoxide, g-CO/MJ-fuel											
Delivery to Transfer Station	0.019	0.012	0.009	0.007	0.005	0.004	0.002	0.001	0.001	N/A	N/A
Pre-treatment WM	0.014	0.009	0.007	0.005	0.004	0.002	0.001	0.001	0.000	N/A	N/A
Pre-treatment w/o WM	0.002	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.003	0.002
Fuel Production	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Vehicle Operation	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002
Avoided Electricity	-0.023	-0.015	-0.011	-0.009	-0.006	-0.005	-0.002	-0.002	-0.001	N/A	N/A
Avoided Natural Gas	-0.003	-0.002	-0.001	-0.001	-0.001	-0.001	0.000	0.000	0.000	N/A	N/A
Total	0.012	0.009	0.008	0.007	0.006	0.005	0.004	0.004	0.004	0.006	0.006
Percent Contribution, %											
Delivery to Transfer Station	150	133	119	108	90	73	44	31	24	N/A	N/A
Pre-Treatment WM	109	96	85	76	63	48	25	15	10	N/A	N/A
Pre-Treatment w/o WM	15	14	13	12	11	9	7	6	5	52	33
Fuel Production	19	25	30	34	40	47	57	62	64	29	31
Vehicle Operation	9	12	14	16	19	22	27	29	30	19	35
Avoided Electricity	-182	-161	-145	-131	-109	-89	-54	-39	-31	N/A	N/A
Avoided Natural Gas	-21	-18	-16	-15	-12	-10	-6	-4	-3	N/A	N/A
Reduction, %											
Compared to Soybean	116	63	36	20	3	-12	-28	-33	-36	0	5
Compared to LSD	106	55	30	14	-2	-16	-31	-36	-39	-5	0

Table SI-S21. Without GTW Waste Management Scenario for Particulate Matter Emissions

Diesel Type	GTW 2%	GTW 3%	GTW 4%	GTW 5%	GTW 7%	GTW 10%	GTW 20%	GTW 30%	GTW 40%	Soy-bean	LSD
Particulate Matter, g-PM/MJ-fuel											
Delivery to Transfer Station	0.019	0.012	0.009	0.007	0.005	0.004	0.002	0.001	0.001	N/A	N/A
Pre-treatment	0.002	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.003	0.002
Fuel Production	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Vehicle Operation	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002
Total	0.005	0.005	0.005	0.004	0.004	0.004	0.004	0.004	0.004	0.006	0.006
Percent Contribution, %											
Pre-treatment	35	27	22	19	15	12	8	6	5	52	33
Fuel Production	44	49	53	55	58	60	63	64	64	29	31
Vehicle Operation	21	23	25	26	27	28	30	30	30	19	35
Reduction, %											
Compared to Soybean	-7	-17	-22	-25	-29	-31	-34	-35	-36	0	5
Compared to LSD	-11	-21	-26	-28	-32	-34	-37	-38	-39	-5	0

Mono-Nitrogen Oxide

The mono-nitrogen oxide (NO_x) emissions were determined for the GTW-biodiesel process from 2-40% lipid content and compared to the soybean-biodiesel process and LSD process shown in Figure SI-S8.



A)
Mono-Nitrogen Oxides, g-NOx/MJ-Fuel
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
$NO_x = 0.011\frac{1}{x} + 0.055$
$R^2 = 1.0$
GTW 2%
GTW 3%
GTW 4%
GTW 5%
GTW 7%
GTW 10%
GTW 20%
GTW 30%
GTW 40%
Soybean
LSD
Flaring: Diesel Type
B)
Mono-Nitrogen Oxides, g-NOx/MJ-Fuel
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
$NO_x = 0.0084\frac{1}{x} + 0.054$
$R^2 = 1.0$
GTW 2%
GTW 3%
GTW 4%
GTW 5%
GTW 7%
GTW 10%
GTW 20%
GTW 30%
GTW 40%
Soybean
LSD
Co-Generatoin: Diesel Type
C)
Mono-Nitrogen Oxides, g-NOx/MJ-Fuel
0.1
0.08
0.06
0.04
0.02
0
$NO_x = 0.00066\frac{1}{x} + 0.057$
$R^2 = 1.0$
GTW 2%
GTW 3%
GTW 4%
GTW 5%
GTW 7%
GTW 10%
GTW 20%
GTW 30%
GTW 40%
Soybean
LSD
W/O WM: Diesel Type
GTW Delivery to Transfer Station
Pre-Treatment WM
Pre-Treatment w/o WM
Fuel Production
Vehicle Operation
Avoided Electricity
Avoided Natural Gas
Total
Theoretical Total

338

Figure SI-S8. Mono-nitrogen Oxide Complete Parametric Study of GTW-Biodiesel Compared to Soybean-biodiesel and LSD for A) Flaring landfill gas, B) Co-generation of landfill gas, and C) without GTW waste management. The stacked bars represent GTW-biodiesel stages: delivery of GTW to transfer station (red), pre-treatment WM (orange with blue dots), pre-treatment without WM (orange), fuel production (yellow), vehicle operation (gray), avoided electricity production from co-generation (light green), and avoided natural gas from co-generation (teal). The total NOx (black bar) and modeled curve (black line) are also shown.

The following tables show the NOx emissions by process stage, the percent contribution of each process stage, and the percent reduction compared to soybean-biodiesel and LSD for each of the waste scenarios.

Table SI-S22. Landfill Gas Flaring Scenario for Mono-nitrogen Oxide Emissions

Diesel Type	GTW 2%	GTW 3%	GTW 4%	GTW 5%	GTW 7%	GTW 10%	GTW 20%	GTW 30%	GTW 40%	Soy-bean	LSD
Mono-nitrogen Oxide, g-NOx/MJ-Fuel											
Delivery to Transfer Station	0.406	0.271	0.203	0.162	0.115	0.081	0.040	0.026	0.019	N/A	N/A
Pre-treatment WM	0.128	0.084	0.062	0.049	0.035	0.023	0.010	0.006	0.004	N/A	N/A
Pre-treatment w/o WM	0.033	0.022	0.017	0.013	0.009	0.007	0.003	0.002	0.002	0.032	0.025
Fuel Production	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.011	0.013
Vehicle Operation	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.033
Total	0.625	0.434	0.339	0.282	0.217	0.168	0.110	0.091	0.082	0.080	0.071
Percent Contribution, %											
Delivery to Transfer Station	65	62	60	58	53	48	36	29	24	N/A	N/A
Pre-treatment WM	20	19	18	17	16	14	9	6	4	N/A	N/A
Pre-treatment w/o WM	5	5	5	5	4	4	3	2	2	40	34
Fuel Production	3	5	6	7	9	12	18	22	25	14	19
Vehicle Operation	6	8	11	13	17	22	33	40	45	46	47
Reduction, %											
Compared to Soybean	684	445	325	254	172	110	39	15	3	0	-10
Compared to LSD	774	507	374	294	203	134	54	28	14	11	0

