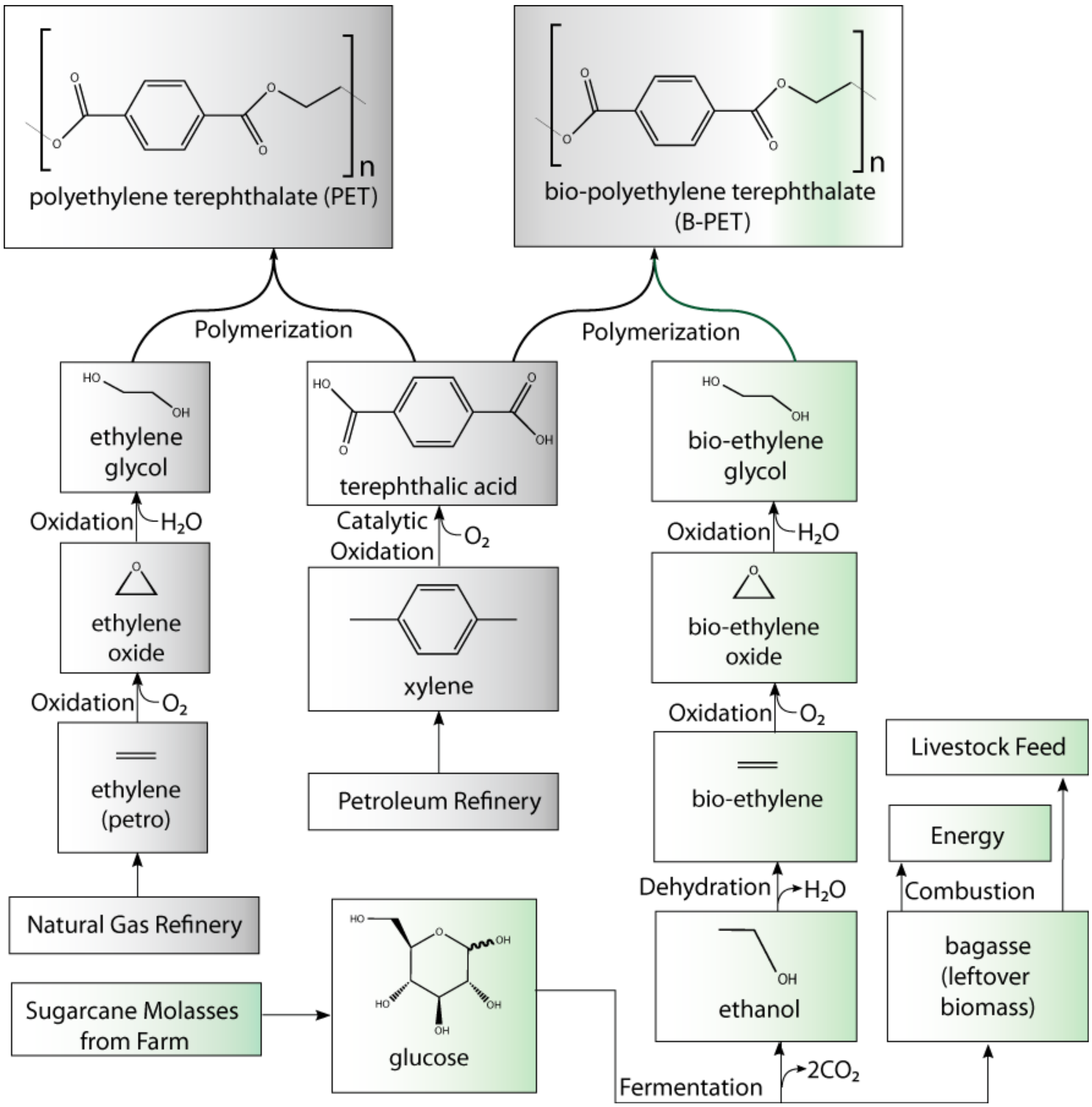
LIFE CYCLE ASSESSMENT AND GREEN DESIGN: AN ASSESSMENT OF GREEN DESIGN IN A CASE STUDY OF PLASTICS

This thesis uses life cycle assessment to evaluate the effectiveness of current green design principles.

This is the process for making PET and B-PET



For the production of PET, ethylene glycol is produced from the ethylene produced through Natural gas refinery. For B-PET, ethylene glycol is produced from the ethylene produced through Sugarcane molasses.

The process of replacing PET with B-PET results in intended environmental benefit as well as an unintended environmental detriment. In the case of B-PET, it reduces the usage of petroleum products. According to several studies, it is evident that there is a 12% reduction in non-renewable energy usage in the case of B-PET. Still, fertilizer and pesticides used to grow crops for biomass cause a significant effect on the environment.

Some of the relevant results from life cycle impact assessments in The BREW Project and Brehmer were given in the below table.

