DEFINING ENVIRONMENTAL IMPACTS OF RECYCLING PLASTIC FILM WASTES

Abstract:

This study assesses the environmental impacts of different plastic film waste recycling systems using life-cycle assessment. Three collection scenarios, urban area curbside collection, rural area curbside collection, and consumer drop-off, and two final disposal methods, landfill and incineration with energy recovery are analyzed in this study. IMPACT 2002+ method is used to evaluate their environmental impacts, i.e. human health, ecosystem quality, climate change and resource. Sensitivity analysis on different variables (recycling rate and waste to energy conversion rate et al.) was also conducted. The results show the advantage of recycling over landfilling and incineration in terms of environmental impacts. Recycling rate and energy conversion efficiency is two key parameters to keep the overall environmental benefits.

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1. Introduction

1.1 Overview and Context

P&G group has ambitious vision on their sustainability development, they want 90% of packaging to be recyclable or programs are in place to create the ability to recycle it by 2020. To support P&G's vision and goals for packaging material recycling, this study will conduct a life cycle assessment (LCA) study to compare environmental impacts of various end-of-life pathways for post-consumer recycled films.

As one of the most rapidly growing segments of the packaging industry, flexible packaging combines the best qualities of plastic, paper, and aluminum foil to deliver a broad range of protective properties while employing a minimum of material (Flexible Packaging Association, 2016). Plastic films are defined as any package or any part of a package the shape of which can be readily changed (Flexible Packaging Association, 2016). Unlike rigid plastic (e.g., soft drink bottles and butter tubs), plastic films are flexible in nature (Testin and Vergano, 1997). Plastic films compose a broad category of materials that can be relatively simple or complex depending on the demands of a product or package. Plastic films can be made with different resins, each with a unique combination of properties that makes it ideal for certain applications. For example, low-density polyethylene (LDPE) film acts as a gas barrier, which is necessary for packaging things that cannot be exposed to air such as chicken. Polyvinyl chloride (PVC) film is gas permeable and necessary for packaging such things as red meat, which requires a small amount of oxygen inside the package to remain fresh. (Testin and Vergano, 1997).

1.2 Life Cycle Assessment Methodology

LCA methodology has been developed to better understand and address the potential impact associated with products and services throughout their life cycle. LCA addresses the environmental aspects and potential environmental impact (e.g., use of resources and the release of pollutants) throughout a product's or process's life cycle. LCA bases all results in relation to a well-defined functional unit, allowing for direct comparisons among competing products or systems, as well as alternate forms of the same product or system. Among other uses, LCA can: identify opportunities to improve the environmental performance of products or processes at various points in their life cycle; inform decisions (e.g., strategic planning, priority setting, product or process design); inform the selection of environmental performance indicators and measurement methods; support marketing efforts (e.g., producing an environmental product declaration); and more. An LCA is comprised of four phases: a) Goal and scope definition: defining the purposes of the study, determining the boundaries of the system life cycle in question and identifying important assumptions that will be made; b) Inventory analysis: compiling a complete record of the important material and energy flows throughout the life-cycle, in additional to releases of pollutants and other environmental aspects being studied; c) Impact assessment: using the inventory compiled in the prior stage to create a clear and concise picture of environmental impacts among a limited set of understandable impact categories; and d) Interpretation: identifying the meaning of the results of the inventory and impact assessment relative to the goals of the study. The principles, framework, requirements and guidelines to perform an LCA are described by the international standards ISO 14040 series. (ISO 2006)

2. Goal and Scope

2.1 Objective of the Study

The objective of the present study is to comprehensively define the life cycle environmental impacts over the recycling process of wastes, including collection, processing at material recovery facility (MRF), and final disposal. This study will discuss the environmental impacts at plastic film wastes recycling.

2.2 Functional Unit

The purpose of the process in question is to recycle the plastic film waste. The Functional unit is 1 ton of recyclable wastes, within with there are 6-kilogram plastic film. The compositions are the same for single-stream collection and pre-sorted drop-off. The waste composition is shown below. We will particularly focus on the plastic films.

Table 1 Composition of recyclable wastes in 2012 (US EPA, 2014)

Types of Municipal Solid Waste (recyclable)	Waste fraction (%)
Newsprint	19.5
Corrugated Cardboard	17.8
Mixed Paper	30.3
HDPE – translucent container	1.1
PET - container	2.1
Film	0.6
Aluminum	0.9
Ferrous metal	1.6
Glass - Brown	5.0

Glass - green	7.1
Glass - clear	5.3
Non-recyclable	8.7

Table 2 Segments of plastic film wastes in 2012 (Flexible Packaging Association, 2013)

Types of Plastic Film Waste	Waste fraction (%)
LDPE	68.9
PET	12.1
HDPE	6.8
PP	8.5
PVC	3.1
PS	0.5

In 2012, 250.9 million tons of municipal solid waste was generated in the U.S., 2.81% of which was plastic film waste and only 2% of the solid wastes were recovered (US EPA, 2014). Previous studies assessed the feasibility of recycling paper and other packaging waste. Recycling is proven a better option than either landfilling or incineration for papers in most included life cycle environmental impact categories (Villanueva and Wenzel, 2007). Paper recycling is also beneficial, and is of particular interest from a management perspective because it can be controlled by the pulp and paper industry (Pickin et al.,2002). For other packaging waste, such as rigid plastic, aluminum, and tin-plated steel, recycling is environmentally preferable to disposal by a substantial margin (Morris, 2005). However, the environmental impact of plastic film recycling has not been studied.

