Life Cycle Assessment of Reusable and Single-use Plastic Bags in California

January 2011

Produced under contract by:

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Chico Research Foundation*

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Funding provided by

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Acknowledgements

The author would like to acknowledge and thank Keep California Beautiful non-profit organization for providing funding for the research project. The author would also like to acknowledge Mr. Bob Boughton of CA Department of Toxic Substances and Control (DTSC), and Mr. Jim Hill of California Department of Resources Recycling and Recovery (CalRecycle) for comments and suggestions for the report.

Glossary

BBL	Barrel: a commercial unit of volume that can be used to measure liquids and is defined in the United States as representing 31.5 gallons
CO_2 eq	Carbon dioxide equivalent emissions
EOL	End-of-Life
GHG	Green House Gases including CO_2, methane, water vapor, nitrous oxide, and ozone
GSM	Grams per square meter
GJ	Giga joules of energy
MJ	Mega joules of energy
HDPE	High density polyethylene plastic
LDPE	Low density polyethylene plastic
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
PCR	Post Consumer Resin
PE	Polyethylene plastic
PP	Polypropylene plastic

Executive Summary

Reusable plastic bags can have lower environmental impacts than single-use polyethylene plastic grocery bags. Keep California Beautiful non-profit environmental group funded an environmental impact study on the use of reusable plastic bags in California with California State University, Chico. Life cycle assessment (LCA) tools were used to calculate the energy usage, water usage, green house gas emissions, and waste generation for reusable PP and LDPE plastic bags as compared to single-use plastic and paper bags.

Three LCA studies from around the world are used for comparison. The first study, from Boustead Consulting and Associates in the United States, found that single-use plastic bags require less energy, fossil fuel, and water than an equivalent amount of paper bags. Also, single-use plastic bags generate less solid waste, acid rain, and green house gases than paper bags. The LCA study did not consider the environmental impacts of reusable bags. The second study from Hyder Consulting Pty Ltd of Victoria Australia, found that reusable polypropylene bags had the lower environmental impacts than reusable cotton bags, single-use plastic bags, and single-use paper bags. The Australian LCA study did not consider using recycled plastic to produce reusable bags. The third study from Scottish Executive of Edinburgh, Scotland, found that reusable plastic bags, that are used 20 times or more, have less environmental impacts than all other types of lightweight carrier bags, including, paper, plastic, or degradable plastic. The Scottish report found that the reusable bags are not likely be recycled. The Scottish LCA study did not consider use of recycled plastics in the production of reusable plastic bags.

The CSU, Chico California LCA study expanded the three LCA studies to include reusable polypropylene (PP), reusable recycled polyethylene (PE), single-use polyethylene, and single-use paper bags. The Chico, California LCA study modified the Boustead data to include reusable polypropylene plastic bag, reusable polyethylene plastic bag, and recycled polyethylene plastics in PE reusable bags. The LCA study also included data from the Australian LCA on the number of uses (52) per year and the number of bags (10) used in a weekly trip. The Chico California LCA study used the environmental indicator table for plastic and paper bags from the Scottish report. The Chico California LCA study also included the environmental effects of washing 20% of the reusable bags to remove harmful bacteria that can grow when the bags are used to carry meats and some dairy products. The Chico California LCA report found that reusable bags have lower environmental impacts than single-use plastic bags after they are used 8 times. Reusable plastic bags use less energy, emit less pollution, release less green house gases, and create less solid waste than single-use plastic bags and single-use paper bags when used more than 8 times. However, non-woven PP reusable bags will use four times more water than the equivalent single-use plastic bags after 52 uses, or 1-year of weekly uses. Recycled polyethylene reusable bags have the least amount of energy use, green house gas emissions, and solid waste generation.

Currently, PP non-woven bags could not be produced from PCR due to the lack of recycling infrastructure in the Unites States. However, PE reusable bags could be made with PCR in concentrations of 40% to 100% PCR. Likewise, single-use plastic bags can be produced with 40% to 100% PCR. The use of PCR can offer significant environmental benefits for reduced carbon dioxide emissions, reduced solid waste, and reduced pollution.

Sustainable plastic bags also must minimize the exposure to consumers of toxins, including heavy metals. In January of 2006, California laws went into effect that limit the amount of regulated metals, including cadmium and lead, in product packaging. Unfortunately, several reusable polypropylene bags had high levels of heavy metals, also known as, regulated metals. As a comparison, heavy metals were not found in reusable polyethylene (PE) bags or single-use polyethylene plastic bags. Regulated metals were identified with a Bruker AXS S2 Ranger XRF testing machine. The XRF machine can identify the presence of metals in the plastic sample but does not measure the concentration of the metals. The XRF identified qualitatively the presence of regulated metals but does not provide a quantitative analysis. Cadmium was found in 35% of the non-woven PP bags. Trace amounts of lead were found in 20% of the reusable PP non woven bags. No heavy metals were found in reusable polyethylene plastic bags. Most of the regulated metals were identified in the plastic insert at the bottom of the bag. The US standard allows the following amounts of regulated metals: lead (150 mg/kg), cadmium (17 mg/kg), copper (750 mg/kg), nickel 210 mg/kg), zinc (1400 mg/kg), and mercury (8.5 mg/kg).[1] Further wet-chemistry methods can be done in the future to determine the concentrations of the regulated metals, though the work is outside the scope of this research project.

The research report was evaluated by personnel from the Department of Toxic Substances and Control (DTSC) and the California Department of Resources Recycling and Recovery (CalRecycle) organizations in Sacramento, CA. The research report was evaluated by those two organizations for clarity and accuracy for life cycle assessment standards and protocols. The report was changed to include more accurate LCA assumptions and criteria. The report was modified to provide more transparent functional units and better comparison criteria. The report was well received by both organizations and was thought to provide relevant data for the sustainable evaluations of plastic bags and reusable bags.

Introduction

Plastic bags made from polyethylene plastics have become a perceived environmental nuisance. Recently, reusable plastic bags are available to replace single-use plastic grocery bags. Also, single-use paper bags can be used instead of single-use plastic bags or reusable plastic bags. The effects that these bags have on the environment are important concerns for society of today. The environmental impacts can be measured by which of these bag choices produces the least amount of Green House Gases (GHG), the least amount of pollution, the least amount of solid waste, and requires the least amount of water. Also, consumer choices involving the number of times that the reusable bags are used to replace single-use plastic bags can result in different environmental consequences. The environmental impacts of single-use versus reusable bags are evaluated using Life Cycle Assessment (LCA) tools.

Keep California Beautiful of Sacramento, CA initiated a research project with the Institute for Sustainable Development at California State University, Chico to compare the environmental impact of reusable recycled polyethylene plastic bags, as compared to reusable non-woven polypropylene (PP) plastic bags and single-use HDPE plastic grocery bags. The reusable PP bags are imported from China and the reusable polyethylene bags are produced in California. Paper bags were used for comparison purposes though outside the scope of the research project. The research project scope did not include reusable cotton bags. The research project will encompass three environmental impact areas for plastic bags:

- Life Cycle Assessment (LCA),
- Regulated metal content in the plastic bags, and
- Environmentally sustainable evaluations based on environmental specialists.

