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Life Cycle Assessment of Recycling High-Density Polyethylene Plastic Waste

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ABSTRACT

Increasing production and use of various novel plastics products, a low recycling rate, and lack of effective recycling/disposal methods have resulted in an exponential growth in plastic waste accumulation in landfills and in the environment. To better understand the effects of plastic waste, Life Cycle Analysis (LCA) was done to compare the effects of various production and disposal methods. LCA shows the specific effects of the cradle-to-grave or cradle-to-cradle scenarios for landfill, incineration, and mechanical recycling. The analysis clearly indicates that increasing recycling of plastics can significantly save energy and eliminate harmful emissions of various carcinogens and GHGs into the environment. As recycling increases, the need for virgin-plastic production can be greatly reduced. Furthermore, the results of this study may help improve current mechanical recycling processes as well as potential future recycling methods, such as chemical recycling. Concerns about the current recycling/disposal methods for plastics have brought increasing attention to the waste accumulation problem. However, with the current COVID-19 pandemic, plastic accumulation is expected to increase significantly in the near future. A better understanding of the quantitative effects of the various disposal methods can help guide policies and future research toward effective solutions of the plastic waste problem.

KEYWORDS

Life Cycle Analysis (LCA); mechanical recycling; microplastic; chemical recycling; plastic policy

1 Introduction

Plastics are constantly and consistently used in our daily lives, surrounding us in all items, including parts of automobiles, food and beverage containers, and items of clothing. The versatility for this type of material is expanding, creating a higher demand, and thus, higher rates of production. Plastic production has been increasing exponentially since 1950, but recently, alarming rates of 350 million tonnes of plastic are being produced annually [1–5]. Of the accumulated plastic, only 9% is recycled within the United States [4,5]. With 79% of plastics being sent to landfills, detrimental effects include the long degradation times and the release of toxins into the environment [2]. The other common option is incineration, which gained usage in the late 1990's. However, the effects of this method also release carcinogens and other chemicals into the air, contributing significantly to the environmental burden.



Low rates of recycling are prominent across countries, but more so in the United States. Countries such as India and South Korea have higher rates of recycling at 60% and 45%, respectively [6]. It should also be noted that these countries have strict guidelines and policies to ensure compliance of consumers and industries. To help solve the plastic waste problem, specifically within the United States, more education and understanding are needed to guide policymakers as well as plastic producers.

To help understand the extent of the plastic accumulation problem, Life Cycle Analyses (LCA) have been employed to assess the effects of various production and disposal methods. LCA is an analysis tool that calculates environmental impacts of a material, considering the manufacturing, transport, handling, and disposal of the product. Previously, this method has been used to understand effects of producing certain novel polymers, such as bio-based polymers. However, there is limited research on the disposal scenarios of olefin-based plastics [7–11]. More recently, LCA has begun to be used to determine the effects of packaging re-use in various countries in Europe and Asia. However, LCA for the plastic waste in the United States is limited. Rigamonti et al. [12] has used LCA to evaluate five scenarios of plastic waste management for Western European countries; specifically, they compared how much separation and sorting of the plastic waste should be done before the sorted plastics were sent to landfills or incinerators. This study did not take into consideration impacts regarding additional polymer processing (e.g., compounding) required to reuse plastic waste [12]. To expand these efforts, Khoo [13] performed an analysis of mechanical recycling of plastics in Singapore using LCA to assess the effects of the process and determine the value of converting these recycled plastics to usable forms of energy. The study emphasized the usefulness of recycling plants to handle large amounts of plastic waste in areas where land is limited for landfill disposal. Kreiger et al. [14] explored if 3D printing could be an energy-efficient method to mechanically recycle HDPE waste within the United States. This study concluded that if this method was used, the energy usage to produce 1 kg of HDPE can be reduced by 89%. However, little is reported about the energy consumption and the environmental burdens of different polymer processing steps within the mechanical recycling process, which is the focus of this study.

Here, LCA is used to understand the processing methods for recycling plastics. LCA was used to show general trends and quantitative results from energy consumption, greenhouse gas emissions (GHG), and various environmental burdens caused by landfilling, incineration, and mechanical recycling. As new technologies are being developed as potential solutions to the plastic accumulation problem, LCA can be a useful tool for comparing the impacts of various solutions. Upcoming technologies include the use and production of biopolymers, 3D printing from recycled plastics, and chemical recycling. These new methods will be discussed and compared with the conventional methods. As one important goal of conducting LCA studies is to inform and guide policy makers based on this holistic analysis; a policy discussion is presented at the end of this study.

