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Life cycle assessment of end-of-life treatments for plastic film waste

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ABSTRACT

Plastic film waste can cause a variety of environmental impacts and pose a significant challenge for the consumer product industry. Understanding the environmental tradeoffs of various end-of-life strategies for plastic film waste is thus important for developing and deploying appropriate sustainable solutions. In this paper, we use life cycle assessment (LCA) to assess the environmental impacts of various plastic film waste treatment systems. We consider four different waste treatment scenarios for plastic films: landfill disposal of mixed waste; incineration of mixed waste; recycling of mixed waste; and recycling of recyclable waste. The results demonstrate a considerable advantage of recycling over landfill disposal or incineration. The main environmental benefit is from the recycle of plastics that can substitute for the production of plastics from virgin materials. From a sensitivity analysis, five key parameters are identified that affect the aggregate environmental impact including mass fraction of films in the waste, recycling rate, utilization rate, waste-to-energy conversion rate, and the type of energy can be substituted by the recovered energy from incineration.

1. Introduction

Film-based packaging, also known as flexible packaging, refers to any package or portion of a package for which the shape can be easily changed, including bags, pouches, labels, liners, wraps, rollstock, or other flexible products (Flexible Packaging Association, 2016). Flexible packaging utilizes the best qualities of materials such as plastic, paper, and aluminum foil to deliver a wide range of protective functions within the smallest possible amount of material (Flexible Packaging Association, 2016). Each flexible package is produced with particular film that has a unique combination of attributes for a specific application. For example, low-density polyethylene (LDPE) films have high clarity and moderate stretch ability, which can be used as bread bags. Conversely, high-density polyethylene (HDPE) films have certain degree of opacity and low stretch ability, which can be used as grocery bags and air cushions for packaging.

Owing to its adaptability and capability for conserving resources, the production of flexible packaging has been steadily growing over the past 10 years. In 2016, annual sales of flexible packaging in the U.S. were about $30.2 billion, comprising 19% of the $164 billion U.S. packaging industry and its second largest segment (Flexible Packaging Association, 2017).

The scale of plastic film production causes significant environmental impacts. After entering the marine environment, plastic waste is ingested by 44% of seabird species, and at least 267 species of marine organisms are affected by plastic waste around the world (Moore, 2008). Most film waste is currently disposed with other municipal waste. Landfill disposal, the conventional approach for municipal waste management, requires a large amount of space, and has been identified as one of the major sources of methane emissions contributing to climate change (Kumar et al., 2004). Incineration reduces the need for landfill disposal and can recover energy from combustion of waste. However, hazardous air pollutants are generated and released during incineration (Wiles, 1996). Recycling meanwhile is generally recognized for its environmental benefit of allowing the reuse of discarded materials. Recycled plastic films can be used to make various new products, such as composite lumber, crates, and bags (The Association of Plastic Recyclers, 2018). Nonetheless, a survey of programs in 2010 shows that curbside sites for bag and film recycling are only accessible to 10.8% of the U.S. population (Moore Recycling

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Associates, 2012). Only few curbside collection programs accept plastic films because post-consumer films must be clean and dry to be recycled and films can clog sorting machines at materials recovery facilities (MRF) (The Association of Plastic Recyclers, 2018). Moreover, the collection and transportation of recyclable waste also consume energy and resources, the amounts of which vary and depend on the location and type of waste. Given these considerations, an analysis is presented herein of the environmental burdens and benefits of various end-of-life treatments for plastic film waste.

Life cycle assessment (LCA) is a method to assess the holistic environmental impacts of a product or process in all of its life cycle stages, including resource extraction, materials processing, manufacturing, transport, use, and end-of-life disposal. Because it encompasses all stages of a product's life cycle and a wide range of environmental impacts, LCA can help direct policy and technology development to avoid environmental burden shifting among different stages and types of impacts. Since the 1990s, researchers have conducted various LCA studies on waste management strategies (Mølgaard, 1995; Barton et al., 1996; Craighill and Powell, 1996). Björklund and Finnveden (2005) reviewed 40 LCA case studies and found that recycling is, in most cases, preferable to landfill disposal or incineration with respect to life cycle energy use and global warming potential. Laurent et al. (2014) reviewed 222 LCA studies of solid waste management systems and concluded that the LCA results largely depend upon local attributes.

The majority of the reviewed studies focused on solid waste management in Europe, with only a few addressing solid waste management in North America. Morris (2005) concluded that for most conventionally recoverable materials, recycling consumes less energy and imposes lower environmental burdens than landfill disposal or incineration. Cabaraban et al. (2008) determined that bioreactor landfill disposal is favored over in-vessel composting in terms of energy use, cost, and airborne and waterborne emissions. To balance environmental impacts and costs, Thorneloe et al. (2007) used a municipal solid waste decision support tool to assess options for waste management. Kaplan et al. (2009) applied an optimization model and showed that the most cost-effective option for solid waste management is to implement curbside recycling for only a portion of the population. Overall, these previous studies have mainly focused on conventional recoverable materials, such as cardboard, mixed paper, aluminum cans, and plastic bottles. The life cycle environmental impacts of plastic film waste have not been investigated. In this research, we evaluate the life cycle environmental impacts of three end-of-life treatments for post-consumer plastic films: recycling, landfill disposal, and incineration. Our results consider the tradeoffs between these options and identify processes within the waste management system that significantly contribute to environmental impacts. These insights are intended help guide the development of waste management strategies for post-consumer plastic films.