Project Management

The research project can be broken into three phases, as displayed in the Appendix, which includes, life cycle assessment, regulated metal testing, and environmental sustainable evaluations of he LCA report. The first phase will provide a LCA report for the plastic bag alternatives and include life cycle inventory and assessment of reusable plastics bags, single-use plastic bags, and single-use paper bags. The second phase of the research will provide a regulated metals testing report for lead and cadmium concentrations in the plastic bags. The third phase of the research provides evaluations of the methodology and format of the report from California Department of Resources Recycling and Recovery (CalRecycle) and California Department of Toxic Substances and Control (DTSC) organizations.

Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA), also known as “cradle-to-grave” analysis, tracks the environmental impact of products from the creation of raw materials, to the fabrication and use of the product, and finally to the disposal or reuse of the product. The LCA process includes a Life Cycle Inventory (LCI) of all of the inputs of making a product and all of the outputs or wastes of the production, use, and disposal of the product. The LCA process, described in Figure 1, usually involves fours steps, including: Goal and Scope, Life Cycle Inventory, Life Cycle Impact Assessment, and Interpretation.

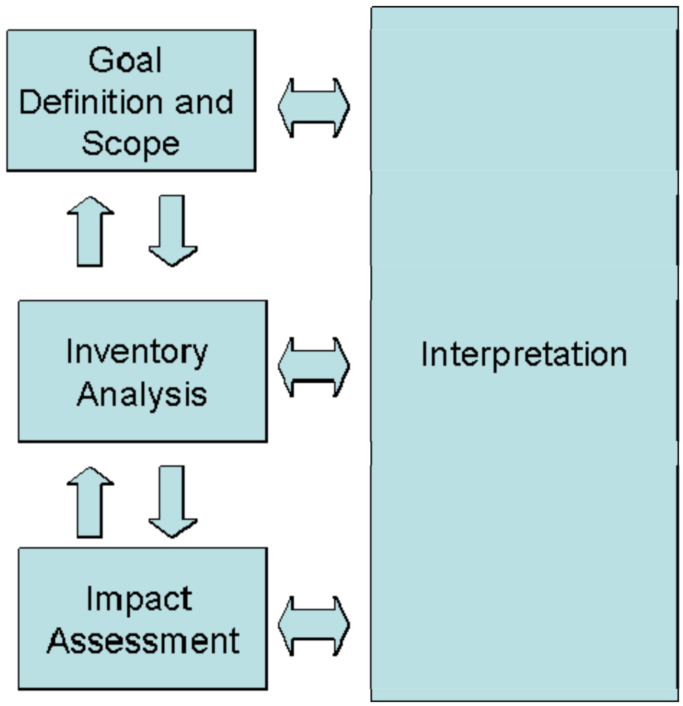

Figure 1. Phases of a Life Cycle Assessment

The goal of our LCA study is to compare the environmental impacts of reusable plastic bags and single-use plastic grocery bags. The scope of the study will compare equal carrying capacity of the different types of plastic bags. The functional unit is the number of bags that a consumer uses in one year. The number of single-use plastic and paper bags are compared with the number of reusable plastic bags in one year. The second step of the LCA process, Life Cycle Inventory, tabulates the energy, fuel, water, and material inputs needed to produce and use plastic and paper bags and also lists the waste that is created when the plastic and paper bags are made, used, and thrown away.

The third step of the LCA process, Life Cycle Impact Assessment, takes the inventory of energy, fuel, water, materials, pollution, and waste and rearranges them in terms of the scope from the first step, to provide a comparison of environmental measures on a per unit basis. The fourth step of the LCA process involves interpreting the results from the Life Cycle Impact Assessment step and suggesting the most environmentally desirable product. The research will compare the environmental impacts of reusable plastic bags and single-use plastic and paper bags.

ISO Standards on LCA

The International Organization for Standardization (ISO) published standards for Life Cycle Assessment (LCA). LCA compares environmental performance of products in terms of greenhouse gas emissions, pollution generation, waste generation, energy consumption, water consumption, and other resource consumption. LCA compares these items in terms of a measurable quantity of the products. The ISO standards (ISO 14040and 14044) [2, 3] requires four steps, including, goal and scope, inventory analysis, life cycle assessment, and interpretation. ISO 14040 provides an overview of the life cycle assessment practice, applications and limitations. ISO 14044 provides requirements and guidelines for LCA and provides a guide to prepare, conduct, and evaluate a LCA. Most LCA are developed with dedicated software packages. [4] According to the survey from 2006, 58% of respondents used GaBi Software,[5] developed by PE International, 31% used SimaPro,[6] developed by Pré Consultants, and 11% a series of other tools.

Literature Review of LCA on Plastic Bags

Environmental aspects of plastic and paper bags have been analyzed by several researchers. Three LCA studies are summarized in this report. The three studies conducted the LCA per ISO standards. The first study, from Boustead Consulting and Associates, compares the LCA of single-use plastic bags with single-use paper. The "cradle to gate" analysis included the environmental impacts of plastic bags from the creation of the plastic from raw materials to plastic pellets. It is not considered "cradle to grave" analysis since it did not include consumer use, transportation, nor end-of-life (EOF) effects on the environment. The second study from Hyder Consulting Pty Ltd of Victoria Australia, is a cradle to grave analysis that includes EOF and transportation. It compares the LCA of single-use plastic and paper bags with reusable plastic and cotton bags. The third study from Scottish Executive of Edinburgh, Scotland, compares the effects of a bag tax on consumers and the LCA of single-use plastic, paper, and compostable bags versus reusable plastic bags. In the following report the numbers presented in tables are rounded to reflect average values in the reports.

U.S. LCA of Single-use Plastic Bags

The Boustead report is comprehensive in its evaluation of the life cycle assessments of paper and plastic bags. [7] The Boustead report was funded by the American Chemical Council Plastics Division. The information on the compostable bag was incomplete and not included in our LCA study. The Boustead report compares Life Cycle Assessments of 1500 plastic bags with 1000 paper bags and 1000 compostable plastic bags. The 1.5:1 ratio was determined from a Franklin report from 1990 that pointed out that consumer bagging behavior illustrates that plastic to paper use ranged from 1:1 all the way to 3:1, depending on the situation. [8] The information for the LCI was taken from Boustead database and from information from plastic suppliers. Plastic bags require less energy, fossil fuel, and water than an equivalent amount of paper bags. Also, plastic bags generate less solid waste, acid rain, and green house gases than paper bags. Paper bags weigh significantly more than the traditional thin plastic bag and use a water-slurry process to manufacture the paper bags. The results are listed in Table 1. Paper bags can use higher recycled content, but the study selected 30% recycled content.

The Boustead report provides an excellent LCA analysis but failed to consider recycled content for plastics and the effects of using reusable bags instead of single-use bags. The report uses 30% recycled paper content which might be low. Other paper products have higher recycled content. Further research studies can determine the significance of using higher recycled content.