2.3 System Boundaries and Description

The post-consumer wastes recycling was divided into three principle life cycle stages: (1) collection of the wastes; (2) processing at material recovery facility; (3) End of life disposal (landfilling, incineration). Within each of these stages, the LCA considers all identifiable “upstream” inputs to provide as comprehensive a view as is practical of the total influence of the product system. For example, when considering energy used for transportation, not only are the emissions and fuel used by the truck moving the products considered, but also the additional processes and inputs needed to produce that fuel. In this way, the production chains of all inputs are traced back to the original extraction of raw materials.

After wastes generated at household, they can be either collected by single unit truck at curbside, or dropped off by consumers using their own vehicles. Different vehicles used and different distance travelled at urban or rural areas could cause difference on environmental impacts at collection. After the wastes get processed at MRF, the recovered wastes can be used as raw materials for remanufacturing, while the residuals will be sent to either landfill or incinerator. So in total there are six pathways dealing with film waste recycling.

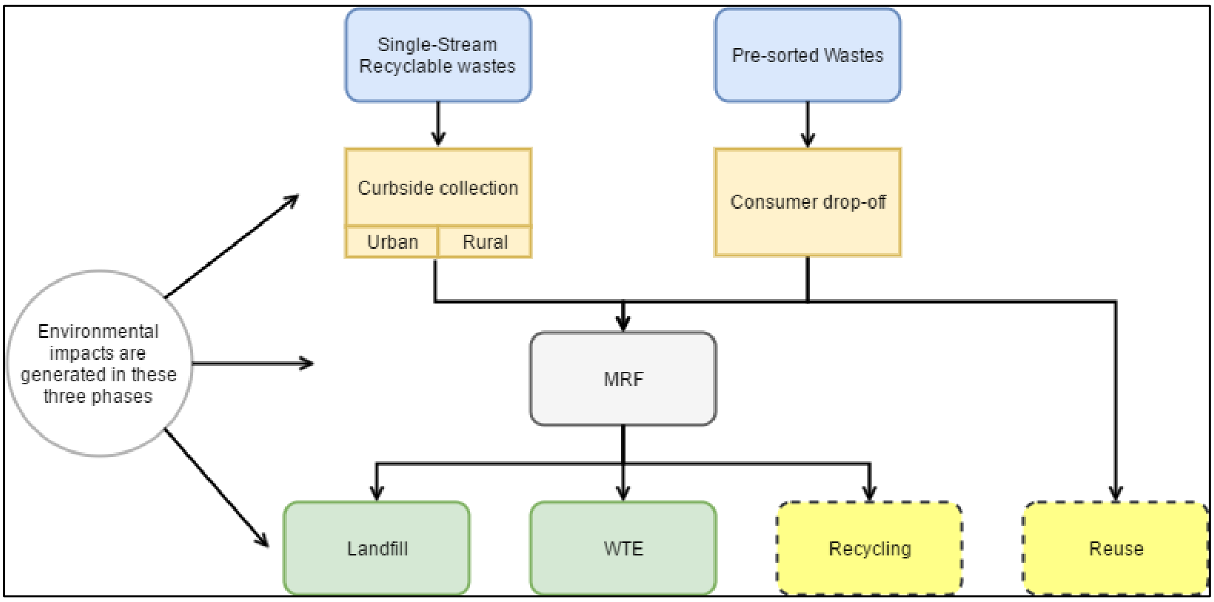


Figure 1 Pathways of plastic film wastes recycling

The pathways are defined below:

1. Wastes are collected at curbside in urban area, processed at MRF, residuals landfilled;
2. Wastes are collected at curbside in urban area, processed at MRF, residuals incinerated;
3. Wastes are collected at curbside in rural area, processed at MRF, residuals landfilled;
4. Wastes are collected at curbside in rural area, processed at MRF, residuals incinerated;
5. Wastes are dropped off by consumer, processed at MRF, residuals landfilled;
6. Wastes are dropped off by consumer, processed at MRF, residuals incinerated;

Other than the recycling of plastic film wastes, landfilling or incinerating the plastic film waste will also be calculated to show the benefits of film recycling.

2.4 Inventory Data and Information Collection

In obtaining and selecting among available data, considerations of representativeness, consistency, accuracy, and geographic and temporal relevance have been considered. The data has been selected that best meets this combination of criteria. Most data (e.g. distance travelled at collection, electricity consumption at MRF) were obtained from journal articles and EPA reports.