Table SI-S23. Landfill Gas Co-Generation Scenario for Mono-nitrogen Oxide Emissions

Diesel Type	**GTW 2%**	**GTW 3%**	**GTW 4%**	**GTW 5%**	**GTW 7%**	**GTW 10%**	**GTW 20%**	**GTW 30%**	**GTW 40%**	**Soy-bean**	**LSD**
Mono-nitrogen Oxide, g-NOx/MJ-Fuel											
Delivery to Transfer Station	0.406	0.271	0.203	0.162	0.115	0.081	0.040	0.026	0.019	N/A	N/A
Pre-treatment WM	0.142	0.094	0.070	0.055	0.039	0.026	0.012	0.007	0.004	N/A	N/A
Pre-treatment w/o WM	0.033	0.022	0.017	0.013	0.009	0.007	0.003	0.002	0.002	0.032	0.025
Fuel Production	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.011	0.013
Vehicle Operation	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.033
Avoided Electricity	-0.112	-0.075	-0.056	-0.045	-0.032	-0.022	-0.011	-0.007	-0.006	N/A	N/A
Avoided Natural Gas	-0.048	-0.032	-0.024	-0.019	-0.014	-0.010	-0.005	-0.003	-0.002	N/A	N/A
Total	0.479	0.337	0.266	0.223	0.175	0.138	0.096	0.082	0.074	0.080	0.071
Percent Contribution, %											
Delivery to Transfer Station	85	80	76	73	66	58	42	32	26	N/A	N/A
Pre-treatment WM	30	28	26	25	22	19	12	8	6	N/A	N/A
Pre-treatment w/o WM	7	7	6	6	5	5	3	3	2	40	34
Fuel Production	4	6	8	9	12	15	21	25	27	14	19
Vehicle Operation	8	11	14	17	21	27	39	45	50	46	47
Avoided Electricity	-23	-22	-21	-20	-18	-16	-12	-9	-8	N/A	N/A
Avoided Natural Gas	-10	-9	-9	-9	-8	-7	-5	-4	-3	N/A	N/A
Reduction, %											
Compared to Soybean	501	323	234	180	120	74	20	2	-6	0	-10
Compared to LSD	570	371	272	212	145	93	34	14	4	11	0

Table SI-S24. Without Waste Management Scenario for Mono-nitrogen Oxide Emissions

Diesel Type	GTW 2%	GTW 3%	GTW 4%	GTW 5%	GTW 7%	GTW 10%	GTW 20%	GTW 30%	GTW 40%	Soy-bean	LSD
Mono-nitrogen Oxides, g-NOx/MJ-fuel											
Pre-treatment	0.033	0.022	0.017	0.013	0.009	0.007	0.003	0.002	0.002	0.032	0.025
Fuel Production	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.011	0.013
Vehicle Operation	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.033
Total	0.090	0.079	0.074	0.070	0.067	0.064	0.060	0.059	0.059	0.080	0.071
Percent Contribution, %											
Pre-treatment	37	28	22	19	14	10	5	4	3	40	34
Fuel Production	22	26	27	29	30	32	34	34	35	14	19
Vehicle Operation	41	47	50	52	55	58	61	62	63	46	47
Reduction, %											
Compared to Soybean	13	0	-7	-12	-16	-20	-24	-25	-26	0	-10
Compared to LSD	26	11	3	-1	-7	-11	-15	-17	-18	11	0

Sulfur Oxides

The sulfur oxide (SO_x) emissions were determined for the GTW-biodiesel process from 2-40% lipid content and compared to the soybean-biodiesel process and LSD process shown in Figure SI-S9. The soybean-biodiesel pre-treatment dominates where soybean production accounts for 47% of total emissions due to the use of sulfuric acid in the production of phosphoric acid (P_2O_5) applied as a fertilizer. Soybean-biodiesel combustion does not have SO_x emissions because the feedstock/fuel does not contain sulfur.