Table 1. Life cycle inventory for 1500 plastic bags and 1000 paper bags

	1500 Plastic Bag industry average	**1000 Paper bag (30% recycled)**
Total Energy, MJ	763	2,622
Fossil fuel used, kg	15	23
Municipal solid waste, kg	7	34
Greenhouse emissions, Tonnes CO_2	0.04	0.08
Fresh water usage, gal	58	1004
Mass, g, per paper	6	52

Australian LCA of Reusable Plastic Bags

The second LCA report on plastic bags is from Consulting Pty Ltd of Victoria Australia, which compares the environmental impacts of shopping bag alternatives for carrying goods in Australia.[9] The Australian report was funded by Sustainability Victoria, which was created from the Sustainability Victoria Act 2005. The LCA data in the report was updated from an earlier LCA report from an Australian University of Design for RMIT in 2002 with more accurate values of recycling rates, bag mass, and bag capacity. The HDPE plastic grocery bag was compared with bags made from paper, compostable plastics, cotton, and polypropylene. The cotton and polypropylene bags were reusable bags. The capacity of the bags was similar and able to carry 70 grocery items home from a grocery store for 52 weeks. The Australian study assumed that each trip would require 10 plastic bags. Some of the assumptions in the study are listed in Table 2. Cotton bags can be used more than two years if not damaged from use or from washing cycles. The study assumed two-year expected life to be consistent with reusable PP plastic bag, even though a cotton reusable bag may last longer.

Table 2. Assumptions for the 2007 Australian study

Bag Material	Mass, g	Expected Life	Bags per year
HDPE Single-use	7	Single-use	520
Kraft paper single-use bag	43	Single-use	520
Kraft paper reusable bag	43	Two trips	260
PP reusable bag	95	2-years (104 trips)	5
Cotton calico reusable bag	85	2-years (104 trips)	5

The Australian study calculated the environmental effects of transportation of the different bags with plastic bags being imported from Hong Kong and paper bags being manufactured in Australia. The transportation environmental impacts were negligible. The report also considered End-of-Life scenarios for the plastic and paper bags and whether the bags were recycled, sent to landfill, composted, discarded as litter, or reused as trash liner. The results show that approximately 75% of single-use plastic bags were sent to landfill, 19% reused as trash liners, 5% recycled, and 0.5% discarded as litter. The plastic bags used as trash liners will be sent to landfill with the trash, thus, the total sent to landfill should be 94%. A recent Canadian study found that 40 to 50% of plastic grocery bags are reused to contain garbage or recyclables to the waste and recycling containers for curbside pickup.[10] The reuse of single-use plastic and paper bags for trash liners provides an environmental benefit for carbon offsets by being a substitute for trash bags made from plastic or paper.

The End-of-Life scenarios for other bags include the fact that approximately 99.5% of reusable PP plastic bags are sent to landfill and 0.5% of the bags are discarded as litter. Approximately 99.5% of Kraft paper bags are sent to landfill and 0.5% of the bags are discarded as litter. The paper bags can contain recycled content and provide an environmental benefit. Paper bags can be recycled if they are not contaminated with food. The recycling rate of paper bags is higher in CA than in Australia. Table 3 lists the End-of-Life assumptions. The Australian study assumed that the reusable bags would not be recycled because the volume of bags would not have high enough volume to create a market for them. The study also assumed that the single-use paper bags were sent to landfill as a trash container and not sent to industrial compost facilities.

Table 3. End-of-life assumptions in 2007 Australian Study

Bag Material	Landfill %	Recycled %	Litter %
HDPE Single-use	94.5	5	.5
Kraft paper single-use bag with 100% recycled content	99.5	0	.5
PP reusable bag	99.5	0	.5
Cotton calico reusable bag	99.5	0	.5

The Australian study used a LCA software called SimaPro 5.1 to assess the environmental impact of the carrier bags. The LCA analysis included production of raw materials, manufacturing of the bags, transportation of the bags to retailers, and disposal of the bags at the end-of life. Australian data is used for energy production, material production, transportation, recycling, and waste disposal.

The Australian study found that the reusable polypropylene bags had the least amount of environmental impact. The cotton reusable bag had low environmental impact except for high water usage. The results of the study are listed in Table 4 with relative ratings of 1 (Preferred) to 5 (Unacceptable)

Table 4. Environmental impact of grocery bags in Australia

Bag Material	Energy Consumption	GHG (CO_2 eq)	Material Consumption	Water Use	Disposal Options
PP reusable bag	1	1	1	1	Recycle at major super markets
Cotton calico reusable bag	1	1	1	5	No recycling, sent to landfill
HDPE Single-use	4	2	3	1	Recycle at major super markets
Kraft paper single-use bag	5	5	5	2	Reused as trash liner and sent to landfill

The report was a good evaluation of the importance of reusable bags. The report did not provide enough information on the assumptions of the data for the LCA. The numbers for water use seem low for Kraft paper and the recycling of PP reusable bag can be problematic for recyclers. Also, the reusable bag has a mass of over 90 g which is significantly higher than the single-use bag of 7g. The report though is limited by the different carrying capacities of the plastic and paper bags. The report does show the importance of using recycled plastics in the manufacture of single-use bags but does not show the use of recycled plastic for reusable bags. PP in the reusable bag is not recycled much in the United States (less than 1%) as compared to HDPE (30%). The report also did not include the environmental impacts of washing the reusable bags.

Scottish LCA of Reusable Plastic Bags

The third LCA report on plastic bags is from Scotland and the U.K. that studied the environmental effects of taxes on several plastic bag scenarios. [11] The Scottish report acknowledged the Scottish Waste Strategy Team, Carrier Bag Consortium, Convention of Scottish Local Authorities, Friends of the Earth Scotland, Scottish Retail Consortium, and The Scottish Environment Protection Agency for direction and support during the project. The report used LCA to evaluate the environmental effects of grocery bag consumer choices. The report found that assessing a tax would reduce the use and prevalence of plastic in the environment and that consumption of non-renewable energy, solid waste, greenhouse gas emissions, and eutrophication of lakes and rivers would be significantly less.

The assumptions of the Scottish report are listed in Table 5 including the mass of the bags, relative sizes compared to conventional polyethylene plastic bag, ability for material to be recycled, and the number of bags projected to be used in a year. The relative storage capacity is based on volume carrying bag capacity.

Table 5. LCA assumptions in Scottish report

Bag Material	Mass, g	Relative bag storage	Recyclable	Number of bags per year
HDPE Single-use	8	1	Yes	775 million
LDPE reusable bag	47	4	Yes	8 million
PP reusable non-woven bag	139	20	No	8 million
PP reusable woven bag	226	20	No	8 million
Kraft paper reusable bag	51	8	Yes	39 million

The Scottish report uses LCA data from a Carrefour French study from 2004. [12] The Carrefour LCA study examined energy, fuel, water and other resource requirements for production, manufacture, use, and disposal of several plastic bags. The study considered plastic grocery bags, reusable polyethylene bags, Kraft paper bags with recycled paper content, and compostable plastic bags. The Carrefour LCA study assessed the environmental impact of the energy use, fuel and other resource use, waste generation, GHG emissions, and pollutant emissions.