2. Material and methods

This study is conducted according to the standard four-step LCA procedure of ISO14040/14044 (ISO, 2006), as outlined in the following sections.

2.1. Goal and scope definition

The overall goal of the study is to compare the life cycle environmental impacts of several end-of-life treatments for post-consumer plastic films. Specific goals are to: (1) evaluate and compare environmental impacts of different end-of-life treatments under various collection and waste composition scenarios; (2) identify key parameters affecting the environmental impacts of film waste treatments; and (3) inform film waste management decisions.

The functional unit is chosen to be the film waste contained within one metric ton of either recyclable waste or mixed waste. Following Pressley et al. (2015), the mass fraction of plastic films is assumed to be 0.6% and 2% in recyclable waste and mixed waste, respectively.

The system boundary is defined as spanning from post-consumption to end-of-life (Fig. 1). After a packaged product has been used, its plastic film packaging, or any portion of the product that contains a plastic film, is discarded into either a mixed waste or a recyclable waste stream. Mixed waste is collected by trucks and sent to either a landfill site, an incinerator for energy recovery, or a materials recovery facility (MRF) for recycling. Recyclable waste is

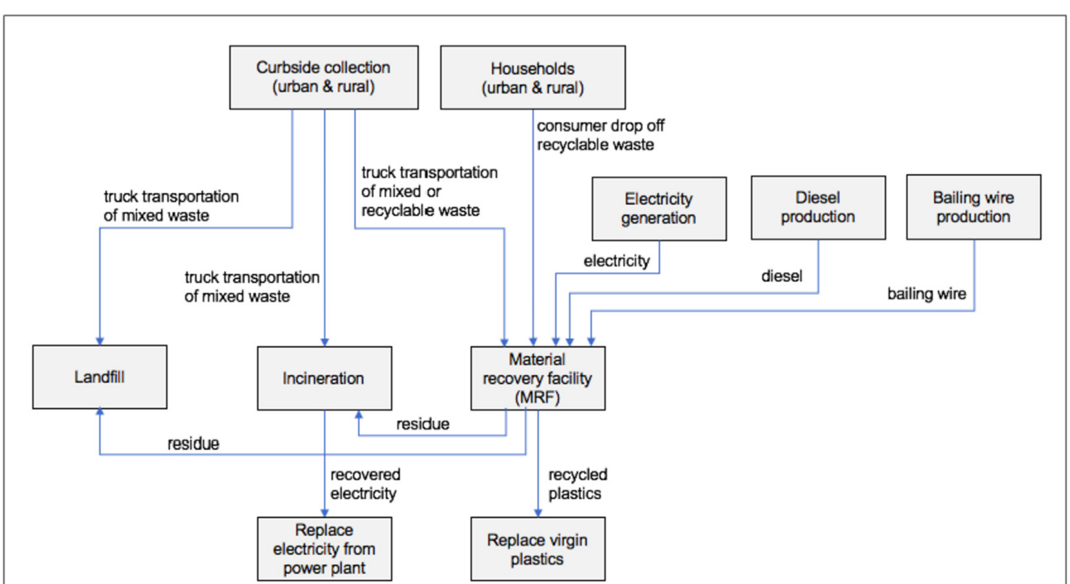

Fig. 1. Process flow diagram of the post-consumer plastic film treatment system.

either collected by trucks or dropped off by consumers to specific collection sites, and then transported to a MRF for recycling. Residues generated during recycling are sent to landfill or to incinerators for energy recovery. In total, four scenarios are considered herein:

- Landfill disposal of plastic films in mixed waste;
- Incineration of plastic films in mixed waste;
- Recycling of plastic films in mixed waste; and
- Recycling of plastic films in recyclable waste.

Upstream processes prior to the post-consumption phase, including the manufacturing and distribution of plastic film products. However, these are not included in the present analysis, given that the purpose of this study is to compare different end-of-life treatments, for which the upstream processes may be considered equivalent. This study focuses on plastic film treatments in the U.S. and represents the industrial average.

2.2. Life cycle inventory analysis

Life cycle inventory (LCI) analysis quantifies the material and energy inputs and emission outputs of a product system. In our study, most of the data for foreground processes, including collection and treatment of waste via landfill, incineration, or recycling, are obtained from peer-reviewed, published studies. References are given when specific data are described. Background process data for upstream material use and transport are from the EcoInvent 2.2 database (EcoInvent, 2010). After all unit process data are compiled, process models and life cycle inventories are constructed for various film waste treatment scenarios using the SimaPro 8.4 LCA software environment (Pre Consultants, 2017).

2.2.1. Waste collection

The collection distance for waste includes its transportation by the collection vehicle starting from the garage where the vehicle is parked and maintained, along the waste collection route, to the destination where the waste is offloaded (e.g., a MRF or incinerator), and then back to the garage. Table A.1 shows the collection distances for recyclable and mixed waste for typical urban locations in the U.S. Nguyen and Wilson (2010) reported that a kilogram of waste collection in rural areas requires approximately 5–6 times as much fuel as an urban route. Therefore, the collection distance for the rural scenario is obtained by multiplying the collection distance for the urban route by a factor of 6. Overall, the collection distance for recyclable waste on a unit mass basis is longer than for mixed waste because the amount of recyclable waste collected is smaller for a given route. For consumer drop-off, a default value of 10 miles (16.1 km) multiplying the fraction of dedicated trips (50%) is used for the roundtrip distance to drop-off site as obtained from the Municipal Solid Waste Decision Support Tool (MSW-DST) (Thorneloe et al., 1999) developed by the U.S. Environmental Protection Agency (EPA).