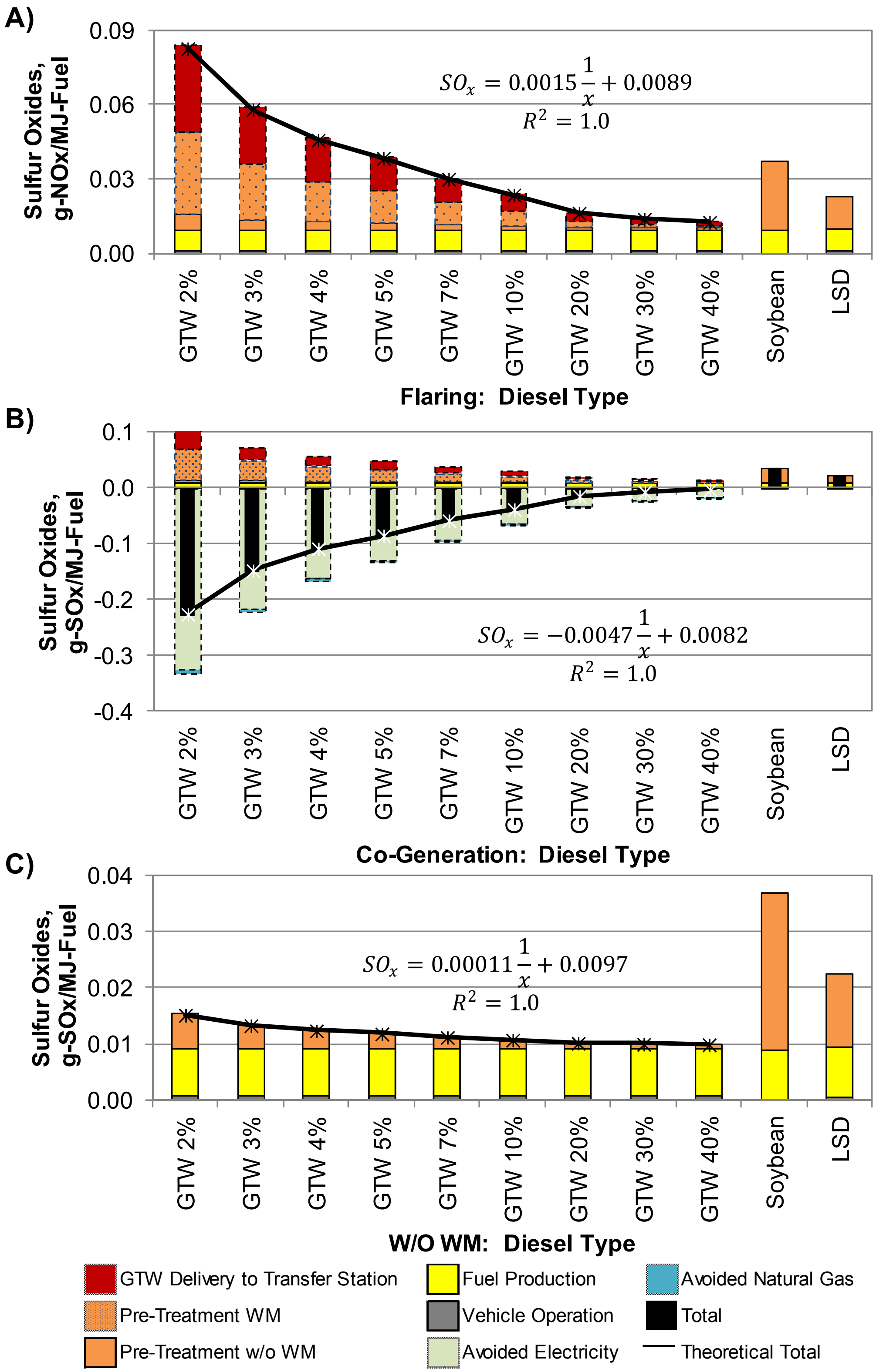

A)
Sulfur Oxides, g-NOx/MJ-Fuel
0.09
0.06
0.03
0.00
$SO_x = 0.0015\frac{1}{x} + 0.0089$
$R^2 = 1.0$
GTW 2%
GTW 3%
GTW 4%
GTW 5%
GTW 7%
GTW 10%
GTW 20%
GTW 30%
GTW 40%
Soybean
LSD
Flaring: Diesel Type
B)
Sulfur Oxides, g-SOx/MJ-Fuel
0.1
0.0
-0.1
-0.2
-0.3
-0.4
$SO_x = -0.0047\frac{1}{x} + 0.0082$
$R^2 = 1.0$
GTW 2%
GTW 3%
GTW 4%
GTW 5%
GTW 7%
GTW 10%
GTW 20%
GTW 30%
GTW 40%
Soybean
LSD
Co-Generation: Diesel Type
C)
Sulfur Oxides, g-SOx/MJ-Fuel
0.04
0.03
0.02
0.01
0.00
$SO_x = 0.00011\frac{1}{x} + 0.0097$
$R^2 = 1.0$
GTW 2%
GTW 3%
GTW 4%
GTW 5%
GTW 7%
GTW 10%
GTW 20%
GTW 30%
GTW 40%
Soybean
LSD
W/O WM: Diesel Type
GTW Delivery to Transfer Station
Pre-Treatment WM
Pre-Treatment w/o WM
Fuel Production
Vehicle Operation
Avoided Electricity
Avoided Natural Gas
Total
Theoretical Total

Figure SI-S9. Sulfur Oxide Complete Parametric Study of GTW-Biodiesel Compared to Soybean-biodiesel and LSD for A) Flaring landfill gas, B) Co-generation of landfill gas, and C) without GTW waste management. The stacked bars represent GTW-biodiesel stages: delivery of GTW to transfer station (red), pre-treatment WM (orange with blue dots), pre-treatment without WM (orange), fuel production (yellow), vehicle operation (gray), avoided electricity production from co-generation (light green), and avoided natural gas from co-generation (teal). The total SOx (black bar) and modeled curve (black line) are also shown.

The following tables show the SOx emissions by process stage, the percent contribution of each process stage, and the percent reduction compared to soybean-biodiesel and LSD for each of the waste scenarios.

Table SI-S25. Landfill Gas Flaring Scenario for Sulfur Oxide Emissions

Diesel Type	**GTW 2%**	**GTW 3%**	**GTW 4%**	**GTW 5%**	**GTW 7%**	**GTW 10%**	**GTW 20%**	**GTW 30%**	**GTW 40%**	**Soy-bean**	**LSD**
Sulfur Oxides, g-SOx/MJ-Fuel											
Delivery to Transfer Station	0.035	0.023	0.017	0.014	0.010	0.007	0.003	0.002	0.002	N/A	N/A
Pre-treatment WM	0.033	0.022	0.016	0.013	0.009	0.006	0.003	0.001	0.001	N/A	N/A
Pre-treatment w/o WM	0.006	0.004	0.003	0.003	0.002	0.002	0.001	0.001	0.001	0.028	0.013
Fuel Production	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.009	0.009
Vehicle Operation	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.001
Total	0.084	0.059	0.046	0.039	0.030	0.024	0.016	0.014	0.012	0.037	0.022
Percent Contribution, %											
Delivery to Transfer Station	42	40	38	36	33	29	21	16	13	N/A	N/A
Pre-treatment WM	40	38	35	33	30	25	16	10	6	N/A	N/A
Pre-treatment w/o WM	7	7	7	7	7	7	7	7	7	76	58
Fuel Production	10	14	18	22	28	35	51	61	67	24	39
Vehicle Operation	1	1	2	2	3	3	5	6	6	0	2
Reduction, %											
Compared to Soybean	127	59	25	5	-18	-36	-56	-63	-66	0	-39
Compared to LSD	272	161	105	72	34	5	-28	-39	-45	64	0

Table SI-S26. Landfill Gas Co-Generation Scenario for Sulfur Oxide Emissions

Lipid Content	GTW 2%	GTW 3%	GTW 4%	GTW 5%	GTW 7%	GTW 10%	GTW 20%	GTW 30%	GTW 40%	Se
Sulfur Oxides, g-SOx/MJ-Fuel										
Delivery to Transfer Station	0.035	0.023	0.017	0.014	0.010	0.007	0.003	0.002	0.002	N
Pre-treatment WM	0.054	0.036	0.026	0.021	0.015	0.010	0.005	0.003	0.002	N
Pre-treatment w/o WM	0.006	0.004	0.003	0.003	0.002	0.002	0.001	0.001	0.001	0.
Fuel Production	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.
Vehicle Operation	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.
Avoided Electricity	-0.325	-0.216	-0.162	-0.130	-0.093	-0.065	-0.032	-0.022	-0.016	N
Avoided Natural Gas	-0.008	-0.005	-0.004	-0.003	-0.002	-0.002	-0.001	-0.001	0.000	N
Total	-0.229	-0.150	-0.110	-0.086	-0.059	-0.039	-0.015	-0.007	-0.003	0.
Percent Contribution, %										
Delivery to Transfer Station	-15	-15	-16	-16	-17	-18	-23	-31	-52	N
Pre-Treatment WM	-24	-24	-24	-24	-25	-26	-30	-38	-57	N
Pre-Treatment w/o WM	-3	-3	-3	-3	-4	-4	-8	-13	-27	76
Fuel Production	-4	-6	-8	-10	-14	-21	-55	-117	-262	24
Vehicle Operation	0	-1	-1	-1	-1	-2	-5	-11	-24	0
Avoided Electricity	142	145	147	150	157	167	216	303	510	N
Avoided Natural Gas	4	4	4	4	4	4	5	8	13	N
Reduction, %										
Compared to Soybean	-722	-507	-399	-335	-261	-205	-141	-119	-109	0
Compared to LSD	-1118	-766	-590	-484	-363	-273	-167	-132	-114	64