The results are summarized in Table 6 for eight environmental indicators with relative ratings of 1 (Preferred) to 5 (Unacceptable)

Table 6. Environmental indicators for plastic and paper bags in Scottish report

Indicator of environmental impact	Single-use HDPE plastic bag	Reusable LDPE plastic bag (2x)	Reusable LDPE plastic bag (20x)	Single-use paper bag
Non-renewable energy	1.0	1.4	.1	1.1
Water use	1.0	1.3	.1	4.0
GHG emissions	1.0	1.3	.1	3.3
Acid rain	1.0	1.5	.1	1.9
Ozone formation	1.0	.7	.1	1.3
Eutrophication	1.0	1.4	.1	14.0
Solid waste	1.0	1.4	.1	2.7

The report found that reusing plastic bags created comparably low environmental impact. The report found that most negative of the environmental impacts come from the production of the plastic pellets and paper from the raw materials in the first stage of manufacturing. The second manufacturing stage of conversion of the pellets and paper into plastic and paper products that are sent to retailers has less environmental impact but not negligible. The end-of life scenarios for grocery bags can have significant impact on the creation of solid waste in the environment.

Other environmental indicators include eutrophication and acid rain generation. The environmental effects on polyethylene and polypropylene reusable plastic bags would be similar due to the similar plastic chemistry and process to manufacture the bags. The Scottish report found that reusable bags have significantly less eutrophication and acid rain generation than single-use plastic or paper bags.

The results from the Scottish report demonstrate that reusable plastic bags have lower environmental impacts than all other types of lightweight carrier bags, including, paper, plastic, or degradable plastic. The report did not list environmental indicators of reusable polypropylene plastic bag. The report did not include the environmental impacts of washing the reusable bags. The report could go further by studying a reusable plastic bag made from recycled plastics. The reusable plastic bag made from recycled plastics will be compared to other single-use plastic bags using LCA.

CSU, Chico, California LCA on Reusable Plastic Bags

This report takes information from the three reports and investigates the environmental impacts of using recycled plastics for reusable plastic bags compared to single-use plastic and paper grocery bags. The plastic bag manufacturing data are based on averages of plastics bag manufacturers in the United States. California plastic bag manufacturers would have lower carbon footprints due to the sources of energy in California are more from natural gas, hydroelectric power, and solar than coal. The Australian and Scottish reports are based on consumer choices and waste management practices and not manufacturing. The Australian, Scottish, and U.S. LCA reports are consistent with then ISO standards for Life Cycle Assessment. Our report also investigates the environmental impacts of washing reusable bags and the resulting water usage that is required.

Table 7. Cradle-to-grave process steps for plastic bags

	Steps	Grocery bag: HDPE	PE Reusable PCR	PP non-woven
1	Produce plastic pellets from oil and natural gas	X	X	X
2	Ship pellet to converter	X	X	X
3	Convert pellet to film	X	X	X
4	Convert film to non-woven			X
5	Ship product to retail stores	X	X	X
6	Consumer uses bag first time	X	X	X
7	Consumer uses bag multiple times per year		X	X
8	Consumer washes 20% of the reusable bag weekly.		X	X
9	Consumer recycles plastic bag	X	X	
10	Consumer throws plastic in trash for landfill			X

In this report, the goal of the LCA is to compare the environmental impacts of reusable plastic bags and single-use plastic grocery bags. The scope of the study will be to compare equal carrying capacity of the different types of plastic bags as demonstrated in the three previous reports. In our case, 1500 single-use plastic bags will be compared with 1000 reusable plastic bags for equal carrying capacity. The cradle-to-grave process steps for plastic bags manufacturing and use is shown in Table 7. Cradle to grave analysis for paper bags would provide balance for the study but was outside the scope of the project. The consumer has the ability to recycle polyethylene bags since the recycling infrastructure is in place in

California. Whereas, the consumer does not have the opportunity to recycle PP non-woven bags due to the lack of infrastructure.

Life Cycle Inventory

The second step of the LCA process, Life Cycle Inventory, tabulates the energy, fuel, water, and material inputs needed to produce and use plastic and paper bags and also lists solid waste that are created when the products are made, used, and thrown away for plastic and paper bags. Polyethylene can have three types of resins that are used for plastic bags, namely, LLDPE, LDPE, and HDPE. HDPE is commonly used for single-use grocery bags. LLDPE and LDPE are commonly used for trash bags and for thicker department store bags. Each of the three polyethylene plastics can be used for reusable plastic grocery bags. Each of the process steps from Table 7 has environmental aspects that affect energy usage, water usage, GHG emissions, pollution, and solid waste generation.

Table 8 lists the cradle to gate aggregate US-averaged values of energy required, solid waste, and GHGs produced during the production of polyethylene and polypropylene. Polyethylene and polypropylene are made from natural gas and petroleum. The amount of energy and water that are needed to make polyethylene and polypropylene as well as the amount of solid waste, pollution and GHG generated during production is provided in Table 8. The polyethylene pellets are extruded and then blown into plastics bags with a blown film extrusion line. Similarly, polypropylene pellets are extruded in a sheet extruder and pressed into non-woven film that is sewn into a bag.

Table 8 shows that PP requires less energy to produce pellets and also then produces less house gases (GHG) due to the lower energy use. PP though produces more solid waste during the manufacturing of plastic pellets. The solid waste and GHG information can be used later in the report to compare the environmental benefits of using recycled plastic as a source for plastic bags rather than virgin plastic. If recycled plastics are used for plastic bags then the amount of energy needed to produce the virgin plastic can be saved when using recycled plastics since the plastic pellet is already available and does not need to be created from raw materials.

Table 8. Energy inputs and waste and GHG outputs for PE and PP plastic resin pellet manufacturing. [13]

Plastic	Energy, GJ per 1,000 kg of plastic	Solid Waste, kg waste per 1,000 kg plastic	GHG, tonnes CO_2 eq
HDPE	69	78	1480
LDPE	74	79	1480
LLDPE	69	74	1480
PP	63	83	1340

Figure 2 describes the energy and resource inputs during the production and use and disposal of plastic bags as well as the waste, GHG, and pollution generation. The cradle-to-grave analysis calculates the environmental impacts of creating plastic pellets from raw materials, transporting them to the plastic bag converter, producing the plastic bags, and transporting the plastic bags to the retailers. The LCA is influenced by choices that consumers make on single-use versus reusable bags, and choices that consumers make on recycling, waste disposal, or waste to energy end-of life options.