The above-mentioned collection distance indicates the distance per collection trip, which divided by the collected waste mass per trip derives the total distance for collecting per functional unit waste. Distance for transporting film waste is then calculated by multiplying the corresponding film mass fraction in recyclable or mixed waste (0.6% and 2%, respectively) (Table A.2). For mixed and recyclable waste collection by trucks, the EcoInvent 2.2 process for truck transport of municipal waste is used to characterize the environmental impact of waste collection (EcoInvent, 2010). For consumer drop-off, the corresponding process for passenger cars is used.

2.2.2. Recycling at MRF

Waste collected and sent to a MRF is sorted to separate and process its recyclable content. Electricity and diesel are consumed at MRF, and bailing wire is used for bundle recycled material. Table A.3 lists the energy and material consumption at a MRF for processing one metric ton of waste. Table A.4 shows the corresponding energy and material consumption with allocation to the film component of the waste stream based on their mass fraction in the waste. These data are for mechanical separation, the mainstream technology used for recycling at a MRF. Incidentally, if accepting film waste, equipment in MRF must be designed or modified to meet the special needs of recycling plastic films. For example, the blades must be properly sharped in order to sheer the films due to their soft, thin and malleable characteristics. Otherwise, films will wrap around the blades and clog the equipment (Testin and Vergano, 1997).

2.2.3. Replace virgin plastics

Recycled plastic films can be used to make composite lumber. They can also be processed into small pellets as raw material substitutes for making new plastic products. According to Pressley et al. (2015), the recycling rate of films is 90% for recyclable waste and 77% for mixed waste. The utilization rate of the recycled films is approximately 66% in the U.S. (Moore Recycling Associates Inc, 2016), which means 66% of the recycled films can be actually used to replace virgin plastic materials. Therefore, multiplying the recycling rate, utilization rate, the composition of film waste, and the mass fraction of films in recyclable waste or mixed waste yields the amount of recycled films. The composition of polymers in film waste is calculated based on the specific types of plastic films and the corresponding polymer composition (Table A.5). Unit process data are shown in Table A.6, in which negative signs indicate outputs for the corresponding processes. The virgin plastics production processes in EcoInvent 2.2 (EcoInvent, 2010) are used to assess the environmental burdens avoided by virtue of plastic film recycling. Here, energy consumption associated with using recycled plastics for packaging applications is not considered, assuming it is the same as using virgin plastics.

2.2.4. Incineration

After film waste is processed at the MRF, the generated residue can be sent to incinerators for energy recovery. The residue rate is 76% for mixed waste and 10% for recyclable waste (Pressley et al., 2015). Collected mixed waste can also be directly sent to incinerators without recycling. Here, consideration is limited to energy recovery from the combustion of plastic films. It is assumed that the composition of the plastic films in the residue is the same as in the film waste. Table A.7 lists the plastic film composition in the residue sent for incineration and the heating value of each type of polymer. The amount of energy generated from combustion of these polymers is calculated assuming an electricity conversion efficiency of 7.7% (Wollny et al., 2001). From the electricity recovered, the mass fraction of the film waste, and the residue rate, the unit process data for incineration is obtained (Table A.8). The emission of hazardous substances such as dioxins generated by incineration are characterized using the incineration datasets in the EcoInvent 2.2 database (EcoInvent, 2010).

2.2.5. Landfill

As an alternative to incineration, residues generated at MRFs and collected mixed waste can be sent to landfill. The amount of film waste that goes to a landfill for burial corresponds to its mass fraction in the mixed waste. For MRF residues, the amount of waste designated for landfill disposal is calculated by multiplying the residual rate of the mixed or recyclable waste with the mass fraction of plastic films in the waste stream (Table A.9). Data characterizing the environmental impacts of landfills are acquired from the EcoInvent 2.2 database (EcoInvent, 2010).

2.3. Life cycle impact assessment

The Building for Environmental and Economic Sustainability method (BEES 4.0) (Lippiatt, 2007) is used to transform the life cycle inventory results into corresponding impact category measures. BEES was developed based on the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) (Bare, 2011). TRACI includes the impact categories of global warming potential, acidification potential, eutrophication potential, fossil fuel depletion, habitat alteration, criteria air pollutants, human health (cancer and non-cancer), smog, ozone depletion, ecological toxicity, and water intake. BEES utilizes these same impact categories and adds an impact measures indoor air quality.

The U.S. EPA Office of Research and Development has developed normalization factors for TRACI (Bare et al., 2006) that also apply to BEES. These factors normalize the relative significance of each impact category compared with national averages per capita per year, allowing comparisons across the various impact categories.

In addition to measuring environmental impacts by different categories in TRACI, BEES further includes weight for each impact category to aggregate all categories of impacts into a single score. We use the most recent weighting scheme developed in 2006 by EPA.