2 Methods and Materials

2.1 Definitions in LCA

In the results presented further in this study, Life Cycle Analysis (LCA) in SimaPro 7.1 was used to determine the effects of production of novel plastics and processes related to handling and disposal of those plastics [15]. LCA is traditionally performed in software or Excel for a holistic evaluation so that unintended consequences can be avoided. At the time of collecting this data, SimaPro 7.1 was the available version of the software. Since then, SimaPro has been updated and has included various databases. Although newer and more specific values have been released, the conclusions from the results of this study remain consistent and can help guide policy discussion for reducing plastic accumulation.

Fig. 1 shows the different ways that LCAs are produced while Tab. 1 summarizes the terminologies used in LCA. Cradle refers to the raw materials needed to make polymers and materials that will be used to manufacture the final product. The gate includes the production and transportation of the product. These

two steps consist of the greatest portion considered in an LCA. Following the gate is the use of the product. Once the consumer has utilized the product, the material can follow through two pathways. The first includes grave, which is the disposal of plastics for no further use. In this specific scenario, the plastics would be sent to a landfill. The other option is to send the products back to the cradle, to be re-processed into a new product. This would be considered recycling of the plastics. Each of these steps requires energy and emits waste.

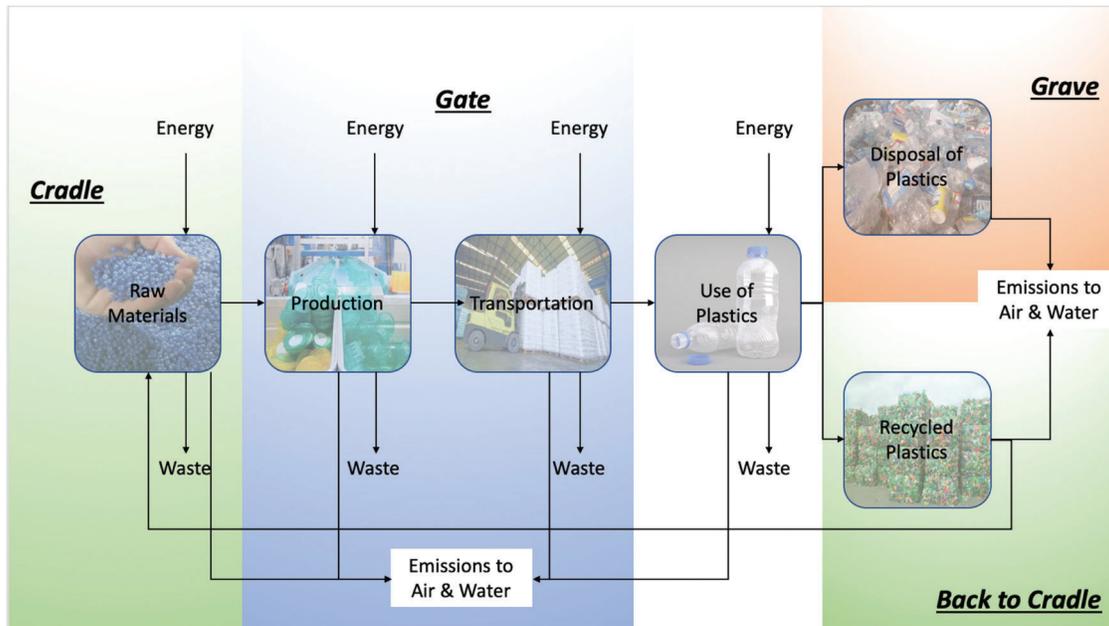


Figure 1: A Life Cycle Analysis (LCA) is differentiated amongst several parts, including cradle, gate, and grave. If the recycling process is to be evaluated, the product would be generated from the cradle and would be sent back to the cradle for production again

Table 1: Terminology and definitions in LCA

LCA Terminology	Definition	Example (i.e., a disposable water bottle)
Assembly	Formation of the product of interest	Formation of a disposable water bottle
Subassembly	Formation of parts of the product of interest	Formation of the cap and plastic wrapper found on a disposable water bottle
Cradle	Production of the product	Production of the water bottle, cap, labeling, etc. and ready for use
Gate	Transportation and handling of the product	Delivering and stocking the water bottle in the market
Grave	Disposal of the product	Landfill or incineration
Cradle-to-Cradle	Refers to the life cycle from the production of the production, including gate, and sending the product back to production (i.e., recycling product)	Following the production of the disposable water bottle, to being stocked in the store, mechanically recycled, and ready for re-production

(Continued)

Table 1 (continued).		
LCA Terminology	Definition	Example (i.e., a disposable water bottle)
Cradle-to-Gate	Refers to life cycle from the production of product to transportation and handling	Following the production of the disposable water bottle to being stocked in the store, ready for purchase or use
Cradle-to-Grave	Refers to life cycle from the production of the product to the disposal of the product (end-of-life)	Following the production of the disposable water bottle, to being stocked in the store, and sent to the landfill or incinerated

The general process of designing an LCA in SimaPro 7.1 is depicted in Fig. 2. SimaPro includes the processes and effects of the different aspects of a cradle-to-grave (i.e., landfilling or incineration) and cradle-to-cradle (i.e., mechanical recycling) scenarios. In this study, the life-cycle burdens and energy consumptions of three disposal scenarios were compared (landfilling, incineration, and mechanical recycling). More details about how to set up the LCA models are available in the Supplementary Data.