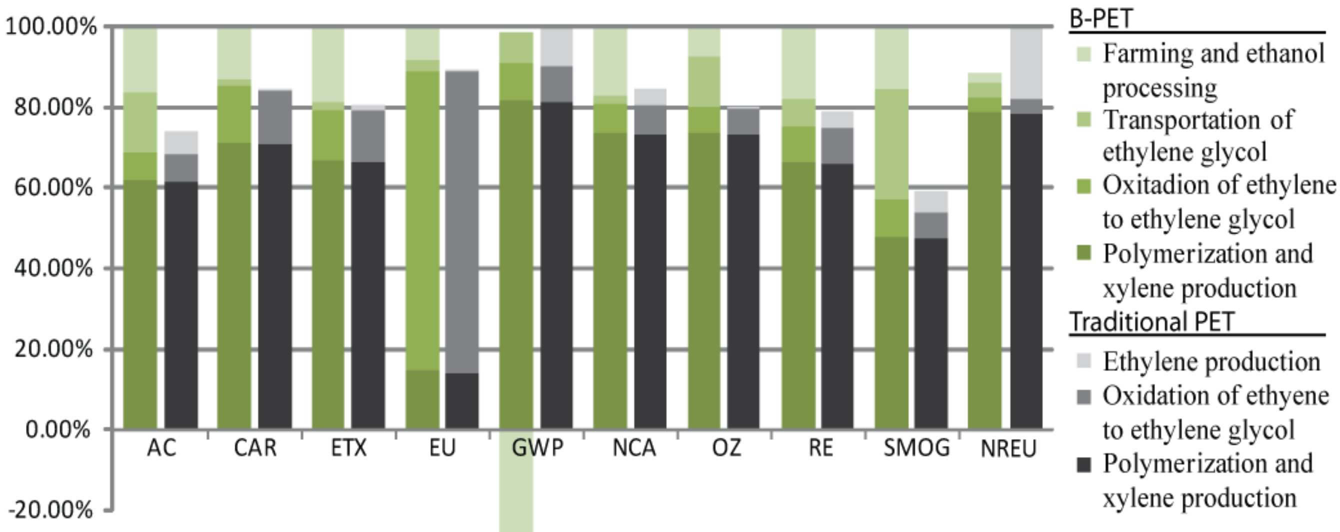
Chemical Product	Reference Product	Study	Non-renewable Energy Savings MJ/kg Chemical	Global Warming Potential Savings kg CO_2/kg
Ethanol	LHVof Gasoline	Brehmer	25-50	N/A
Ethanol	Petro Ethanol Production	BREW	65-85	N/A
Ethanol	Nothing	BREW	13.7, 18.7	N/A
Bio-Ethylene	Ethylene, Petroleum	Brehmer	90	N/A
Bio-Ethylene	Ethylene, Petroleum	BREW	95	1.9
Bio-Ethylene	Nothing	BREW	29.9	N/A

Neither the BREW Project nor the Brehmer study reports environmental impacts other than global warming potential and non-renewable energy use.

For all the life cycle assessments in this thesis, SimaPro life cycle assessment software and the ecoinvent database were used. The goal of this life cycle assessment is twofold, to compare the environmental impacts of PET and B-PET and to include the life cycle impact assessment of B-PET in a later study assessing the efficacy of green design principles in packaging plastics. The functional unit of comparison between PET and B-PET is taken as volum for this thesis, and the boundaries of this life cycle assessment are taken as cradle-to-gate, which means it includes only the environmental impacts from the extraction of raw materials and the production of a product. Using the SimaPro life cycle assessment software, Explicit processes used for each stage of the B-PET life cycle inventory are shown in the table below.

Process	Database	Process Name and Edits
B-PET polymerization	ecoinvent	Polyethylene terephthalate, granulate, bottle grade, at plant/RER U **Edit:** 15,000 miles of transport added; ethylene glycol input replaced with bio-ethylene glycol
Transport of ethylene glycol to US	ecoinvent	Transport, barge tanker/RER U
bio-ethylene glycol production	ecoinvent	ethylene glycol, at plant/RER U **Edit**: ethylene oxide input replaced with bio-ethylene oxide
bio-ethylene oxide production	ecoinvent	ethylene oxide, at plant/kg/RER **Edit**: ethylene input replaced with bio-ethylene
bio-ethylene production (two emissions scenario)	literature	ethylene, at plant, kg. from molasses ethanol; two emissions scenarios are entered as described in Section 2.2.2.1
ethanol production (High and Low emissions scenario)	ecoinvent	Ethanol, 95% in H2O, from sugarcane molasses, at sugar refinery/BR U **Edit**: high and low emissions estimates described in Section 2.2.2.2

Through the comparative study of PET and B-PET, we came to notice that B-PET is the most significant contributor in all impact categories except for global warming potential (GWP) and non-renewable energy use (NREU). The NREU benefit for the B-PET is because, in the case of B-PET, we were using the ethylene produced through sugar molasses contrary to the Natural gas refinery in the case of PET. The GWP benefit of B-PET is due to the CO2 sequestration achieved during the growth of sugarcane during farming, represented by an extension of the GWP bar below the 0% line. Except for these two parameters, there is a drastic increase for B-PET for all the remaining parameters. The table below represents it.