2.4. Interpretation

Since the scenarios investigated in this study do not comprehensively represent all prospective plastic film end-of-life treatments, analyses are conducted to identify and assess the sensitivity of the results to key parameters. Parameters so considered include the collection distance, electricity and diesel consumption at the MRF, recycling rate at the MRF, utilization rate of recycled films, waste-to-energy conversion ratio of the incinerator, type of energy can be substituted by the recovered energy, and mass fraction of films in the waste.

3. Results

Five waste collection scenarios and four MRF residue treatment scenarios are initially considered. The respective “worst-case” scenarios for mixed waste and for recyclable waste are then used as pessimistic conservative estimates to calculate the life cycle impacts of landfill disposal, incineration, and recycling of film waste.

3.1. Comparison of collection scenarios

Fig. 2 shows a comparison of the five collection scenarios. Among these scenarios, consumer drop-off has the highest environmental impact. This is because a passenger car hauls a much smaller amount of waste than a truck does; thus more passenger vehicle trips are needed to accumulate the same amount of waste that can be hauled by a truck. Waste collection in urban areas has a lesser environmental impact than in rural areas on account of the shorter collection distance. The principal environmental impacts attributed to collection are global warming, from carbon dioxide emissions during truck transportation; smog, from nitrogen oxides and particulate matters emissions; and natural resource depletion due to crude oil-based fuel consumption.

3.2. Comparison of MRF residue treatment scenarios

Fig. 3 shows a comparison of the four MRF residue treatment scenarios. Positive values indicate an environmental burden, whereas negative values denote an environmental benefit. Incineration has greater environmental burdens than landfill waste disposal across most of the impact categories. The principal impacts occur in the global warming category due to CO_2 emissions from incineration and the eutrophication category due to chemical oxygen demand in water. Environmental benefits principally accrue from energy recovery during incineration, which avoids the use of fossil fuels and to some extent therefore mitigates eutrophication, water resource appropriation, and natural resource depletion.

3.3. Comparison of waste treatment scenarios

Based on the results shown in Figs. 2 and 3, a “worst-case”

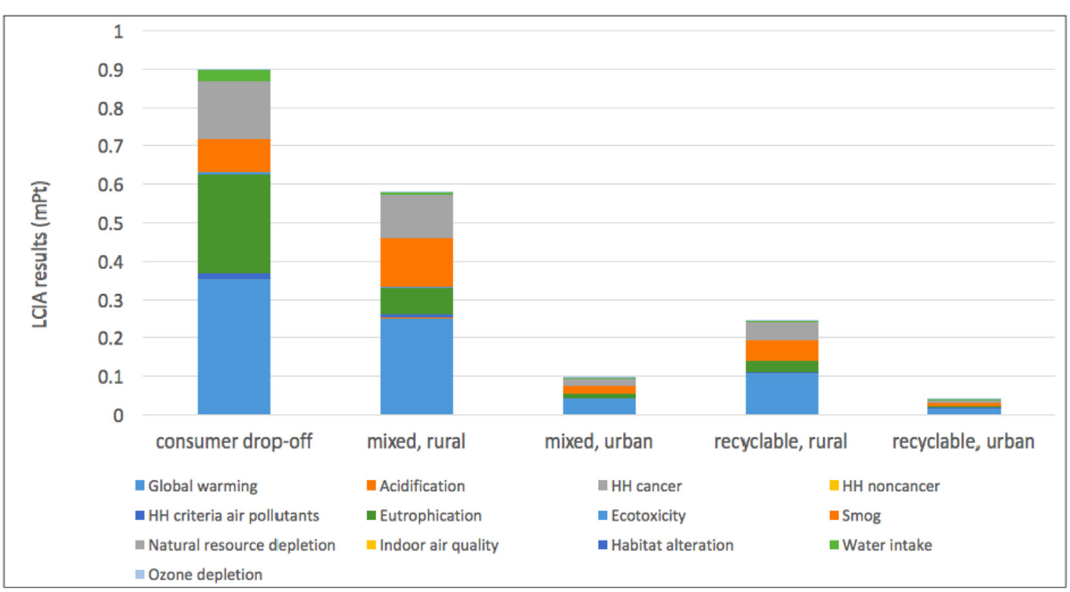

Fig. 2. Environmental impacts of different collection scenarios.