For background life cycle inventory data, the European ecoinvent inventory database (v 2.01) was used for this study as it is a very comprehensive database, both in terms of technological and environmental coverage (Althaus, Doka, and Dones 2007; The Ecoinvent Center 2007; Frischknecht, Jungbluth, and Althaus 2005). It should be noted that using European data to represent North American processes can introduce some bias in certain areas. However, it is believed that the consistency and accuracy of this database make it a preferable option for representing North American conditions compared to other available data for most processes.

In addition, although ecoinvent is of European provenance, it contains information representing many regions of the world. For example, the data we have used to represent electricity use is data created to represent the US electricity grid, even though it is a part of the ecoinvent database.
In two cases, sufficiently representative data was not available in ecoinvent. In one case, use of diesel at MRF was taken from the Franklin USA, which is a professional LCA consulting company. In another case, the production of steel was taken from ETH-ESU 96, which was an older LCI database created by the former energy-materials-environment group at the Swiss Federal Institute of Technology and is presently emerged with ecoinvent.

2.5 Life Cycle Impact Assessment Method

For the present study, Climate Change Score, Water Use, Human Health, Ecosystem Quality, and Resource Depletion have been selected as the primary impact categories. In the impact assessment, the flows of materials, energy, and emissions into and out of each product system are classified and combined based on the type of impact their use or release has on the environment. Described below are the methods used here for estimating environmental impacts. The IMPACT 2002+ impact assessment methodology (Jolliet et al., 2003) has been chosen because it is felt that it represents the best available science in life cycle impact assessment at the time of initiation of this study. In comparison to other methods that might be considered equally robust, it has been selected due to the existence of a method based on scientific principles for combing midpoint‖ indicators that affect a similar endpoint into a single "endpoint" indicator, allowing for a clearer and comprehensive communication of outcomes. In the case of climate change, a modification has been made to the IMPACT 2002+ methodology through substitution of a more current climate change impact assessment method, as described below. IMPACT 2002+ makes assessment of environmental damages at what are known as "midpoint" and "endpoint" (also called "damage") environmental indicators. Endpoint indicators are those that attempt to quantify most directly the subject of concern in terms of damages to health or the environment. For example, the Human Health endpoint indicator in IMPACT 2002+ attempts to estimate us the years of useful life lost (DALYs, disability adjusted life years) due to all the human health impairments that can be quantified with the methodology. Similarly, the Ecosystem Quality indicator reports on the number of species loss that might occur.
Midpoint indicators, in contrast, are steps along the way to calculating the endpoint indicators. For example, the total amount of photochemical oxidation that is caused by all pollutant releases is one midpoint indicator in the IMPACT 2002+ system, and can be combined with many other midpoint indicators to determine the total Human Health endpoint indicator. A schematic of the IMPACT 2002+ system, as implemented here, is show in Figure 2. The midpoint indicators for the IMPACT 2002+ system have also been evaluated to provide additional detail on specific areas of environmental impact and to ensure that the method used to combine these into an endpoint indicator has not resulted in the masking of some categories for which opposite directional results are obtained.