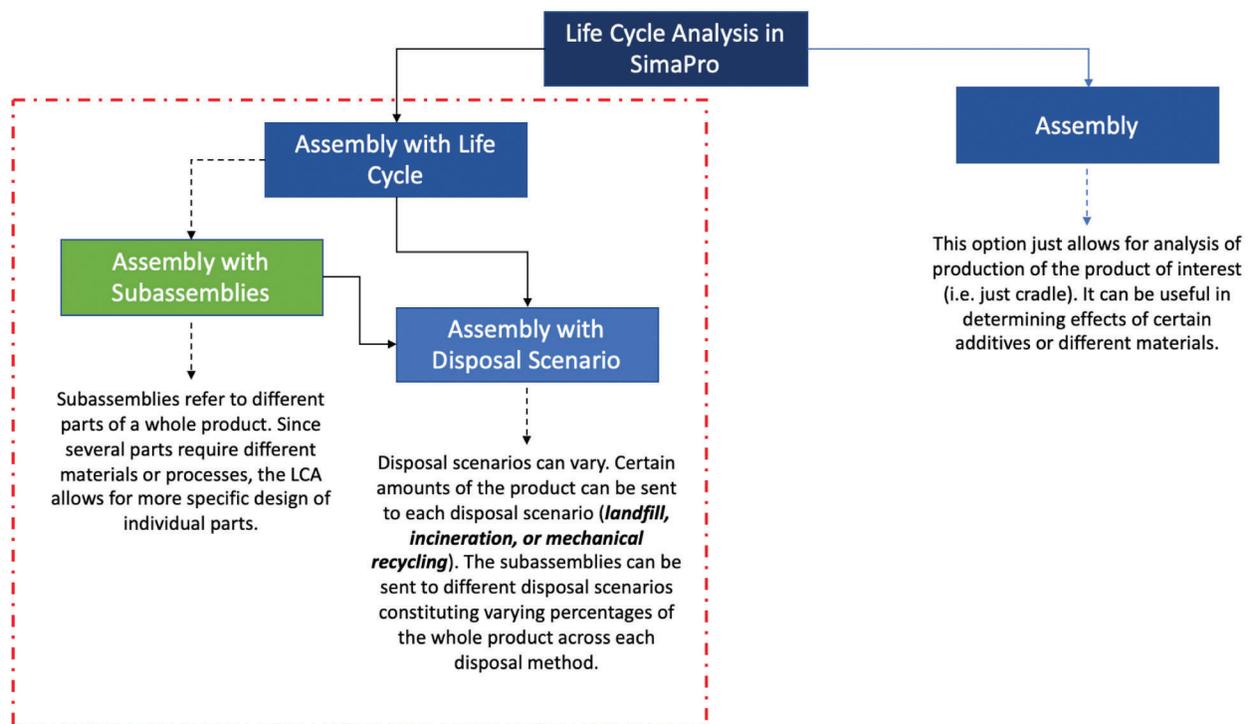


Figure 2: General stepwise process of creating an LCA in SimaPro 7.1. The left-hand side refers to the option that was chosen for this analysis. *Assembly with subassemblies* is an additional option provided in the constructing of this method, allowing for more specific analysis. The right-hand side is just analyzing the production of the product of interest and was not used for this analysis because of a lack of a disposal scenario

2.2 Environmental Burden Considered

The results from LCA are displayed in several categories, which represent different environmental impacts contributed by the production or the processes. The definitions and units of each of these categories are given in Tab. 2.

Categories such as Climate Change and Carcinogens are recorded in Daily-Adjusted-Life-Years (DALY) / kg. This unit was developed by the World Health Organization (WHO) as a measure of the impact on human health. DALY is expressed as the number of years of healthy life lost or the years lived disabled. One DALY would resemble a one-year loss of healthy life for one person; likewise, five DALY would resemble a one-year loss of healthy life for five persons. This unit is useful in understanding how human life is affected based on the analysis. According to the SimaPro Database Manual, malnutrition arises from water deprivation of agricultural users and fisheries as well as implementation of water-related diseases from the lack of water for domestic use. These factors ultimately lead to a decrease in the years of healthy life for the population.