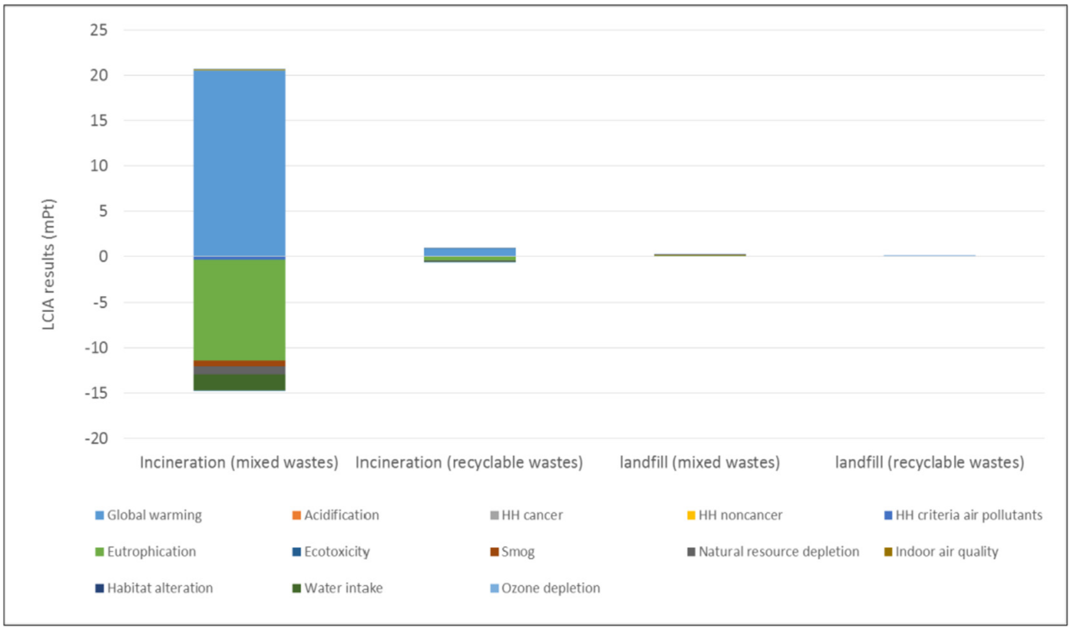

Fig. 3. Environmental impacts of different MRF residue treatment scenarios.

scenario is chosen that considers the disposition of waste gathered along a rural collection route, with incineration of the residues that are generated when waste is sent to a MRF for processing. Note the consumer drop off scenario is not considered because it is currently not a common practice and will not be encouraged based on our analysis. Fig. 4 compares the life cycle impacts of landfill disposal, incineration, and recycling (with incineration of MRF residues) of plastic films in mixed and recyclable waste streams. The results indicate that recycling of either mixed or recyclable waste confers a greater environmental benefit than either direct incineration or landfill disposal of mixed waste. Mixed waste recycling delivers a larger benefit than the recycle of "recyclable" waste, because the mass fraction of film waste is larger in mixed waste than in recyclable waste. The benefits of recycling are mainly manifested in the lower natural resource depletion, water intake, and eutrophication associated with the avoidance of virgin material production for plastic packaging.

3.4. Comparison of different stages for recycling mixed waste

Fig. 5 shows the environmental impact results broken down by process step for the "best-case" scenario of Fig. 4 involving the recycle of plastic films from mixed waste. The incineration of the MRF residue is responsible for the largest environmental impacts, followed by environmental burdens associated with collection. The impact of MRF is almost negligible. The largest environmental

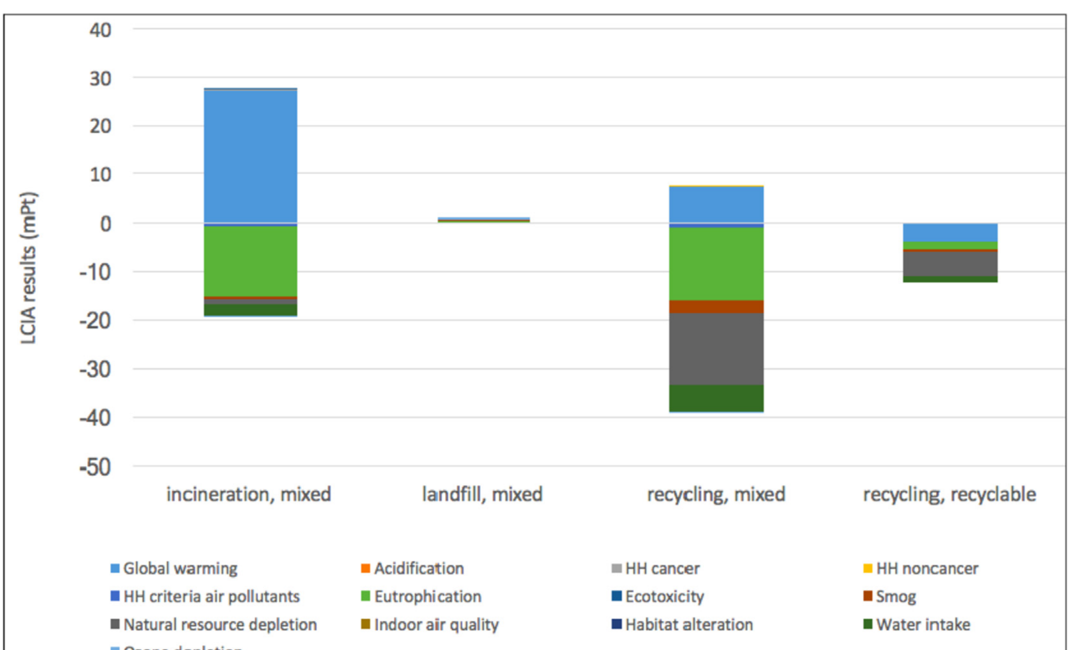

Fig. 4. Environmental impacts of different plastic film end-of-life treatment scenarios.