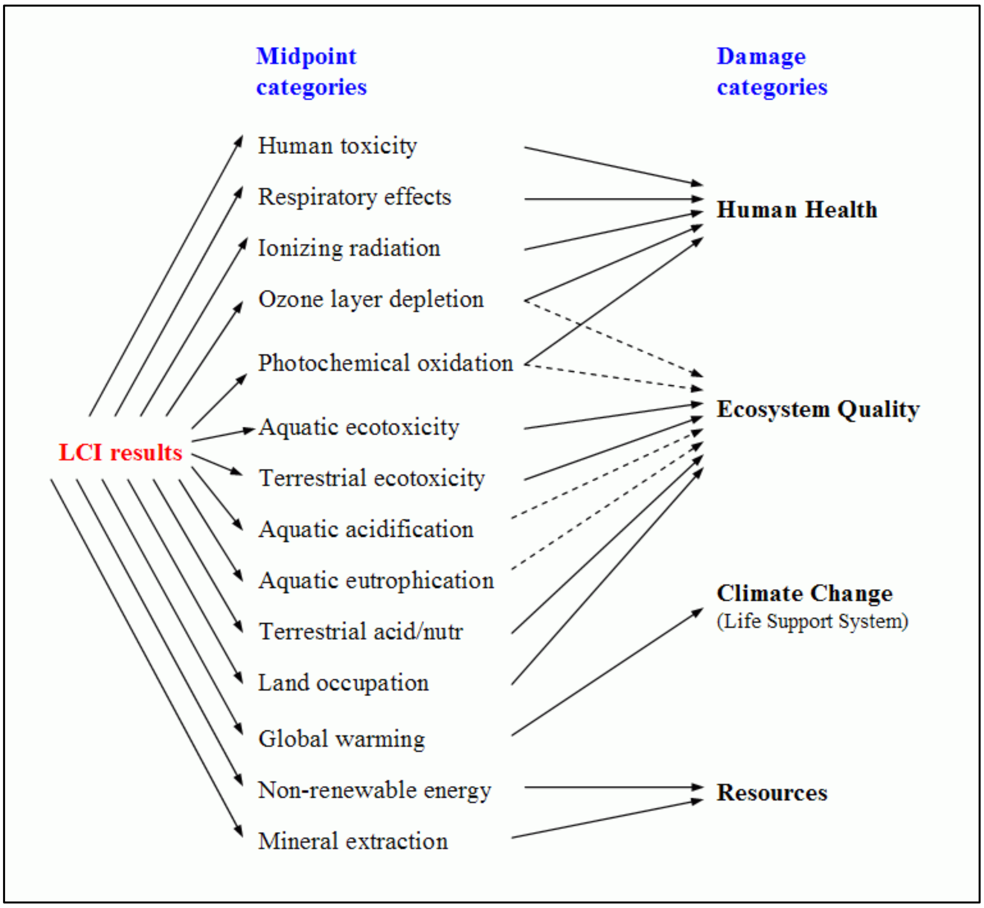


Figure 2: IMPACT 2002+ impact assessment system (adapted from Jolliet et al. 2003)

Each of the impacts reported on here is described briefly below.

Climate Change is represented based on the International Panel on Climate Change's 100-year ratings of the Global Warming Potential of various substances (IPCC 2007). Substances known to contribute to global warming are adjusted based on an identified Global Warming Potential, expressed in kilograms of CO2 equivalents. Because the uptake and emission of CO2 from biological sources can often lead to misinterpretations of results, it is not unusual to omit this biogenic CO2 from consideration when evaluating Global Warming Potentials. Here, we have followed the recommendation of the Publicly Available Standard (PAS) 2050 product carbon footprinting guidance in not considering either the uptake or emission of CO2 from biological systems and correcting biogenic emissions of other gasses accordingly by subtracting the equivalent value for CO2 based on the carbon content of the gas.

Human Health impact can be caused by the release of substances that effect humans through acute toxicity, cancer-based toxicity, respiratory effects, increases in UV radiation and other causes. An evaluation of the overall impact of a system on human health has been made following the Human Health end-point in the IMPACT 2002+ methodology (Jolliet et al., 2003), in which substances are evaluated based on their ability to cause each of a variety of damages to human health.

Ecosystem Quality can be impaired by the release of substances that cause acidification, eutrophication, toxicity to wildlife, land occupation, and a variety of other types of impact. An evaluation of the overall impact of a system on ecosystem quality has been made following the

Ecosystem Quality end-point IMPACT 2002+ methodology(Jolliet et al., 2003), in which substances are evaluated based on their ability to cause each of a variety of damages to wildlife species.

Resource Depletion is caused when non-renewable resources are used or when renewable resources are used at a rate greater than they can be renewed. Various materials can be given greater importance based on their abundance and difficulty to obtain. An evaluation of the overall impact of a system on resource depletion has been made following the Resources end-point in the IMPACT 2002+ methodology(Jolliet et al., 2003), which combines non-renewable energy use with an estimate of the increased amount of energy that will be required to obtain additional incremental amounts of substances from the earth due to removal of resources inventoried for each system (based on the Ecoindicator 99 method). Nonrenewable primary energy use accounts for the consumption of fossil and nuclear resources but excludes sources of renewable energy at all stages of the life cycle and in all upstream processes. This metric is expressed here in megajoules.

3. Inventory analysis and assumptions

The collection distance at different areas, resources consumption at MRF, heat value of different wastes and waste to energy conversion rates are available in journals. Because this study only focuses on the plastic film waste, all the distance and resource consumption are allocated based on weight (e.g. it needs 10 km driving to collect 1 ton recyclable wastes, the environmental impact allocated to plastic film waste is 10*0.006=0.06 km truck driving). The input values are displayed below.

Parameter	Quantity		Data Source
Curbside collection (km)	0.1121 (rural)	0.081534 (urban)	(Jaunich et al., 2016)
Consumer drop-off (km)	5.713654		(Franklin Associate, 2011)
Electricity consumption at MRF (kWh)	0.018		(Pressley, Levis, Damgaard, Barlaz, & DeCarolis, 2015)
Diesel consumption at MRF (L)	0.0042		(Pressley et al., 2015)
Electricity recovered by burning residues (Btu)	30360		(Themelis, Castaldi, Bhatti, & Arsova, 2011)

A few assumptions were made in this study. We assumed that the fuel economy of collection vehicle is always the same, even with different loadings. Both single stream and dual stream waste collection exist in the real world. In single stream collection, all recyclable wastes, such as paper, metal, plastic are commingled in a single cart, collected in a single truck, and processed in a single facility. In dual stream collection, paper is separated from other waste at collection with source separation, and they are separated independently (Fitzgerald et al., 2012). This study only considered single stream recycling (collection and separation) as it provides considerable environmental benefits over dual stream recycling (Fitzgerald et al., 2012).

4. Results

4.1 Environmental impacts of different wastes treatment methods

In this section, four different treatment methods of plastic film wastes are calculated and presented below in Figure 3. Wastes are collected by curbside in urban area for this comparison. Positive values represent overall environmental impact and negative values represent overall environmental benefits.