Table SI-S27. Without GTW Waste Management Scenario for Sulfur Oxide Emissions

Diesel Type	GTW 2%	GTW 3%	GTW 4%	GTW 5%	GTW 7%	GTW 10%	GTW 20%	GTW 30%	GTW 40%	Soy-bean	LSD
Sulfur Oxides, g-SOx/MJ-fuel											
Pre-treatment	0.006	0.004	0.003	0.003	0.002	0.002	0.001	0.001	0.001	0.028	0.013
Fuel Production	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.009	0.009
Vehicle Operation	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.001
Total	0.015	0.013	0.012	0.012	0.011	0.011	0.010	0.010	0.010	0.037	0.022
Percent Contribution, %											
Pre-treatment	41	32	27	24	19	16	11	10	9	76	58
Fuel Production	54	62	67	70	74	77	81	83	84	24	39
Vehicle Operation	5	6	6	6	7	7	8	8	8	0	2
Reduction, %											
Compared to Soybean	-58	-64	-66	-68	-69	-71	-72	-73	-73	0	-39
Compared to LSD	-32	-40	-44	-47	-50	-52	-54	-55	-56	64	0

Sensitivity of model results to Percent FFA Composition of GTW Lipids

GTW lipid composition is also variable. In this model, the assumed free fatty acid content (%FFA) was high which was based off of initial samples of GTW lipids received in the laboratory. In the longitudinal study, the average GTW lipid content was approximately 80%FFA[3]. Therefore, a preliminary analysis was performed to determine the change in GWP_{100}. GTW lipids composition was assumed to be 80% oleic acid and 20% triolein. The triolein was not reacted into biodiesel since the process model does not include transesterification. The triolein remains as the residual co-product, "bio-bunker," in the distillation process. The life cycle inventory was updated for this process and GWP_{100} was determined. Lipid contents of 5% and 30% containing 80%FFA were compared to the consequential LCA approach for 5% and 30% lipid contents shown in Table SI-S10.

Table SI-S28. Comparison of predicted GWP_{100} from consequential LCA for low FFA GTW-biodiesel process and high FFA GTW-biodiesel process.

	GWP_{100} from Low FFA Scenario		GWP_{100} from High FFA Scenario		Ratio of Low FFA to High FFA	
	5% Lipids	30% Lipids	5% Lipids	30% Lipids	5% Lipids	30% Lipids
Pre-Treatment	15.2	2.4	12.5	2.0	1.2	1.2
Fuel Production	16.5	16.5	14.2	14.2	1.2	1.2
Vehicle Operation	4.8	4.8	4.8	4.8	1.0	1.0
Total	36.4	23.7	31.5	21.0	1.2	1.1

The lower FFA does not increase the GWP_{100} significantly for either 5% or 30% lipid contents. The effect of FFA on GWP_{100} is similar to the effect of overall lipid content: the lower the FFA, the higher the GWP_{100}. The lower FFA is equivalent to having a lower lipid content. For example the 5% lipid content with 80% FFA GWP_{100} is the same as 3.5% lipid content with 95% FFA GWP_{100}.

Sensitivity to GTW Composition and Monte Carlo Simulation

The Monte Carlo simulation was performed to determine GWP_{100} of both the attributional and consequential LCA approaches for the GTW-biodiesel process. Two lognormal distributions were used based off of raw GTW lipid contents and dewatered GTW lipid contents. The attributional LCA approach included two scenarios based off of landfill gas flaring and co-generation of landfill gas. The consequential LCA approach omits the impacts associated with GTW waste management and the delivery of GTW to the transfer station because they are nearly the same in the current GTW handling process and the proposed GTW-biodiesel process.

Longitudinal Study

The longitudinal study occurred between June 2014 and June 2015. A 500 gal tank was located at a transfer station in New Jersey. The GTW hauler deposited interior grease trap collections into the tank. The GTW typically settled into three layers: 1) floating solids with extractable lipids, 2) wastewater, and 3) sediments. Each layer width was measured and knowing the diameter of the tank, the volume was estimated. The top floating layer was sampled and heated to remove the lipids. The lipid percent was determined as a percent of the total tank volume (lipids from raw GTW) and as a percent of the floating solids layer (lipids from settled GTW float grease or dewatered GTW). The histogram below depicts the frequency of lipid percentages found throughout the longitudinal study.