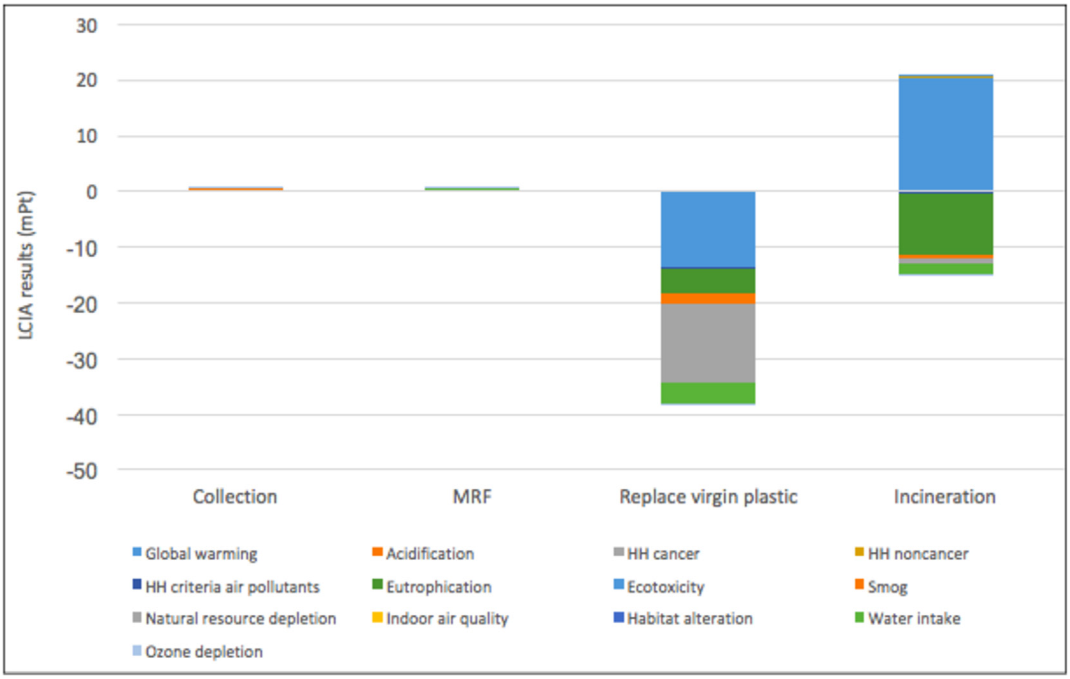

Fig. 5. Environmental impacts of recycling plastic films from mixed waste by process step.

benefit is from replacing virgin plastics, which reduces natural resource depletion and global warming.

3.5. Sensitivity analysis

Table 1 shows the results of sensitivity analysis, wherein the sensitivity is calculated as:

$$Sensitivity = \left|\frac{\Delta output/output}{\Delta input/input}\right|$$

The aggregate environmental impact is relatively insensitive to collection distance and to electricity and diesel consumption at the MRF. This is because, as observed in Fig. 5, the collection and MRF process stages are lesser contributors to the overall life cycle impact. In contrast, the model results are more sensitive to the mass fraction of films in the waste, utilization of combustion energy recovered at the incinerator, recycling rate at the MRF, and utilization rate of recycled plastic films. It bears noting that incinerator energy recovery only reduces the overall environmental impact (as measured through single-score results) if the recovered electricity displaces coal-fired power. Displacement of electricity generation from other energy sources, including natural gas, nuclear, solar photovoltaic, and hydropower, is not warranted according to the sensitivity analysis.

4. Discussion

Interpretation of the findings of this study is subject to several limitations. First, the analysis presented herein presumes the continuation of the current practice that plastic film waste is commingled with other mixed or recyclable waste. It may indeed be environmentally beneficial to separately recycle plastic films with dedicated locations and channels for film recycling. This would presumably require additional transportation, equipment, and operations. On the other hand, recycled plastic films substitute virgin materials and avoid the environmental impacts associated with the extraction and processing of these virgin materials. The cost-benefit analysis for the separate recycling of plastic films is a worthwhile subject that requires additional effort to investigate.

Second, the foreground unit process data in this study are all collected from peer-reviewed literature. Some of these data may not represent the industrial average of the U.S. For example, the data for collection distances in Table A.1 represent a city in the U.S., and the data for waste-to-energy conversion rates in Table A.7 reference incinerators operating in Germany. Sensitivity analysis is therefore performed to assess the effects of parametric variations. For consistency, background data are all obtained from the EcoInvent database, but when U.S.-based data are unavailable, European data are substituted, as in the case for the incineration and virgin plastic production processes.

Third, life cycle cost is not analyzed in this study. The evaluation of economic costs, as well as the potential social impacts of plastic film waste recycling, are required for a comprehensive sustainability assessment that will enable waste management planners and operators to make well-informed decisions (Ekvall et al., 2007).

5. Conclusions

The life cycle assessment conducted in this study indicates there is an environmental advantage for recycling plastic film waste rather than consigning it to landfill disposal or incineration. Recycling appears to be particularly favorable when the plastic film waste is recovered from mixed waste rather than from recyclable waste, on account of the higher mass fraction of plastic films in mixed waste, despite the lower recycle rate. This is not to suggest that recycling of plastic films from recyclable waste be discouraged. Rather, waste management. Instead, policies should encourage consumers to separate plastic films from mixed waste so as to increase the recoverable fraction of plastic films in recyclable waste. This is also confirmed by the sensitivity analyses that increasing the mass fraction of films in waste will significantly improve the environmental benefit of recycling.