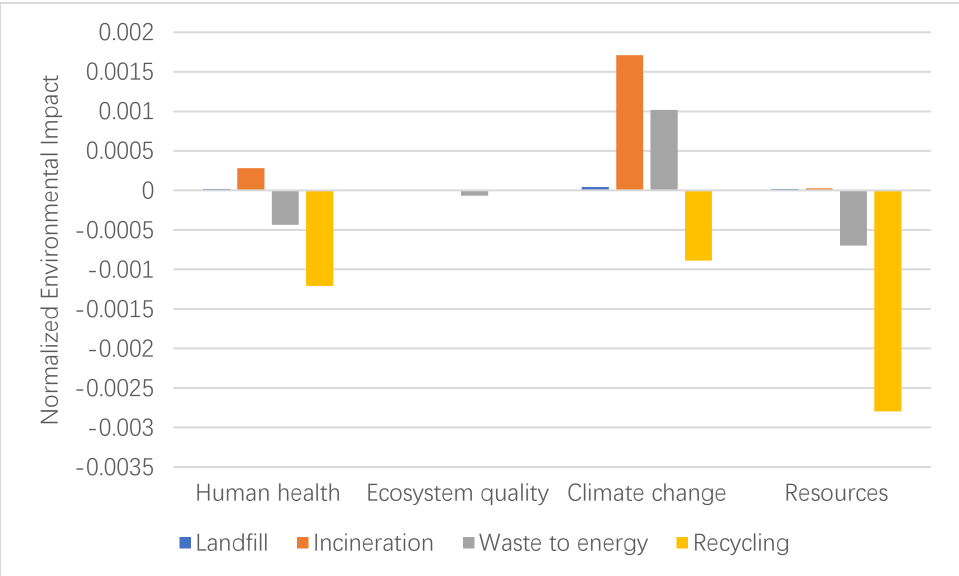


Figure 3 Normalized environmental impacts of different treatment methods of plastic film wastes

Recycling is the best option among the four in terms of these environmental impact categories. The only exception is the ecosystem quality, where incineration with energy recovery is the most environmental-friendly option, however it is negligible in compare with other impacts. To have a deeper understanding on environmental impacts of different recycling scenarios, we modify the input parameters and come up with their environmental impacts accordingly.

4.2 Environmental impacts of different recycling scenarios

There are 4 different parameters contribute to the total environmental impacts occurred at recycling: collection of the wastes; resources and utilities at material recovery facility (MRF); disposal of the residues produced at MRF; and the environmental benefits brought by avoided virgin plastic resins. The variation on each parameter can potentially influence the overall environmental behavior. The normalized environmental impacts of different scenarios, which are defined below, is shown in Figure 4.

1. Wastes collected at curbside in urban area, residuals WTE;

2. Wastes collected at curbside in urban area, residuals landfilled;
3. Wastes collected at curbside in rural area, residuals WTE;
4. Wastes collected at curbside in rural area, residuals landfilled;
5. Wastes collected by commercial drop-off, residuals WTE;
6. Wastes collected by commercial drop-off, residuals landfilled;

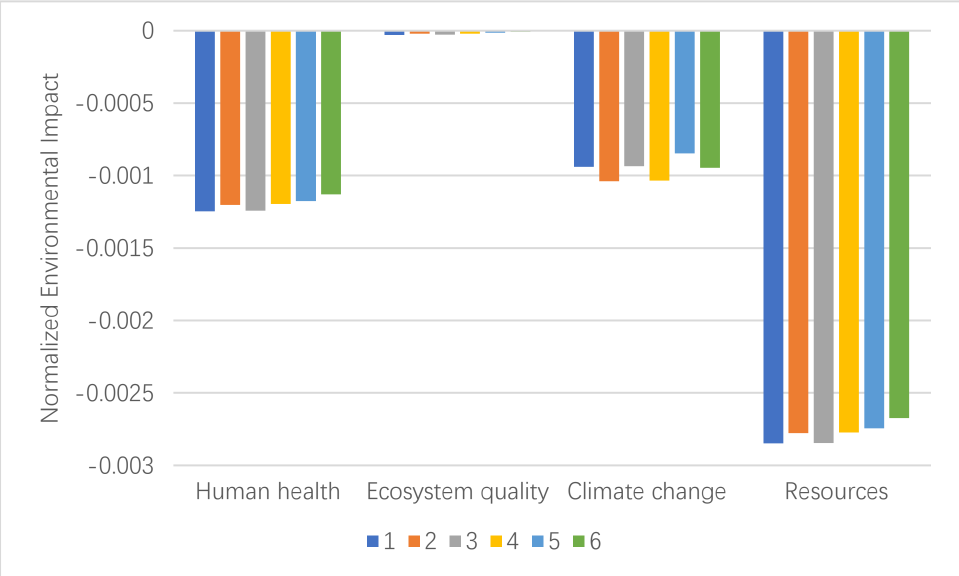


Figure 4 Normalized environmental impacts of different recycling scenarios

From the charts, we can see that with the same collection method, incineration with energy recovery is the better residue disposal method in terms of environmental impact (with most negative values) than landfilling. And recycling with consumer drop-off generates less environmental benefits than curbside collection. However, it's also noticeable that the differences are not significant. To find out the actual contribution of different inputs, we went through the network and the results is shown in Figure 5.