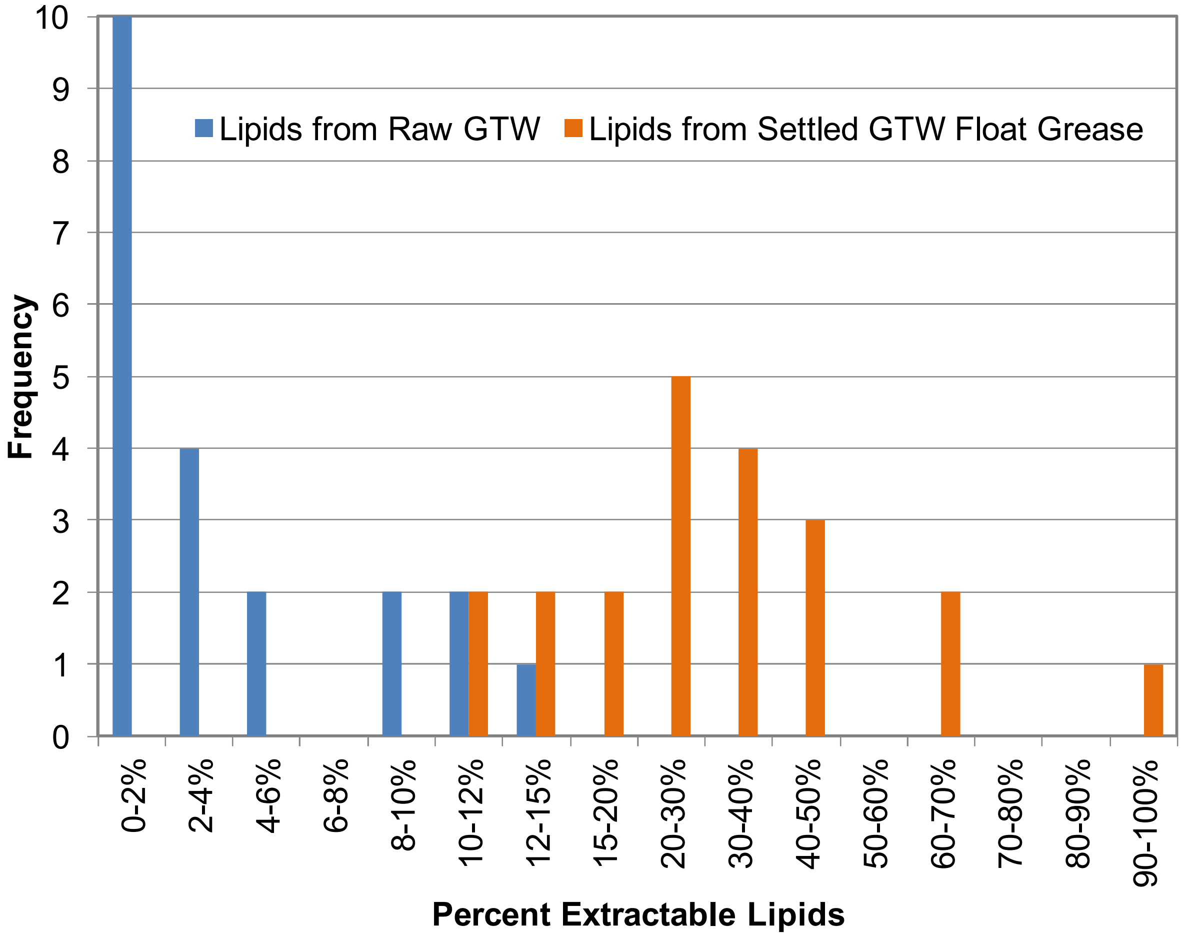


Figure SI-S10. Histogram of lipid contents as a percentage of raw GTW (blue) and as a percentage of settled GTW float grease (orange).

The data of each raw GTW lipid content and dewatered was fit to a lognormal distribution using Oracale Crystal Ball. The cumulative distributions for the lipid contents are shown in Figure SI-S11.

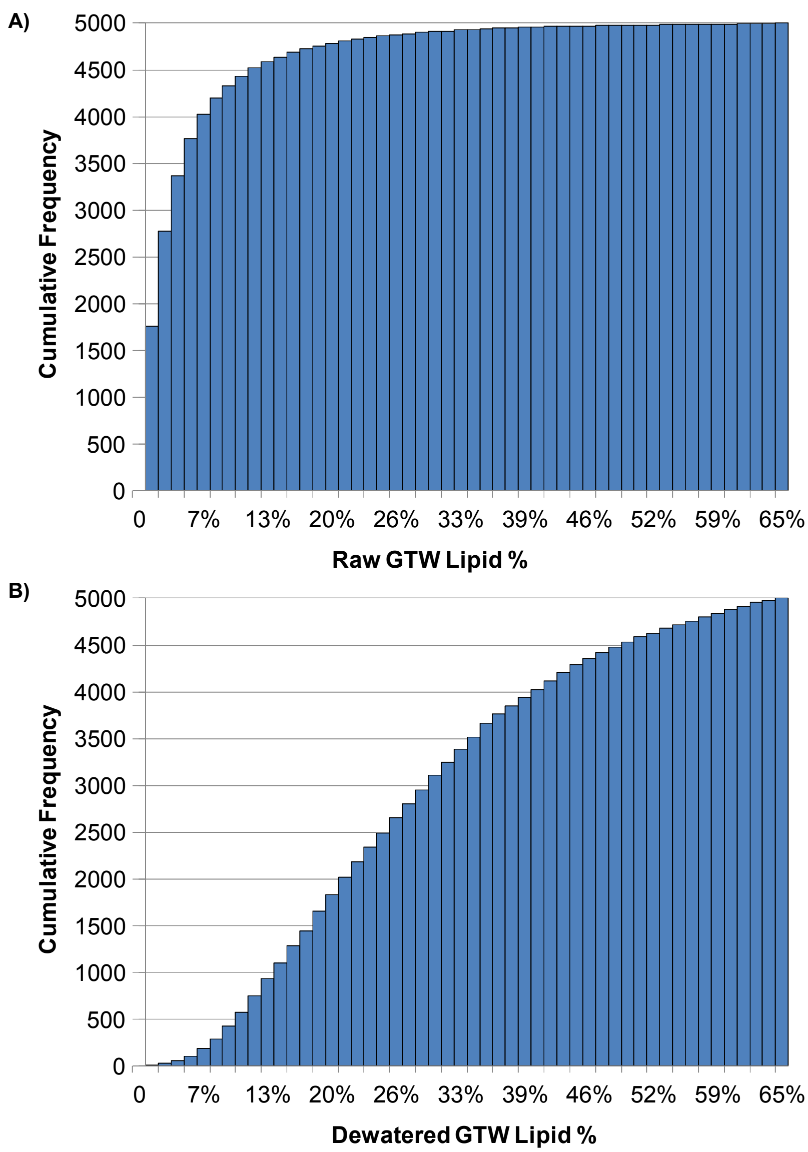


Figure SI-S11. Cumulative distributions for lipid content (as a mass fraction) used in the Monte Carlo simulation for A) Raw GTW and B) Dewatered GTW.

The cumulative distribution for the raw GTW has a faster rate than the dewatered GTW as the median is 2% lipids and 27% for raw GTW and dewatered GTW, respectively. 90% confidence for the raw GTW distribution is 11% lipid content; lipid concentrations less than 10% were shown to have larger environmental impacts. This result emphasizes the need for GTW dewatering since the lipids are concentrated and result in higher lipid contents and therefore lower environmental impacts.