Besides mass fraction of films in waste, sensitivity analysis also identified the recycling rate at the MRF, utilization rate, and incinerator waste-to-energy ratio as key parameters governing the life

Table 1
Parameters in the sensitivity analysis.

Parameters	Description	Baseline	Extent of variation	Change in LCIA single-score result relative to baseline	Sensitivity
Collection distance	Total distance traveled by vehicles to collect or drop off 1 ton of waste	1.08 km	75% longer	Increase 1.4%	0.02
			50% longer	Increase 0.9%	
			25% longer	Increase 0.5%	
			25% shorter	Decrease 0.5%	
			50% shorter	Decrease 0.9%	
			75% shorter	Decrease 1.4%	
Electricity and diesel fuel consumption at MRF	Electricity and diesel consumed at MRF to separate plastic film waste from other waste	0.156 kWh electricity and 0.546 MJ diesel	75% higher	Increase 0.9%	0.01
			50% higher	Increase 0.6%	
			25% higher	Increase 0.3%	
			25% lower	Decrease 0.3%	
			50% lower	Decrease 0.6%	
			75% lower	Decrease 0.9%	
Recycling rate at MRF	Percentage of plastic film waste that can be recycled	77%	50%	Increase 35%	1.22
			60%	Increase 22%	
			70%	Increase 9%	
			80%	Decrease 4%	
			90%	Decrease 17%	
Utilization rate of recycled plastic films	Percentage of recycled plastic films used to replace the virgin plastic	66%	50%	Increase 30%	1.22
			60%	Increase 11%	
			70%	Decrease 7%	
			80%	Decrease 26%	
			90%	Decrease 44%	
Waste-to-energy conversion rate at incinerators	Electricity that can be substituted by plastic film waste incineration	7.7%	10%	Decrease 24%	0.81
			20%	Decrease 129%	
			30%	Decrease 233%	
			40%	Decrease 338%	
			50%	Decrease 443%	
Type of electricity replaced at incinerators	Energy source replaced by electricity recovered from incinerating MRF recycling residues	US average mix	Coal	Decrease 47%	NA
			natural gas	Increase 48%	
			Solar photovoltaic	Increase 72%	
			nuclear	Increase 77%	
			hydro	Increase 80%	
Mass fraction of films in the waste	The weight percentage of films in the mixed waste	2%	5%	Decrease 299%	1.99
			10%	Decrease 797%	
			15%	Decrease 1296%	
			20%	Decrease 1794%	
			25%	Decrease 2292%	

cycle environmental impacts of plastic film end-of-life treatments. More investigation is needed to collect data to better characterize MRF recycling, utilization, and waste incineration processes. Technology development should consider improvements to MRF recycling, utilization, and waste incineration efficiency, as the analysis presented herein suggests that such efforts will deliver greater environmental rewards than shortening plastic film waste collection route distances or reducing energy consumption at MRF.

Consumer drop-off is found to have the highest environmental impacts because more trips are required to collect the same amount of waste compared to trucks. Therefore, on-purpose drop-offs are not encouraged. Effective policy design should consider how to make curbside collection sites available and convenient for more residents.

Since significant benefits are shown from recycling plastic films, additional resources should be dedicated to improving the overall recycling rate. There are still technical barriers for film recycling. Tailored equipment is needed for films recycling. However, to make the equipment investment economically variable, sufficient volume of plastic film waste is required. This requires the cooperation of multiple stakeholders. First, packaging designers should design clear and easy to understand labels indicating recyclability and provide necessary instructions, such as to keep the film dry and clean and to recycle it to specific collection sites. Second, communities should collaborate with industry experts to educate residents for plastic film recycling and encourage their participation. In addition, before the volume of recycled films is sufficient, public funding is required to make the recycling profitable.

Acknowledgement

This work was supported by Procter & Gamble through the MCubed Diamond Program at the University of Michigan.

Appendix

Table A.1
Transportation data for collecting one metric ton of waste.

Parameters	Mixed waste, urban	Mixed waste, rural	Recyclable waste, urban	Recyclable waste, rural	Consumer drop-off	Unit	Data source
Distance between collection route and destination	20	120	35	208	NA	km	Data for mixed and recyclable waste are from Jaunich et al. (2016);
Distance between destination and garage	28	168	40	241	NA	km	Data for consumer drop-off are from MSW-DST and Franklin associates, 2011
Distance between garage and collection route	6.0	36	3.5	21	NA	km	
Total distance	54	324	78	470	16.1	km	
Waste mass per trip	21[a]	21	21	21	0.015[b]	t	

Note.
[a] 21 is the load of the transport dataset we use in EcoInvent, assuming the truck is fully loaded.
[b] 0.015 is calculated by 16.9 pounds (household recyclables generated per week) times 2 (recyclables dropped off every other week) times 0.00045t/pounds.

Table A.2
Unit process data for collecting one metric ton of film waste.

Materials	Mixed, urban	Mixed, rural	Recyclable, urban	Recyclable, rural	Consumer drop-off	Unit	Upstream processes
Truck transportation	0.05	0.31	0.02	0.13	NA	t km	Transport, municipal waste collection, lorry 21t/CH S
Consumer transportation	NA	NA	NA	NA	3.15	km	Transport, passenger car {RoW} | market for | Alloc Def, S

Note: The units of the two transportation system processes in EcoInvent are different, because the mass of the freight contributes a larger fraction of the total transported mass for truck transport of waste than for consumer drop-off of waste using passenger cars.