All the green design Principles were reduced into themes, which are quantitatively or qualitatively evaluated by metrics. The table below shows each associated metric with its principal.

Theme	Metric	Principles Referenced
Avoid Waste	Atom Economy	GC 2, A1, A3
Material Efficiency	Density	GE 8, GE4
Avoid Hazardous Materials/Pollution	TRACI Health and Ecotoxicity Impacts	GC 3-5, 11; GE 2
Maximize Energy Efficiency	Total Energy Demand	GC 6, A 10, GE 3,4, 10
Use of Renewable Sources	Percent from Renewable Soruces	GC 7, GE 12
Use Local Sources	Feedstock Distance	GE 10
Design products for recycle	Percent Recycled	GE 3,6, 9, and 11
Design to Degrade	Biodegradability	GC 10
Cost Efficiency	Price	GE 9

A decision matrix was used to create two single-value metrics for each polymer, one evaluating each polymer for life cycle environmental impacts and the other evaluating each polymer for adherence to green design principles. Results from both assessments are normalized to the average across all polymers. Various polymers were ranked concerning adherence to green design principles or Life cycle Assessment using this decision matrix.

Based on these green design metrics, various polymers were evaluated. The results are as shown below.

Material	Overall Atom Economy (%)	Carcinogens (kg benz. eq /L)	Non-Carcinogens (kg tolu. eq/ L)	Respiratory Effects (kg PM2.5 eq/ L)	Ecotoxicity (kg benz. eq/ L)	Cumulative Energy Demand (MJ eq/ L)	%Renewable Material	Distance of Feedstocks	% Recovery	Biodegradeable	Price (USD/ L)
PET	80%	$1.1x10^{-2}$	62.9	$4.9x10^{-3}$	5.72	123.8	0%	Intern.	18%	N/A	4.13
B-PET	62%	$1.3x10^{-2}$	72.7	$5.7x10^{-3}$	6.98	146.2	15%	Intern.	18%	N/A	4.13
PVC	55%	$1.1x10^{-2}$	31.7	$7.3x10^{-3}$	0.40	82.9	0%	Intern.	0%	N/A	4.02
PLA-NW	80%	$6.1x10^{-2}$	22.5	$1.2x10^{-3}$	1.21	79.4	100%	Region.	0%	Indus.	4.66
PLA-G	80%	$8.4x10^{-3}$	37.5	$3.1x10^{-3}$	4.31	98.3	100%	Region.	0%	Indus.	4.66
PHA-G	48%	$7.2x10^{-3}$	30.0	$3.1x10^{-3}$	2.76	91.5	100%	Region.	0%	Backyard	6.20
PHA-S	48%	$1.1x10^{-2}$	30.0	$2.1x10^{-3}$	2.76	91.5	100%	Region.	0%	Backyard	6.20
HDPE	100%	$6.5x10^{-4}$	18.7	$1.3x10^{-3}$	0.65	73.4	0%	Intern.	10%	N/A	1.52
LDPE	100%	$6.9x10^{-4}$	19.6	$1.5x10^{-3}$	0.82	72.3	0%	Intern.	5%	N/A	1.58
GPPS	98%	$3.2x10^{-3}$	92.7	$2.5x10^{-3}$	1.79	92.2	0%	Intern.	1%	N/A	2.35
PC	59%	$3.0x10^{-3}$	85.6	$9.5x10^{-3}$	3.13	128.9	0%	Intern.	0%	N/A	5.25
PP	100%	$5.8x10^{-4}$	16.8	$1.2x10^{-3}$	0.54	67.6	0%	Intern.	0%	N/A	1.78

Using these metrics, based on the decision tree, ranking for each of the polymers was given.

Material	Green Design Rank	LCA Rank
PLA (NatureWorks)	1	6
PHA (Utilizing Stover)	2	4
PHA (General)	2	8
PLA (General)	4	9
High Density Polyethylene	5	2
Polyethylene Terephthalate	6	10
Low Density Polyethylene	7	3
Bio-polyethylene Terephthalate	8	12
Polypropylene	9	1
General Purpose Polystyrene	10	5
Polyvinyl chloride	11	7
Polycarbonate	12	11

From these rankings, we can understand that Biodegradable polymers sit on top of the green design rankings, mainly owing to their low energy demand, use of renewable materials, and biodegradability. Except for PET, petroleum polymers exhibit lower life cycle environmental impacts as they adhere more strictly to green design principles. While biopolymers exhibit a range of life cycle environmental impacts, their rank based on green design principles does not vary widely, except for B-PET.

As shown through the LCA results, a decrease in fossil fuel use from switching to renewable resources results in significant increases in other impact categories such as eutrophication, human health impacts, and eco-toxicity. These impacts result both from fertilizer use, pesticide use, and land-use change required for agriculture production, as well as from the fermentation and other chemical processing required to turn the biomaterial into useful plastic.