Model Fitting Data

The environmental impacts were estimated by using the equation derived for the model fitting and using the distribution of the lipid contents. The equation used to determine "Total Eqn SI-S11" was calculated using SI-S11 shown again below:

$$\frac{I_{Total}}{E_{Biodiesel}} = \left(\frac{\hat{I}_{PT}}{\phi \Delta \hat{H}_c}\right)\frac{1}{x} + \left(\frac{\hat{I}_{FP}}{\phi \Delta \hat{H}_c} + \frac{\hat{I}_{VO}}{\Delta \hat{H}_c}\right) \quad \text{(SI-S11)}$$

Where,

$\hat{I}_i$ = environmental impact intensity of process stage i per unit mass of input (PT = pre-treatment, FP = fuel production, and VO = vehicle operation: combustion emissions)

$\Delta \hat{H}_C$ = heat of combustion of biodiesel (lower heating value, MJ/kg)

Φ = yield of fuel production process

x = lipid content

$E_{Biodiesel}$ = energy content of biodiesel produced

Table SI-S29. GWP_{100} Model Fitting Data

	x (vol)	2%	3%	4%	5%	7%	10%	20%	30%	40%
	1/x (vol)	50.00	33.33	25.00	20.00	14.29	10.00	5.00	3.33	2.50
	1/x (mass)	55.98	37.26	27.93	22.32	15.91	11.10	5.49	3.61	2.68
	kg GTW	1.44	0.96	0.72	0.57	0.41	0.29	0.14	0.09	0.07
Flare	IPT Flare	207	137	103	82	58	40	20	13	9
	Total	226	156	122	101	77	59	39	32	28
	Total Eqn SI-S11	226	156	122	101	77	59	39	32	28
	Theoretical Total (slope*1/x+intercept)	223	155	121	100	77	59	39	32	29
Co-Gen	IPT Co-G	143	95	71	57	40	28	13	8	6
	Total	162	114	90	76	59	47	32	27	25
	Total Eqn SI-S11	162	114	90	76	59	47	32	27	25
	Theoretical Total (slope*1/x+intercept)	161	113	89	75	59	47	32	28	25
W/O WM	IPT w/o	31	21	16	13	9	6	3	2	1
	Total	50	40	35	31	28	25	22	21	20
	Total Eqn SI-S11	50	40	35	31	28	25	22	21	20
	Theoretical Total (slope*1/x+intercept)	50	40	34	31	28	25	22	21	20

IVO	IFP	phi	density GTW
4.79	14.19	1.03	1.11

Table SI-S30. Fossil CED Model Fitting Data

	x (vol)	2%	3%	4%	5%	7%	10%	20%	30%	40%
	1/x (vol)	50.00	33.33	25.00	20.00	14.29	10.00	5.00	3.33	2.50
	1/x (mass)	55.98	37.26	27.93	22.32	15.91	11.10	5.49	3.61	2.68
	kg GTW	1.44	0.96	0.72	0.57	0.41	0.29	0.14	0.09	0.07
Flare	IPT Flare	1.43	0.95	0.71	0.57	0.40	0.28	0.14	0.09	0.06
	Total	1.72	1.24	1.00	0.85	0.69	0.56	0.42	0.37	0.35
	Total Eqn SI-S11	1.71	1.23	0.99	0.84	0.68	0.56	0.41	0.36	0.34
	Theoretical Total (slope*1/x+intercept)	1.70	1.23	0.99	0.85	0.68	0.56	0.42	0.37	0.35
Co-Gen	IPT Co-G	0.70	0.46	0.34	0.27	0.19	0.13	0.06	0.04	0.03
	Total	0.98	0.74	0.63	0.56	0.48	0.42	0.35	0.32	0.31
	Total Eqn SI-S11	0.97	0.74	0.62	0.55	0.47	0.41	0.34	0.31	0.30
	Theoretical Total (slope*1/x+intercept)	0.97	0.74	0.62	0.55	0.48	0.42	0.35	0.32	0.31
W/O WM	IPT w/o	0.51	0.34	0.25	0.20	0.14	0.10	0.05	0.03	0.02
	Total	0.79	0.62	0.54	0.48	0.43	0.38	0.33	0.32	0.31
	Total Eqn SI-S11	0.78	0.61	0.53	0.48	0.42	0.37	0.32	0.31	0.30
	Theoretical Total (slope*1/x+intercept)	0.78	0.62	0.53	0.48	0.43	0.38	0.33	0.32	0.31

IVO	IFP	phi	density GTW
0.00	0.28	1.03	1.11

Table SI-S31. Carbon Monoxide Model Fitting Data

	x (vol)	2%	3%	4%	5%	7%	10%	20%	30%	40%
	1/x (vol)	50.00	33.33	25.00	20.00	14.29	10.00	5.00	3.33	2.50
	1/x (mass)	55.98	37.26	27.93	22.32	15.91	11.10	5.49	3.61	2.68
	kg GTW	1.44	0.96	0.72	0.57	0.41	0.29	0.14	0.09	0.07
Flare	IPT Flare	0.131	0.087	0.065	0.052	0.037	0.026	0.013	0.008	0.006
	Total	0.206	0.162	0.140	0.127	0.112	0.101	0.088	0.083	0.081
	Total Eqn SI-S11	0.206	0.162	0.140	0.127	0.112	0.100	0.087	0.083	0.081
	Theoretical Total (slope*1/x+intercept)	0.204	0.161	0.140	0.127	0.112	0.101	0.088	0.083	0.081
Co-Gen	IPT Co-G	0.128	0.445	0.333	0.266	0.190	0.132	0.065	0.043	0.032
	Total	0.203	0.160	0.139	0.126	0.111	0.100	0.087	0.083	0.081
	Total Eqn SI-S11	0.203	0.519	0.408	0.341	0.264	0.207	0.140	0.118	0.106
	Theoretical Total (slope*1/x+intercept)	0.202	0.159	0.138	0.125	0.111	0.100	0.087	0.083	0.081
W/O WM	IPT w/o	0.021	0.014	0.011	0.008	0.006	0.004	0.002	0.001	0.001
	Total	0.096	0.089	0.086	0.083	0.081	0.079	0.077	0.076	0.076
	Total Eqn SI-S11	0.096	0.089	0.085	0.083	0.081	0.079	0.077	0.076	0.076
	Theoretical Total (slope*1/x+intercept)	0.096	0.089	0.086	0.083	0.081	0.079	0.077	0.076	0.076