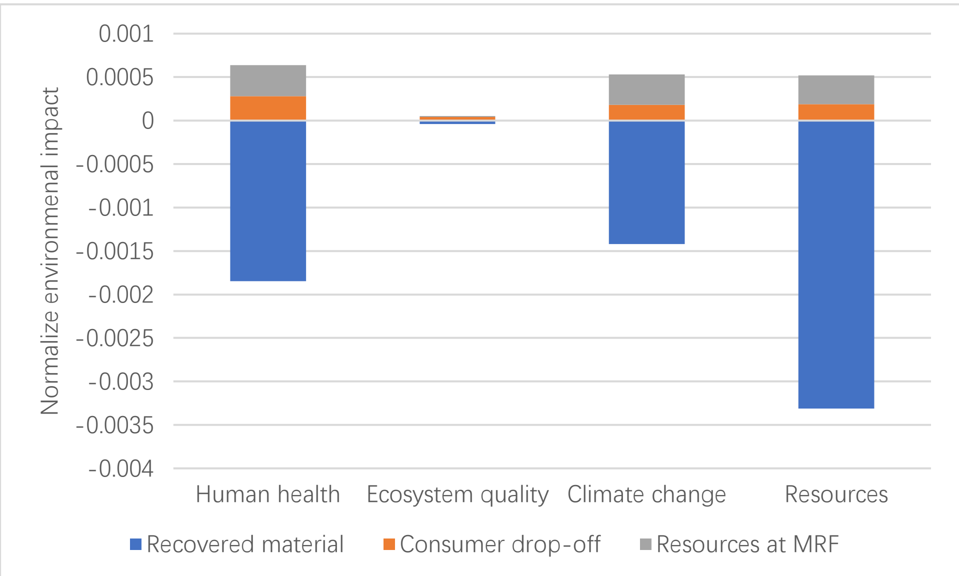


Figure 5 Contribution of different factors in plastic film wastes recycling (collected at urban area, residuals

landfilled)

The environmental benefits brought by avoided virgin materials dominate the environmental impacts occurred at the recycling process. It is the same story for the other 5 scenarios, with smaller values at collection phase.

4.3 Sensitivity analysis

Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs (Saltelli). We have five points of sensitivity to test:

1. Recycling rate;
2. Waste to energy conversion efficiency;
3. Collection distance;
4. Electricity consumption at material recovery facility;
5. Diesel use at material recovery facility.