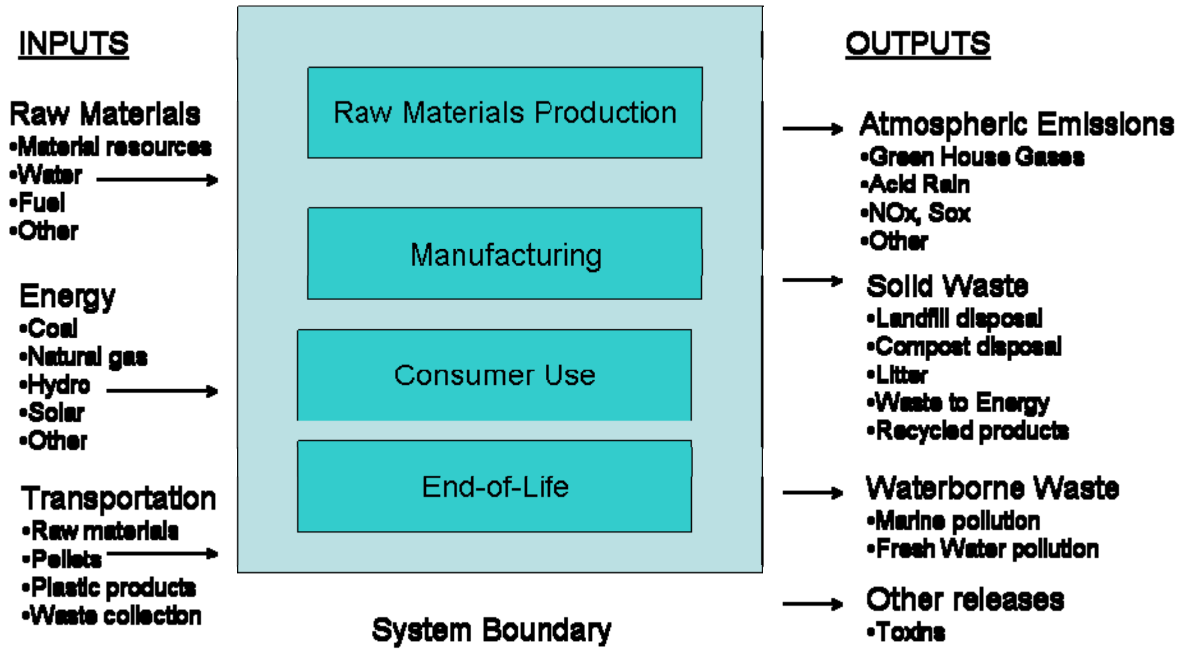

Figure 2. Process flow of inputs and outputs for plastic bag manufacturing, use, and end-of-life

End-of-Life Scenarios

End-of-Life scenarios for plastic bags have important environmental consequences. The End-of-Life options for the plastic bags are to be recycled, incinerated for energy, sent to landfill, or discarded as litter. Several reports suggest that single-use plastic bags are often reused again for a trash liners. The reused plastic bag can be filled with trash and then discarded with the trash to the landfill. Reusing plastic bags can replace some small trash bags. Reuse of the single-use plastic bags is an important issue but difficult to quantify. It needs to be studied further but is outside the scope of this research. The single-use plastic bag term is generally accepted to refer to HDPE plastic bags that are available at grocery and retail stores. Australian and Scottish LCA reports found that the reusable bags and paper bags are mostly sent to landfill (99.5%). The remaining 0.5% was discarded as litter. The single-use plastic bags can be recycled at a rate of 5% which is similar to the U.S. recycling rate of plastic bags. The remaining single-use plastic bags are sent to landfill (94.5%) or discarded as litter (0.5%).

In our study, the end of life for reusable plastic bags would be similar to the Australian and Scottish LCA results, except that the reusable polyethylene bag would be able to use the recycling infrastructure that is established for single-use polyethylene bags. The reusable non-woven polypropylene plastic bags would not be recycled since there is not an infrastructure established to collect them. Both polyethylene and polypropylene based reusable bags could be incinerated along with paper trash and single-use plastic bags. Though, since it would be the same for all bags it will be neglected in this study. Table 9 lists the end-of-life scenarios for the plastic and paper bags. The table is based on data from the Scottish and Australian LCA reports. In the, United States the recycling rate of single-use plastic bags is approximately 5% on average. Reusable polyethylene plastic bags could expect the same recycling rate of 5%. Reusable polypropylene bags though would not have the same recycling rate due to the lack of recycling infrastructure for polypropylene. Paper bags are readily recyclable and a recycling infrastructure exists for them.

Table 9. End-of-life scenarios for plastic and paper bags

Grocery bag alternative	Recycled %	Landfill %
Single-use HDPE bag	5	94.5
Reusable non-woven PE bag	5	94.5
Reusable non-woven PP bag	0	95.5
Paper bag	10 to 40	60 to 90

Recycling infrastructure exists for polyethylene and PET in 11 states that have beverage return laws. Post-consumer resin (PCR) can be used for recycled plastics content if the collection and sorting infrastructure is available and that the PCR can be certified. Both of these conditions exist for PET and HDPE bottles and for polyethylene plastic bags. The American Chemical Council (ACC) published a report in 2008 that claims that for plastic bottles, 1.451 billion PET bottles were recycled at a rate of 27%, 936.7 billion HDPE bottles were recycled at a rate of 29%, and 21.2 million PP bottles were recycled at a rate of 11.4%.[14] The recycled PET can be made into new bottles or into fiber for strapping or woven products. The recycled HDPE can be made into bottles or into plastic lumber.

Secondly, the American Chemical Council (ACC) also published a report in 2008 that claims that for plastic bags and film, 832 million pounds of post-consumer film was collected for recycling and then converted to film and sheet (4%), plastic lumber (29%), export (57%), and other (10%). All of the post-consumer film was made with polyethylene.[15]

Thirdly, the American Chemical Council (ACC) also published a report in 2008 that claims that 361 million pounds of post-consumer non-bottle rigid plastic was recovered in 2008.[16] Polyethylene and PET were the most commonly collected plastics, accounting for 38% and 25% respectively. The recycled rigid plastics were collected from commercial recycling efforts, curbside collections, and community drop-off collections. Most material recovery facilities (MRF) in the West sort out PET (#1) and HDPE (#2) bottles and then bale the remainder of the rigid plastics together as “mixed rigid” plastics. In 2008, 62% of the rigid plastics that were collected were converted in the US or Canada. In 2008, 38% of the rigid plastics that were collected were then exported overseas. Polypropylene copolymers are used commonly for car battery housings. The recycling rate of car batteries is high (between 98 and 99%). [17] However, use of recycled PP from car batteries can lead to exposure to regulated metals, e.g., Pb and Cd.

Thus, a recycling infrastructure exists for PET and polyethylene plastics. PET can be recycled from bottles and then easily converted to fiber that can be made into a woven plastic bag. Polyethylene can be recycled from bottles, film, sheet, or bags and then converted back to plastic bags in single-use or thicker reusable plastic bags.

Polypropylene bottles and other rigid products would not easily be converted back to non-woven or woven plastic bags due to the lack of collection and recycling infrastructure. Also, certification of PCR content would need to be developed for PP that would be similar to existing programs for polyethylene plastic bags. [18] Recycled PP would come from a variety of product sources, each with a different melt flow properties, density, and additives. Recycled PP sources could be contaminated with regulated metals that would not be suitable for reusable plastic bag use. Reusable non-woven PP plastic bags are made in an extrusion process that creates a sheet of PP that is then made into reusable plastic bags through a stitching process. The manufacturing process would need a consistent recycled input stream which may be difficult if the majority of the recycled PP is baled with mixed plastics at local MRFs and sent overseas.