IVO	IFP	phi	density GTW
0.066	0.0087	1.03	1.11

Table SI-S32. Particulate Matter Model Fitting Data

	x (vol)	2%	3%	4%	5%	7%	10%	20%	30%	40%
	1/x (vol)	50.00	33.33	25.00	20.00	14.29	10.00	5.00	3.33	2.50
	1/x (mass)	55.98	37.26	27.93	22.32	15.91	11.10	5.49	3.61	2.68
	kg GTW	1.44	0.96	0.72	0.57	0.41	0.29	0.14	0.09	0.07
Flare	IPT Flare	0.03	0.02	0.02	0.01	0.01	0.01	0.00	0.00	0.00
	Total	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.00
	Total Eqn SI-S11	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.00
	Theoretical Total (slope*1/x+intercept)	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01
Co-Gen	IPT Co-G	0.01	0.41	0.30	0.24	0.17	0.12	0.06	0.04	0.03
	Total	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00
	Total Eqn SI-S11	0.01	0.41	0.31	0.25	0.18	0.12	0.06	0.04	0.03
	Theoretical Total (slope*1/x+intercept)	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00
W/O WM	IPT w/o	0.002	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000
	Total	0.005	0.005	0.005	0.004	0.004	0.004	0.004	0.004	0.004
	Total Eqn SI-S11	0.005	0.005	0.004	0.004	0.004	0.004	0.004	0.004	0.004
	Theoretical Total (slope*1/x+intercept)	0.005	0.005	0.005	0.004	0.004	0.004	0.004	0.004	0.004

IVO	IFP	phi	density GTW
0.001	0.002	1.03	1.11

Table SI-S33. Mono-Nitrogen Oxides Model Fitting Data

	x (vol)	2%	3%	4%	5%	7%	10%	20%	30%	40%
	1/x (vol)	50.00	33.33	25.00	20.00	14.29	10.00	5.00	3.33	2.50
	1/x (mass)	55.98	37.26	27.93	22.32	15.91	11.10	5.49	3.61	2.68
	kg GTW	1.44	0.96	0.72	0.57	0.41	0.29	0.14	0.09	0.07
Flare	IPT Flare	0.57	0.38	0.28	0.22	0.16	0.11	0.05	0.03	0.02
	Total	0.62	0.43	0.34	0.28	0.22	0.17	0.11	0.09	0.08
	Total Eqn SI-S11	0.62	0.43	0.34	0.28	0.22	0.17	0.11	0.09	0.08
	Theoretical Total (slope*1/x+intercept)	0.62	0.43	0.34	0.28	0.22	0.17	0.11	0.09	0.08
Co-Gen	IPT Co-G	0.42	0.42	0.31	0.25	0.18	0.12	0.06	0.04	0.03
	Total	0.48	0.34	0.27	0.22	0.18	0.14	0.10	0.08	0.07
	Total Eqn SI-S11	0.48	0.48	0.37	0.31	0.24	0.18	0.12	0.09	0.08
	Theoretical Total (slope*1/x+intercept)	0.47	0.33	0.26	0.22	0.17	0.14	0.10	0.08	0.08
W/O WM	IPT w/o	0.033	0.022	0.017	0.013	0.009	0.007	0.003	0.002	0.002
	Total	0.090	0.079	0.074	0.070	0.067	0.064	0.060	0.059	0.059
	Total Eqn SI-S11	0.090	0.079	0.073	0.070	0.066	0.063	0.060	0.059	0.058
	Theoretical Total (slope*1/x+intercept)	0.090	0.079	0.074	0.070	0.067	0.064	0.060	0.059	0.059

IVO	IFP	phi	density GTW
0.04	0.02	1.03	1.11

Table SI-S34. Sulfur Oxide Model Fitting Data

	x (vol)	2%	3%	4%	5%	7%	10%	20%	30%	40%
	1/x (vol)	50.00	33.33	25.00	20.00	14.29	10.00	5.00	3.33	2.50
	1/x (mass)	55.98	37.26	27.93	22.32	15.91	11.10	5.49	3.61	2.68
	kg GTW	1.44	0.96	0.72	0.57	0.41	0.29	0.14	0.09	0.07
Flare	IPT Flare	0.07	0.05	0.04	0.03	0.02	0.01	0.01	0.00	0.00
	Total	0.08	0.06	0.05	0.04	0.03	0.02	0.02	0.01	0.01
	Total Eqn SI-S11	0.08	0.06	0.05	0.04	0.03	0.02	0.02	0.01	0.01
	Theoretical Total (slope*1/x+intercept)	0.08	0.06	0.05	0.04	0.03	0.02	0.02	0.01	0.01
Co-Gen	IPT Co-G	-0.24	0.23	0.17	0.14	0.10	0.07	0.03	0.02	0.02
	Total	-0.23	-0.15	-0.11	-0.09	-0.06	-0.04	-0.02	-0.01	0.00
	Total Eqn SI-S11	-0.23	0.24	0.18	0.15	0.11	0.08	0.04	0.03	0.02
	Theoretical Total (slope*1/x+intercept)	-0.23	-0.15	-0.11	-0.09	-0.06	-0.04	-0.02	-0.01	0.00
W/O WM	IPT w/o	0.006	0.004	0.003	0.003	0.002	0.002	0.001	0.001	0.001
	Total	0.015	0.013	0.012	0.012	0.011	0.011	0.010	0.010	0.010
	Total Eqn SI-S11	0.015	0.013	0.012	0.012	0.011	0.011	0.010	0.010	0.010
	Theoretical Total (slope*1/x+intercept)	0.015	0.013	0.012	0.012	0.011	0.011	0.010	0.010	0.010

IVO	IFP	phi	density GTW
0.001	0.008	1.03	1.11

The table below shows the slopes and intercepts used in the analysis.

Table SI-S35. Equation Slope and Intercept for Model Fitting

	Flaring		**Co-Generation**		**w/o WM**	
	slope	intercept	slope	intercept	slope	intercept
GWP_{100}	4.1	18	2.8	18	0.6	19
CED	0.028	0.28	0.014	0.28	0.010	0.28
CO	0.0026	0.075	0.0025	0.075	0.00042	0.075012
PM	0.00068	0.0033	0.00018	0.0033	0.000035	0.0036
NOx	0.011	0.055	0.0084	0.054	0.00066	0.057
SOx	0.0015	0.0089	-0.0047	0.0082	0.00011	0.0097

Where,

Slope = (y = Total, x = 1/x)*density

Intercept = (y = Total, x = 1/x)

Monte Carlo Results

The statistical results of the distributions and Monte Carlo trials are summarized in Table SI-S12; these results include mean, median, standard deviation, minimum, maximum, 10% confidence and 90% confidence. For all data, the percentage of trials that were less than or equal to soybean-biodiesel and low sulfur diesel are shown.