The results of sensitivity analysis are shown in Figure 6 to Figure 10

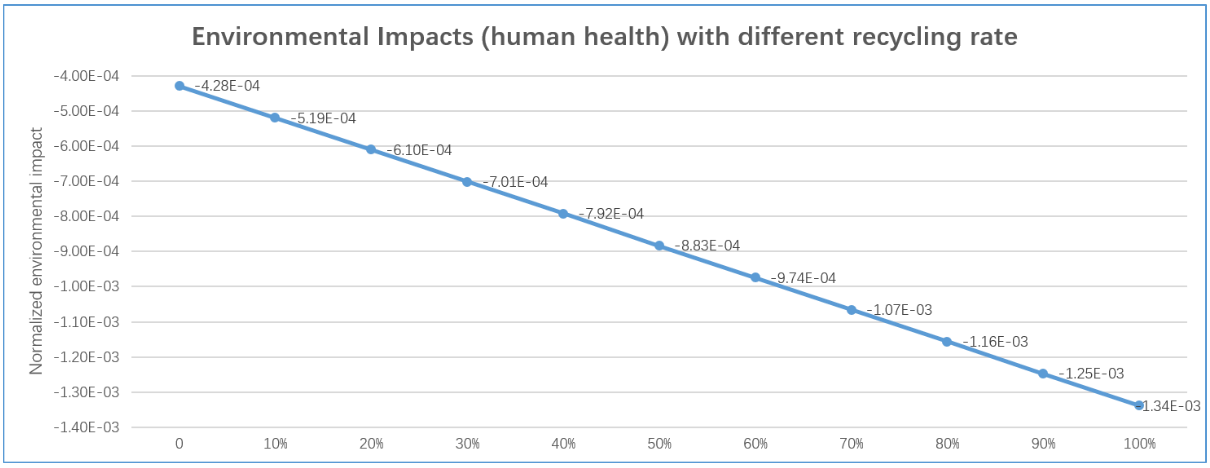


Figure 6 Sensitivity Analysis on recycling rate

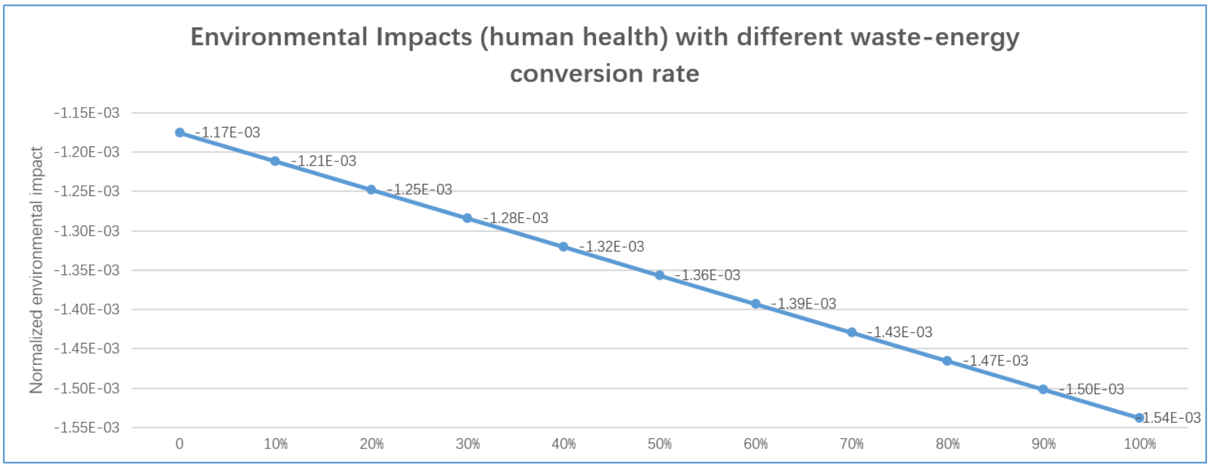
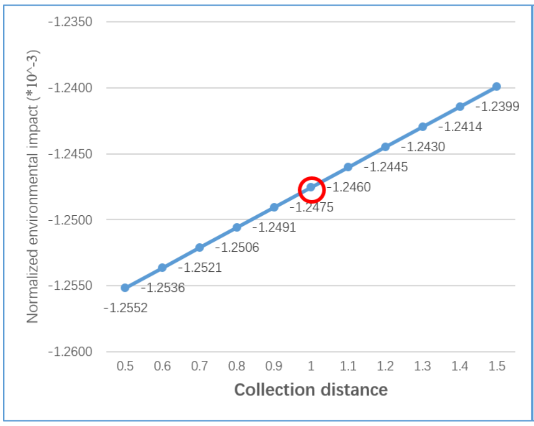


Figure 7 Sensitivity analysis on waste to energy conversion efficiency

In our study, the default values of recycling rate is 90% and waste to energy conversion rate is 20%, and the normalized environmental impact on human health is 1.25E-03. In the sensitivity analysis, we test the environmental impacts with different recycling rate, from 0 to 100% and different energy conversion rate, from 0 to 100%. The normalized environmental impacts with different recycling rate range from -4.28E-04 to -1.34E-03 while the results range from -1.17E-03 to – 1.54E-03 with different waste to energy conversion rates. Recycling rate is a more sensitive input in the setting, however, it should be clarified that waste to energy conversion efficiency could be more sensitive in scenarios with low recycling rate since more wastes will be sent to incinerator, which will make incineration with energy recovery more important to the total environmental impact.