The use of PCR can offer significant environmental benefits for reduced carbon dioxide emissions, reduced solid waste, and reduced pollution. Currently, PP non-woven bags could not be produced from PCR due to the lack of recycling infrastructure in the Unites States. Likewise, single-use plastic bags can be produced with 40% to 100% PCR. Likewise, PE reusable bags could be made with PCR in concentrations of 40% to 100% PCR.

CSU Chico Life Cycle Assessment (LCA)

Life cycle inventory (LCI) of the plastic bag manufacturing process can be determined based on the data from the Boustead report, the Australian report, and the Scottish report. The methodology used in this report combines the data from the Boustead report with the reusable bag data from the Australian and Scottish report.

The methodology for the CSU, Chico LCA normalizes the Boustead data energy use, GHG emissions, water usage, and waste generation for polyethylene plastic bags to the mass of the bag. The functional unit for the LCA analysis is a plastic bag of equal carrying capacity that would be used in one-year time span by consumers. The analysis assumes 1 trip per week that includes 10 bags.

The normalize Boustead data used in the LCA analysis include values of energy use, GHG emissions, water usage, and waste generation per kg of polyethylene. The reusable polyethylene and polypropylene bags will have the same dimensions and not include handles. The reusable polyethylene thickness is 0.003 inches, whereas, the reusable polypropylene bag is 80 grams per square meter of bag. The LCA of polypropylene is calculated based on combining the Boustead data with the PP pellet manufacturing data from Table 8. The LCA of the PP per kg is calculated to include GHG emissions, energy usage, water usage, and waste generation per kg or PP. The LCA of reusable polyethylene and polypropylene bags are calculated by multiplying the per kg LCA by the mass of the reusable bags. Thus we can determine the energy use, GHG emissions, water usage, and waste generation of three bags, i.e., HDPE grocery bag (Boustead data), reusable polyethylene bag (modified Boustead data), and reusable non-woven polypropylene bag (modified Boustead data). Lastly, the environmental credits for using recycled polyethylene in the reusable polyethylene bag is determined by subtracting the amount of energy use, GHG emissions, water usage, and waste generation from the virgin resin that was replaced by the recycled plastic and add the amount of energy and GHG produced by converting the recycled polyethylene to plastic pellets.

The assumptions of the new LCA are listed in the following:

- The Boustead data for single-use HDPE bag can be used to represent the manufacturing process of the thicker reusable polyethylene bag since it is made with the blown film extrusion process.

- The Boustead data for single-use HDPE bag can be modified to represent the manufacturing process of the thicker reusable non-woven polypropylene bag since the non-woven PP bag is made with sheet extrusion process which requires similar energy use as blown film extrusion.

- The production of PP non woven bags has the same values for GHG, waste generation, energy usage, and water usage as HDPE blown film bags.

- The non-woven PP bag is 80 grams per square meter (GSM). The two options for polypropylene non-woven bags are 80 GSM and 100 GSM based on industry standards.

- Transportation of non-woven polypropylene from China to Los Angeles has a distance of approximately 11,000 kilometers. The GHG emissions from fuel consumptions are approximately 3% of the overall GHG emissions from the bag manufacturing based on data from the Australia report.

- Reusable polyethylene is manufactured in California and distributed throughout the United States.

- Transportation of reusable non-woven polypropylene and reusable polyethylene bags through out the United States accounts for 1% of the overall GHG emissions. This 1% value is an estimate based on experience of the author.

- The dimensions of the non-woven reusable bag are the same as the dimensions of the polyethylene reusable bag. The difference is the thickness of the bags.

- For 40% recycled LLDPE, the energy, GHG, waste, and water that is required from the pellet production is subtracted from the bag manufacturing minus the conversion costs of the recycled bag to pellets. The recycled content of 40% is the largest acceptable value for polyethylene plastic bag manufacturers who were consulted by the author.

- The cost of conversion of recycled polyethylene to pellets is $.04 per pound of PCR. The energy costs are $0.13 per KW-h energy cost. The conversion of energy costs to GHG is based on 0.524 lbs of CO_2 per kW-h from PG&E. The numbers used in this step were estimates provided to the author from several polyethylene plastic bag manufacturers.

- The pellet manufacturing conversion of recycled polyethylene to pellets does not require any water and does not generate much waste. Most of the water is created from the pellet creation or from washing the bags. These environmental elements are disregarded.

- The number of reusable bags used by the consumer per trip is 10 based on the Australian study.

- The number of bags with meats or eggs is 20% and will require washing every week. The analysis assumes 2 bags out of 10 would be used to carry meats or eggs. Consumer choices to limit the meats and egg consumption can reduce the 20% value. Vegan consumers would not have as much bacteria contamination from meats and eggs.

- The wash cycle includes 20 bags in 20 gallons that are washed with detergent and then rinsed with water for a required 2 gallons for every bag for the wash cycle. The values of the water required for washing was determined by the author during field studies of a Kenmore washing machine.

- Reusable polyethylene bags could be wiped with disinfectant cloth after exposure to meats and eggs and rinsed with soapy water. The texture of the blown film bag makes it easier to wash than the non-woven bag. The volume of water needed would be two bags per gallon of water.

- The energy used in a washing and drying of the reusable bags was not considered.

- The environmental impacts of detergents during the washing of the bags were not considered.

The LCI includes the manufacturing of plastic pellets and paper from raw materials, the conversion of plastic pellets into plastic bags, conversion of paper into paper bag, and transportation to the retail stores. The “cradle to grave analysis” can illustrate the environmental benefits of reusing the plastic bag and the benefits of using recycled plastic.

Life Cycle Assessment (LCA)

The third step of the LCA process, Life Cycle Impact Assessment, takes the inventory of energy, fuel, water, materials, pollution, and waste and rearranges them in terms of the scope from the first step, to provide a comparison of environmental measures. In our case, the amount of energy, water, materials, and fuel needed to make 1500 plastic grocery bags can be compared with the amount of energy, water, materials, and fuel needed to make 1000 reusable plastic bags and 1000 paper bags. Likewise, the pollution, Green house Gases (GHG), and solid waste produced to make 1000 plastic garbage bags will be compared to the waste produced from 1000 reusable plastic bags and 1000 paper bags.

Table 10 lists the cradle-to-gate life cycle inventory of single-use plastic bags, single-use paper bags, reusable non-woven polypropylene plastic bags, and reusable polyethylene (LLDPE) plastic bags. The table lists grocery bags with equal amount of carrying capacity for up to 1 year or 52 weeks. This is consistent with the Australian LCA. Single-use paper bags are presented as a comparison but are outside the scope of the research. The LCA data for paper bags is from the Boustead report. Recycling content is included in the reusable polyethylene bag. The reusable bags are washed at a rate of 20% of the bags over the time period in the table. The single-use plastic bag is smaller than the reusable and paper bags. Thus, 1500 single-use plastic bags has similar carrying capacity as 1000 reusable plastic and single-use paper bags. This is consistent with the Boustead report.

The data is Table 10 represents the environmental impacts of using equal-carrying capacity bags for 1 year.