Table SI-S36. Statistical Data from Monte Carlo Simulation Environmental Impacts of GTW-Biodiesel

	Mean	Median	Std Dev	Min	Max	10th Percentile	90th Percentile	<= Soy	<= LSD
Lognormal Distribution, *%Lipids*									
Raw GTW	5%	2%	7%	0.15%	64%	0%	11%		
Dewatered GTW	29%	27%	14%	3%	65%	12%	49%		
GWP_{100}, *g-CO_2-eq/MJ-Fuel*									
Raw GTW w/ Flare	352.10	197.86	418.76	24.64	2719.69	54.86	851.33	0%	24%
Raw GTW w/ Co-Generation	249.79	142.75	290.60	22.54	1892.80	43.51	596.24	1%	34%
Raw GTW w/o WM	69.57	46.17	63.51	19.90	428.67	24.49	145.29	12%	80%
Dewatered GTW w/ Flare	37.15	33.68	11.85	24.56	156.52	26.55	51.54	2%	99%
Dewatered GTW w/ Co-Generation	31.22	28.81	8.22	22.49	114.06	23.87	41.21	20%	100%
Dewatered GTW w/o WM	21.80	21.27	1.80	19.89	39.90	20.19	23.98	95%	100%
Fossil CED, *MJ/MJ-Fuel*									
Raw GTW w/ Flare	2.59	1.52	2.90	0.32	18.99	0.53	6.05	0%	41%
Raw GTW w/ Co-Generation	1.41	0.88	1.42	0.30	9.41	0.40	3.09	0%	63%

Raw GTW w/o WM	1.10	0.72	1.02	0.30	6.88	0.37	2.32	0%	73%
Dewatered GTW w/ Flare	0.41	0.39	0.08	0.32	1.24	0.34	0.51	0%	100%
Dewatered GTW w/ Co-Generation	0.34	0.33	0.04	0.30	0.74	0.30	0.39	0%	100%
Dewatered GTW w/o WM	0.33	0.32	0.03	0.30	0.62	0.30	0.36	0%	100%
Carbon Monoxide, *g-CO/MJ-Fuel*									0%
Raw GTW w/ Flare	0.29	0.19	0.26	0.08	1.78	0.10	0.60	3%	34%
Raw GTW w/ Co-Generation	0.28	0.19	0.26	0.08	1.74	0.10	0.59	3%	34%
Raw GTW w/o WM	0.11	0.09	0.04	0.08	0.35	0.08	0.16	31%	86%
Dewatered GTW w/ Flare	0.09	0.08	0.01	0.08	0.16	0.08	0.10	54%	100%
Dewatered GTW w/ Co-Generation	0.09	0.08	0.01	0.08	0.16	0.08	0.10	55%	100%
Dewatered GTW w/o WM	0.08	0.08	0.00	0.08	0.09	0.08	0.08	100%	100%
Particulate Matter, *g-PM/MJ-Fuel*									
Raw GTW w/ Flare	0.06	0.03	0.07	0.00	0.45	0.01	0.14	2%	3%
Raw GTW w/ Co-Generation	0.02	0.01	0.02	0.00	0.12	0.00	0.04	18%	19%
Raw GTW w/o WM	0.01	0.01	0.00	0.00	0.03	0.00	0.01	61%	64%
Dewatered GTW w/ Flare	0.01	0.01	0.00	0.00	0.03	0.00	0.01	47%	54%
Dewatered GTW w/ Co-Generation	0.00	0.00	0.00	0.00	0.01	0.00	0.00	98%	99%
Dewatered GTW w/o WM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100%	100%
Mono-Nitrogen Oxides, *g-NOx/MJ-Fuel*									
Raw GTW w/ Flare	0.97	0.55	1.15	0.07	7.47	0.16	2.34	1%	0%
Raw GTW w/ Co-Generation	0.74	0.42	0.86	0.07	5.58	0.13	1.76	1%	0%

Raw GTW w/o WM	0.11	0.09	0.07	0.06	0.49	0.06	0.19	42%	29%
Dewatered GTW w/ Flare	0.11	0.10	0.03	0.07	0.43	0.08	0.15	15%	0%
Dewatered GTW w/ Co-Generation	0.09	0.09	0.02	0.07	0.34	0.07	0.12	34%	11%
Dewatered GTW w/o WM	0.06	0.06	0.00	0.06	0.08	0.06	0.06	100%	100%
Sulfur Oxides, *g-SOx/MJ-Fuel*									
Raw GTW w/ Flare	0.13	0.07	0.15	0.01	0.98	0.02	0.31	25%	10%
Raw GTW w/ Co-Generation	-0.37	-0.20	0.48	-3.08	0.00	-0.94	-0.03	100%	100%
Raw GTW w/o WM	0.02	0.01	0.01	0.01	0.08	0.01	0.03	93%	79%
Dewatered GTW w/ Flare	0.02	0.01	0.00	0.01	0.06	0.01	0.02	100%	93%
Dewatered GTW w/ Co-Generation	-0.01	-0.01	0.01	-0.15	0.00	-0.03	0.00	100%	100%
Dewatered GTW w/o WM	0.01	0.01	0.00	0.01	0.01	0.01	0.01	100%	100%

Comparison to LCA for GTW-biodiesel production by Tu and McDonnell[12]

The GWP_{100} and CED_{Fossil} data for the comparison below was estimated from Figure 6 and 7 in the Tu and McDonnell paper. The lower heating value of 125.2 MJ/gal[8] was used to convert the Tu and McDonnell data to a MJ of fuel basis. The system boundaries between the analyses are similar; however, this work (Hums et al) contains the combustion of the fuel in a vehicle. The without anaerobic digestion scenario includes the transportation of waste solids to a landfill; however the analysis does not include the landfill gas emissions.

Table SI-S37. Comparison of LCA results for biodiesel produced from GTW

Author	Waste Scenario	GWP_{100} gCO_2eq/MJ-fuel avg	5%	95%	CED_{Fossil} MJ/MJ-fuel avg	5%	95%
Tu/McDonnell	w/Anaerobic Digestion	12	12	20	0.34	0.30	4.39
Tu/McDonnell	w/o Anaerobic Digestion	40	20	987	0.60	0.36	13.58
Hums et al	Raw GTW: Landfill Flare	352	42	1255	2.59	0.44	8.85
Hums et al	Raw GTW: Landfill Co-gen	250	34	877	1.41	0.36	4.46
Hums et al	Raw GTW: No Waste Treatment	37	26	59	1.10	0.34	3.30
Hums et al	Dewatered GTW: Landfill Flare	37	26	59	0.41	0.33	0.56
Hums et al	Dewatered GTW: Landfill Co-gen	31	23	47	0.34	0.30	0.42
Hums et al	Dewatered GTW No Waste Treatment	22	20	25	0.33	0.30	0.38

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