Table A.3
Energy and material consumption at a MRF for one metric ton waste.

Parameters	Mixed waste	Recyclable waste	Unit	Data source
Electricity	7.8	6.2	kWh	Pressley et al., 2015
Diesel	0.7	0.7	L	
Bailing wire	0.6	0.3	kg	
Heat value of diesel	39	39	MJ/L	World Nuclear Association, 2016

Table A.4
Unit process data for MRF for disposal of one metric ton of film waste.

Materials	Mixed waste	Recyclable waste	Unit	Upstream processes
Electricity	0.16	0.37	kWh	Electricity, at grid, US/US
Diesel	0.55	0.16	MJ	Diesel, combusted in industrial equipment/US
Bailing wire	0.012	0.018	kg	Steel, unalloyed {GLO} market for Alloc Def, S

Table A.5
The composition of polymers in film waste.

Plastic film formats	bags	cut/ wrap	flow warp	wraps	lay flat/ pillow pouches	standup prouches	retort pouches	lidding	sleeve labels	shrink bunding	stretch films	retail carry bags	storage bags	trash bags	overall	Data source
Annual volume in 2012 (MM lbs)	4796	254	53	1365	3321	946	16	11	817	866	938	2212	612	1129	17336	Flexible Packaging Association, 2013
Composition of polymers in each plastic film format																
LDPE	61%	46%	–	72%	40%	32%	–	–	11%	100%	100%	19%	100%	100%		
HDPE	2%	11%	–	–	–	–	–	–	–	–	–	38%	–	–		
PET	–	–	–	–	29%	60%	18%	40%	21%	–	–	–	–	–		
PP	–	38%	100%	–	30%	–	42%	10%	5%	–	–	–	–	–		
PVC	–	–	–	–	–	–	–	–	54%	–	–	–	–	–		
PS	–	–	–	–	–	–	–	–	9%	–	–	–	–	–		
Calculated composition of polymers in film waste (MM lbs)																
LDPE	2926	117	0	983	1328	303	0	0	90.	866	938	420.	612	1129	9711	68.9%
HDPE	96	28	0	0	0	0	0	0	0	0	0	840.	0	0	964	6.8%
PET	0	0	0	0	963	568	3	4	172	0	0	0	0	0	1710	12.1%
PP	0	96	53	0	996	0	7	1	41	0	0	0	0	0	1194	8.5%
PVC	0	0	0	0	0	0	0	0	441	0	0	0	0	0	441	3.1%
PS	0	0	0	0	0	0	0	0	74	0	0	0	0	0	74	0.5%
Total															14095	100.0%

Table A.6
Avoided virgin plastics per metric ton of processed waste.

Materials	Mixed waste	Recyclable waste	Unit	Upstream processes
LDPE	−7.0	−2.46	kg	Polyethylene, LDPE, granulate, at plant/RER S
HDPE	−0.70	−0.24	kg	Polyethylene, HDPE, granulate, at plant/RER S
PET	−1.23	−0.43	kg	Polyethylene terephthalate, granulate, amorphous, at plant/RER S
PP	−0.86	−0.30	kg	Polypropylene, granulate, at plant/RER S
PVC	−0.32	−0.11	kg	Polyvinylchloride, at regional storage/RER S
PS	−0.05	−0.02	kg	Polystyrene, general purpose, GPPS, at plant/RER S

Table A.7
Energy generated from combustion of one metric ton of plastic film waste.

Polymer	Portion of film waste (%)	Lower heating value (MJ/ton)	Energy generated (kJ)	Data source
LDPE	68.9	44.3	30500	(Themelis and Mussche, 2014)
HDPE	6.8	44.3	3030	
PET	12.1	23.9	2900	
PP	8.5	44.3	3750	
PVC	3.1	19.2	600	
PS	0.5	41.5	216	
Total	100	–	41000	

Table A.8
Unit process data of incineration for disposal of one metric ton of waste.

Materials	Directly incinerated after collection (mixed waste)	Incineration after recycling at MRF		Unit	Upstream processes
		mixed waste	recyclable waste		
PE (LDPE &HDPE)	15.1	11.5	0.45	kg	Disposal, polyethylene, 0.4% water, to municipal incineration/CH S
PET	2.4	1.8	0.07	kg	Disposal, polyethylene terephthalate, 0.2% water, to municipal incineration/CH S
PP	1.7	1.3	0.05	kg	Disposal, polypropylene, 15.9% water, to municipal incineration/CH S
PVC	0.62	0.48	0.02	kg	Disposal, polyvinylchloride, 0.2% water, to municipal incineration/CH S
PS	0.10	0.08	0.003	kg	Disposal, polystyrene, 0.2% water, to municipal incineration/CH S
Energy recovered	−63.2	−48.0	−1.9	MJ	Electricity, production mix US/US S

Table A.9
Unit process data for landfilling one metric ton of waste.

Materials	Directly sent to landfill after collection (Mixed waste)	Landfill disposal of residues after recycling at MRF		Unit	Upstream processes
		Mixed waste	Recyclable waste		
Landfill waste	20	15.2	0.6	kg	Disposal, plastic plaster, 0% water, to inert material landfill/CH S

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