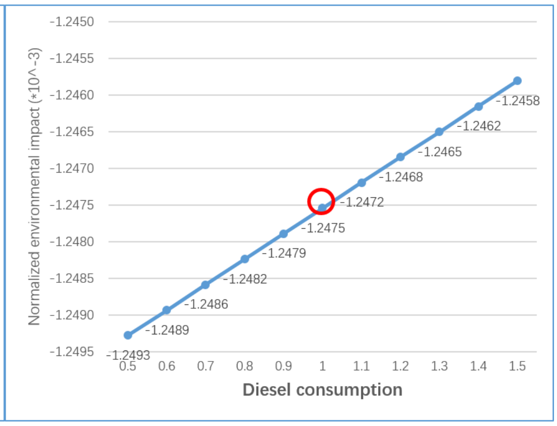


Figure 8

Figure 9

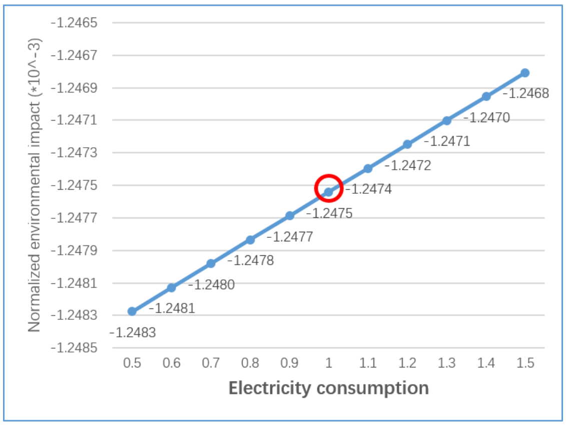


Figure 10

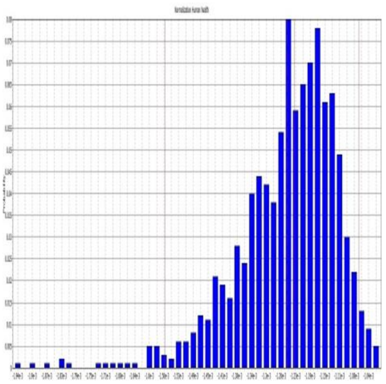
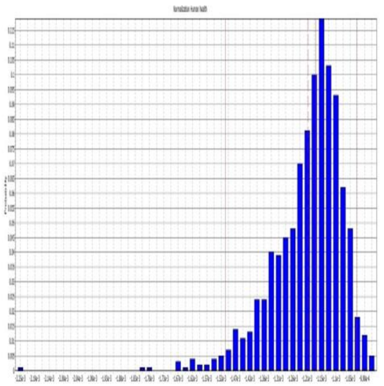
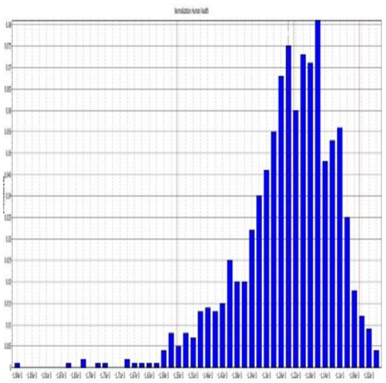
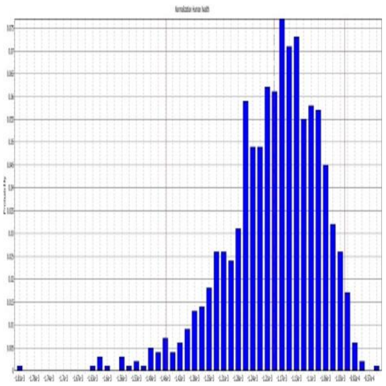
Figure 8-10 present sensitivity analysis on collection distance, and diesel and electricity consumption at MRF. On the x axis, 1 represents the input used in our study, 1.1 is 10% more and 0.9 is 10% less, so in total we have -50% to 150% of the inputs for these three analysis. The ranges are very narrow for the sensitivity analysis on these three variables. They are less sensitive than recycling rate and conversion efficiency in this study. We have known that collection distance and resources consumptions don't play important role in the total environmental impact from Figure 5, this makes sense that they are also not sensitive. However, this could be different for other studies where these three variables play more important roles.

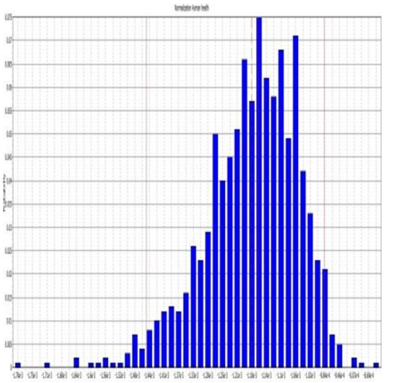
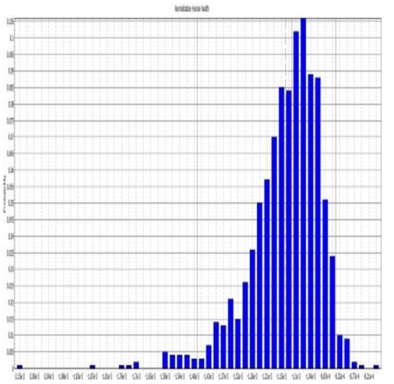
4.4 Uncertainty Analysis

At LCI level, the uncertainty introduced into inventory due to the cumulative effects of input uncertainty and variability of inventory data was quantified by using either statistical methods or expert judgment-based approach (Guo & Murphy, 2012). At the LCIA level, Monte Carlo simulation was applied to estimate the uncertainties of LCIA results. Based on the uncertainty of LCI data expressed as a probability distribution, the Monte Carlo function built in SimaPro 7.0 software was run with 1000 iterations at a significance level $\alpha = 0.05$, and the distribution of environmental impacts will be displayed below. From the graph we can see the frequency of different values of environmental impact and hence interpret the difference between each other.

Table 3 Uncertainty analysis of 6 scenarios on the impact of human health

Scenario	Distribution	Mean	Median

1. Wastes are collected at curbside in urban area, processed at MRF, residuals landfilled;		-0.00125	-0.00123
2. Wastes are collected at curbside in urban area, processed at MRF, residuals incinerated;		-0.00120	-0.00118
3. Wastes are collected at curbside in rural area, processed at MRF, residuals landfilled;		-0.00124	-0.00123
4. Wastes are collected at curbside in rural area, processed at MRF, residuals incinerated;		-0.00119	-0.00118

5. Wastes are dropped off by consumer, processed at MRF, residuals landfilled;		-0.00118	-0.00116
6. Wastes are dropped off by consumer, processed at MRF, residuals incinerated;		-0.00114	-0.00111

5. Conclusion

Recycling of plastic film wastes provide significantly larger environmental benefits among all the treatment methods. Different collection distances and residue disposal methods will not have much effect on the final results. To ensure the environmental benefits of recycling, we need to keep the recycling rate and energy recovery efficiency at a reasonable high level. In the last, we cannot single out plastic film from all other wastes, we need to do more research on other waste recycling to have a more comprehensive view of the waste recycling.

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