Table 10. Cradle-to-gate LCA of plastic bags, single-use paper bags, and reusable plastic bags

Environmental impact indicator	1500 HDPE single-use bag	1000 Reusable PP non-woven single-use	1000 Reusable PP non-woven 8 times	1000 Reusable PP non-woven 52 times	1000 Reusable LLDPE bag with 40% PCR single-use	1000 Reusable LLDPE with 40% PCR bag 8 times	1000 Reusable LLDPE with 40% PCR bag 52 times	1000 Paper bag single -use
Non-renewable energy, GJ	763	3736	467	72	2945	368	57	2620
GHG emissions, CO_2 eq	0.04	0.262	0.033	0.005	0.182	0.023	0.003	0.08
Solid Waste, kg	7.0	34.3	4.29	0.7	34.1	4.3	0.7	34
Fresh water consumption, gal	58	426	85	216	250	40	57	1000
Mass, g	6	42	42	42	44	44	44	52

Table 10 illustrates that single-use reusable bags made from polypropylene or polyethylene have significantly worse environmental impacts than the single-use polyethylene bags. The reusable bags have a better environmental impact if they are used more that 8 times, which is an environmental cross-over point for reuse. The reusable plastic bags have significantly better environmental impact if they are used 26 times (once a week for 6 months) or more.

Table 10 also illustrates that the reusable polyethylene bag has the lowest environmental impact than the reusable polypropylene bag due to the use of recycled polyethylene plastic or PCR.

Environmental Impacts of Washing Reusable Bag

Reusable bags made from polyethylene and propylene can be used as carrier bags in grocery stores. The bags can be used to carry fruits, vegetables, can goods, bottled goods, boxed goods, dairy products, and meats. The dairy products and meats can cause bacteria to grow on the bags. In fact, large numbers of bacteria were found in many reusable bags in a recent study.[19] Also, coliform bacteria were found in half of the bags and E. coli bacteria were found in 12% of the bags. The human health impacts are not typically found in LCA studies but are warranted due to the need to consider health with environmental aspects of consumer choices.

The Australian report recommended that the average consumer uses 10 bags per week for 52 weeks. We could assume that 20% of the bags would have meats or dairy in the bags and would need to be washed. This assumption would vary depending upon the meat and dairy preferences of the consumer. This report assumes that 2 bags per week would need to be washed and that each bag would use 2 gallons of water plus detergent for the wash and rinse cycles in a standard washing machine. This research found that 4 bags fill a 10 quart bucket and 20 bags fill a 20-gallon washing machine. For this research the number of bags used for 52 weeks were multiplied by 20% as the number of bags washed times 2 gallons per bag would determine the amount of water needed to wash the bags for 52 weeks. This amount of water was added to the amount of water needed to produce the reusable plastic bag. The wash cycle of the bags may also cause the bags to deteriorate, especially around the stitching that holds the bag together.

The LCA data in Table 11 can be normalized to the values for single-use plastic bag in a similar fashion as in the Scottish report as presented in Table 6. This can illustrate the environmental effects of using reusable bags and using recycled plastics in the manufacturing of the plastic bags. Table 11 lists the normalized values for environmental impacts that include reusable bags with recycled content and washing of the bags. The values in Table 11 are rounded for clarity.

Table 11 illustrates that 1,000 single-use reusable non-woven PP plastic bags require 5 times more energy, emit 7 times more GHG, generate 5 times more waste, and consume 7 times more water than 1,500 single-use polyethylene plastic bags. On the contrary, the reusable non-woven plastic bag that is used 8 times has equivalent environmental impact as the single-use polyethylene plastic bag. Likewise, the reusable non-woven plastic bag that is used 52 times has significantly lower environmental impact than the single-use polyethylene plastic bag. In fact, if the reusable bag is used once a week for 52 weeks, the reusable non-woven PP bag bags require significantly less energy, emit 87% less GHG, generate 91% less waste. It would however consume 4 times more water than 1,500 single-use polyethylene plastic bags due to washing 20% of the bags every week. Table 11 also illustrates how the reusable polyethylene plastic bag with 40% Post Consumer Resin (PCR) plastic has the lowest environmental impact of all of the carrier bag alternatives.

Table 11. Environmental indicators for single-use plastic bags, single-use paper bags, and reusable plastic bags per standardized single-use polyethylene bag.

Environmental impact indicator	1500 HDPE single-use bag	1000 Reusable PP non-woven single-use	1000 Reusable PP non-woven 8 times	1000 Reusable PP non-woven 52 times	1000 Reusable LLDPE bag with 40% PCR single-use	1000 Reusable LLDPE with 40% PCR bag 8 times	1000 Reusable LLDPE with 40% PCR bag 52 times	1000 Paper bag single-use
Non-renewable energy, GJ	1	5	0.6	**0.1**	4	0.5	**0.1**	3
GHG emissions, CO_2 eq	1	7	0.8	**0.1**	5	0.6	**0.1**	2
Solid Waste, kg	1	5	0.6	**0.1**	5	0.6	**0.1**	5
Fresh water, gal	1	7	1.5	**4**	4	0.7	**1**	17

Table 10 can be rearranged to have the reusable polyethylene bag that is used 52 times as the basis for comparison. Table 12 lists the environmental impacts of plastic and paper bags with reusable polyethylene plastic bag as the basis.

Table 12. Additional environmental indicators for single-use plastic bags, single-use paper bags, and reusable plastic bags per standardized reusable polyethylene bag

Indicator of Environmental Impact	1,000 reusable LLDPE plastic bags with 40% PCR and 52 times	1,000 reusable non-woven PP plastic bags and 52 times	1,500 single-use HDPE plastic bag	1,000 single-use paper bags
Non-renewable energy	1	1.3	13	46
GHG, CO_2 eq.	1	1.7	17	27
Solid Waste Generation, kg	1	1	10	53
Fresh Water, gal	1	4	1	18

The results of our LCA study demonstrate that the reusable polyethylene plastic bag made with 40% PCR and reusable polypropylene plastic bags have lower environmental impacts than other reusable and single-use plastic and paper bags. Reusable LLDPE plastic bags with 40% recycled PCR content have lower energy usage, lower GHG emissions, lower solid waste generation, and lower water usage than reusable non-woven PP bags, single-use plastic bags, and single-use paper bags. Further research can determine the environmental impacts of 100% PCR based reusable and single-use plastic bags.

Regulated Metals Testing

In January of 2006, California laws went into effect that limits the amount of regulated metals, including cadmium and lead, in product packaging. The US EPA standard allows the following amounts of regulated metals: lead (150 mg/kg), cadmium (17 mg/kg), copper (750 mg/kg), nickel 210 mg/kg), zinc (1400 mg/kg), and mercury (8.5 mg/kg).[20] Pigments with green and blue colors cause the amount of copper to increase in plastic. [21] Pigments of heavy yellow can cause the amount of lead to increase in soil.

Reusable and single-use plastic bags were tested for the presence of regulated metals, including cadmium and lead. The following bags were purchased at local grocery and retail stores. Table 13 lists the bags that were tested.

The ten bags were tested for regulated metals with a Bruker AXS S2 Ranger XRF machine. X-ray fluorescence spectrometry can be used to identify metals, powders, and other elements in cement, minerals, mining, metals, slag, oils and lubricants, pharmaceuticals, polymers and RoHS.[22]

The XRF machine performs elemental analysis from Sodium (Na) to Uranium (U) in solids, powders or liquids. The XRF machine can identify the presence of metals in the plastic sample but does not measure the concentration of the metals. The XRF identified qualitatively the presence of regulated metals but does not provide a quantitative analysis.

Plastic samples were taken from the bottom insert in those bags that had the inserts and also from the side walls of the bags. The sample size is small due to the limited duration and scope of the research project. Table 14 lists the regulated metals found in the plastic bags. Cadmium was found in 35% of the non-woven PP bags. Cadmium was the most common metal found in four of the reusable PP bags. Trace amounts of lead were found in 20% of the reusable bags. Most of the regulated metals were identified in the plastic insert at the bottom of the bag. Further wet-chemistry methods can be done in the future to identify concentrations of the regulated metals, though outside the scope of this research work.

Table 13. Reuseable and single-use plastic bags in research study

Store	Color	Country of Manufacture	Material
Grocery Store A	Brown	China	Non-woven PP
Grocery Store B	Green	China	Non-woven PP
Grocery Store C	Purple	China	Non-woven PP
Grocery Store D	Black	China	Non-woven PP
Grocery Store E	yellow/white	USA	Polyethylene
Grocery Store F	White	USA	Polyethylene-single-use
Retail Store A	Green	China	Non-woven PP
Retail Store B	Black	China	Non-woven PP
Retail Store C	Green	China	Non-woven PP
Retail Store D	Black	USA	Polyethylene

Table 14. Regulated metals testing of reusable and single-use plastic bags

Store		Bottom or side	Presence of Cd	Presence of Pb
Grocery Store A	Non-woven PP	Bottom insert	Y	N
	Non-woven PP	Side wall	N	Y
Grocery Store B	Non-woven PP	Bottom insert	Y	N
	Non-woven PP	Side wall	N	N
Grocery Store C	Non-woven PP	Side wall	N	N
Grocery Store D	Non-woven PP	Bottom insert	Y	N
	Non-woven PP	Side wall	N	N
Grocery Store E	Polyethylene	Side wall	N	N
Grocery Store F	Polyethylene	Side wall	N	N
Retail Store A	Non-woven PP	Bottom insert	Y	N
	Non-woven PP	Side wall	N	N
Retail Store B	Non-woven PP	Side wall	Y	N
Retail Store C	Non-woven PP	Bottom insert	N	N
Retail Store D	Polyethylene	Side wall	N	N

Conclusions and Recommendations

Reusable plastic bags can reduce the amount of green house gas emissions, solid waste generation, and acid rain pollution than single-use polyethylene plastic bags. The plastic bag with the least amount of environmental impacts would have the following features:

- Reusable,
- Made from recycled plastics, and
- Lightest weight possible.

Currently, PP non-woven bags could not be produced from PCR due to the lack of recycling infrastructure in the Unites States. However, PE reusable bags could be made with PCR in concentrations of 40% to 100% PCR. Likewise, single-use plastic bags can be produced with 40% to 100% PCR. The use of PCR can offer significant environmental benefits for reduced carbon dioxide emissions, reduced solid waste, and reduced pollution.

The polyethylene based reusable bag with 40% PCR is the plastic bag with the least amount of environmental impacts. The reusable bags though will require more fresh water than a single-use polyethylene bag due to the washing requirements of the bags that carry meats and dairy products.

The research report was evaluated by personnel from the Department of Toxic Substances and Control (DTSC) and the California Department of Resources Recycling and Recovery (CalRecycle) organizations in Sacramento, CA. The research report was evaluated by those two organizations for clarity and accuracy for life cycle assessment standards and protocols. The report was changed to include more accurate LCA assumptions and criteria. The report was modified to provide more transparent functional units and better comparison criteria. The report was well received by both organizations and thought to provide relevant data for the sustainable evaluations of plastic bags and reusable bags.

Appendix

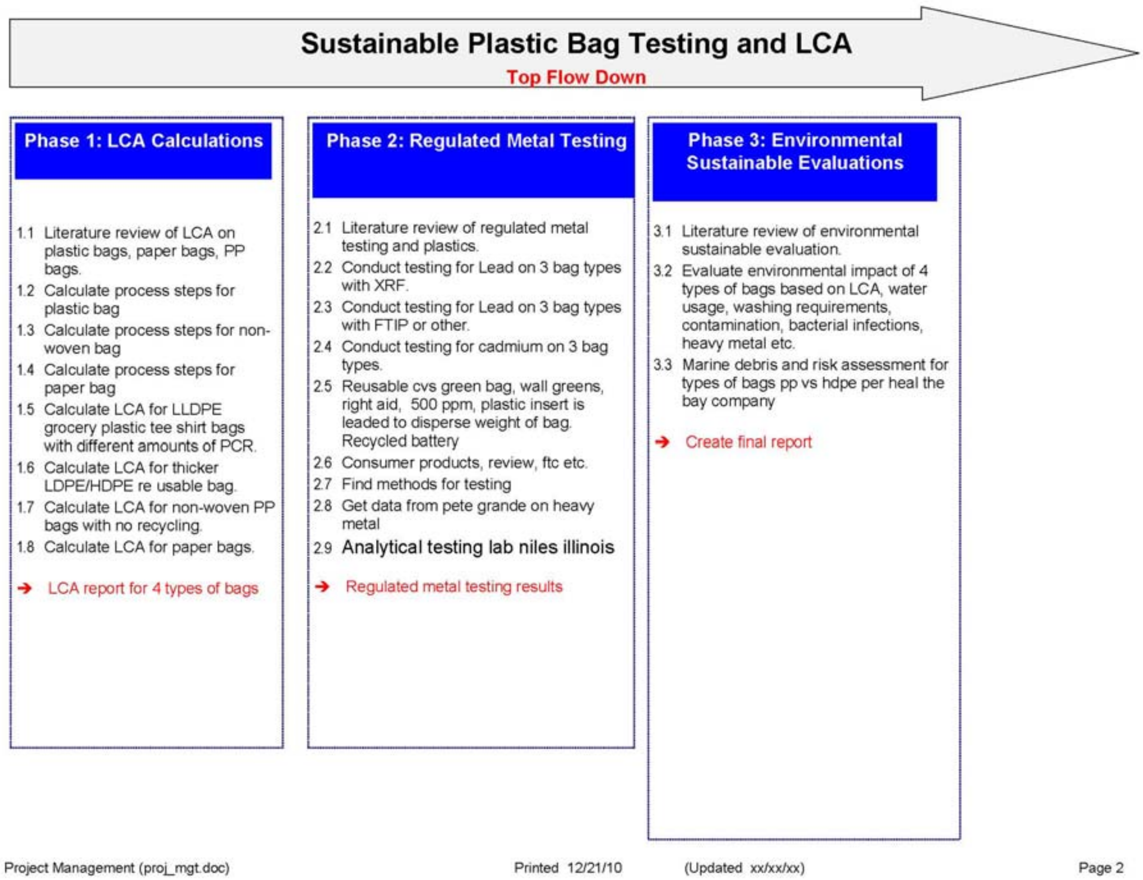

Figure 3. Project management for research study

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