Ecotoxicity and Acidification/Eutrophication represent the impact on ecosystems. Their respective units are comprised of the loss of a species over a certain area during a specific time period. Since these values are represented as fractions, they range from 0 to 1 per kg of product. Values considered to be below 1% (<0.01) are interpreted as low risk to the environment, moderate risk if between 1% and 5% (0.01–0.05), and high risk above 5% (>0.05). It should also be noted that negative values in this category refer to proper handling and management of the released toxins recorded by SimaPro [16,17].

The Fossil Fuels category is represented in terms of the energy resulting from the burning of natural resources, in MJ/ kg. SimaPro analyzes the use of each resource and considers the surplus costs that will result from using each resource in the future over an infinite time period.

Table 2: Possible outputs from a LCA study (definition adapted from the SimaPro Database Manual Methods Library [18])

Result Term (Units)	Definition
Carcinogens (Daily-Adjusted-Life-Years (DALY)/kg)	Emissions of carcinogenic substances into water, air, and soil
Respiratory Organics (DALY/kg)	Emissions of organic substances in the air, resulting in respiratory effects (e.g., summer smog–CO & NO ₂)
Respiratory Inorganics (DALY/kg)	Emissions of dust, sulfur, and nitrogen oxides into the air resulting in respiratory effects (e.g., winter smog)
Climate Change (DALY/kg)	Damage due to an increase of disease and death towards the environment resulting in change of climate (e.g., CO ₂)
Ozone Layer (DALY/kg)	Damage resulting in ozone depletion as a result of increased penetration of UV radiation
Ecotoxicity (Potentially Affected Fraction (PAF)·m ² ·year/kg)	Damage towards the ecosystem due to release of ecotoxic substances in water, air, and soil (e.g., chlorides and sulfides) [19]
Acidification/ Eutrophication (Potentially Disappeared Fraction (PDF) ·m ² ·year)/kg)	Damage towards the ecosystem due to release of acidic substances into the air only
Fossil Fuels (MJ/kg)	Natural resource used in the production and processes involving plastics

3 Results and Discussion

3.1 Development of Life Cycle Analysis Framework

In order to compare the environmental burden of using different methods to manage plastic waste, a life cycle analysis of plastic products was conducted in this study. A typical life cycle of plastic products is

presented in Fig. 3. Three types of plastic waste management—landfill, incineration, and recycling of mixed polymers, were studied. HDPE, accounting for 17% of all types of plastics, is used as a case study because it is one of the major plastics used in industry and has a comprehensive database for analysis.

Before the life cycle analysis was conducted, a flow diagram was created to layout the cycles of the different treatments of plastics that included landfill, incineration, and recycling of mixed polymers (mechanical recycling). It can be seen that, when there is a need for the plastic, it is produced and used as expected. However, most of the plastic is sent to be either landfilled or incinerated. This ends the life cycle for the plastic and, when there is a need, novel plastic needs to be produced again (Fig. 3a). Disposed plastics emit toxic substances into the land while slowly decomposing, and incinerated plastics emit carbon dioxide and other carcinogens that contribute to the buildup of Greenhouse Gases (GHG) in the air. Both contribute to the plastic accumulation problem on the planet. Additionally, these two methods result in significant energy loss. Notably, plastics have a high embodied energy (i.e., the energy used to manufacture plastics and the energy of plastics themselves). Fig. 4 shows the embodied energy of various primary (virgin) and secondary (recycled) plastics. As Fig. 4 shows, the embodied energy of manufacturing primary HDPE is 80 MJ/kg, about two times the energy needed to produce a secondary (recycled) HDPE.

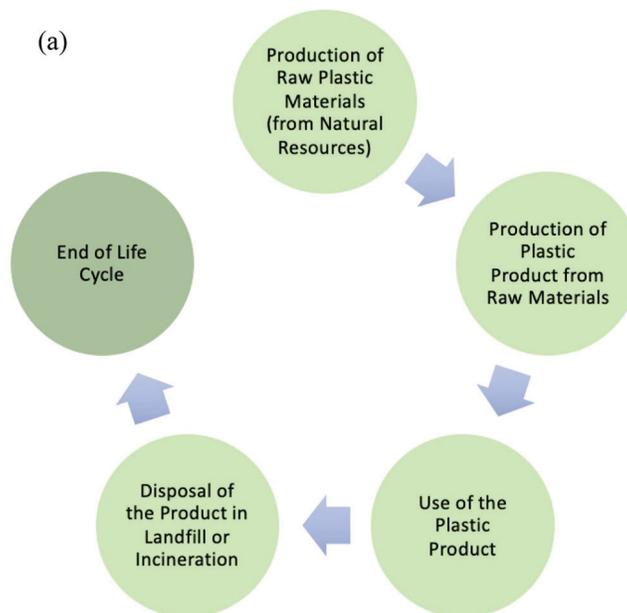


Figure 3: (Continued)

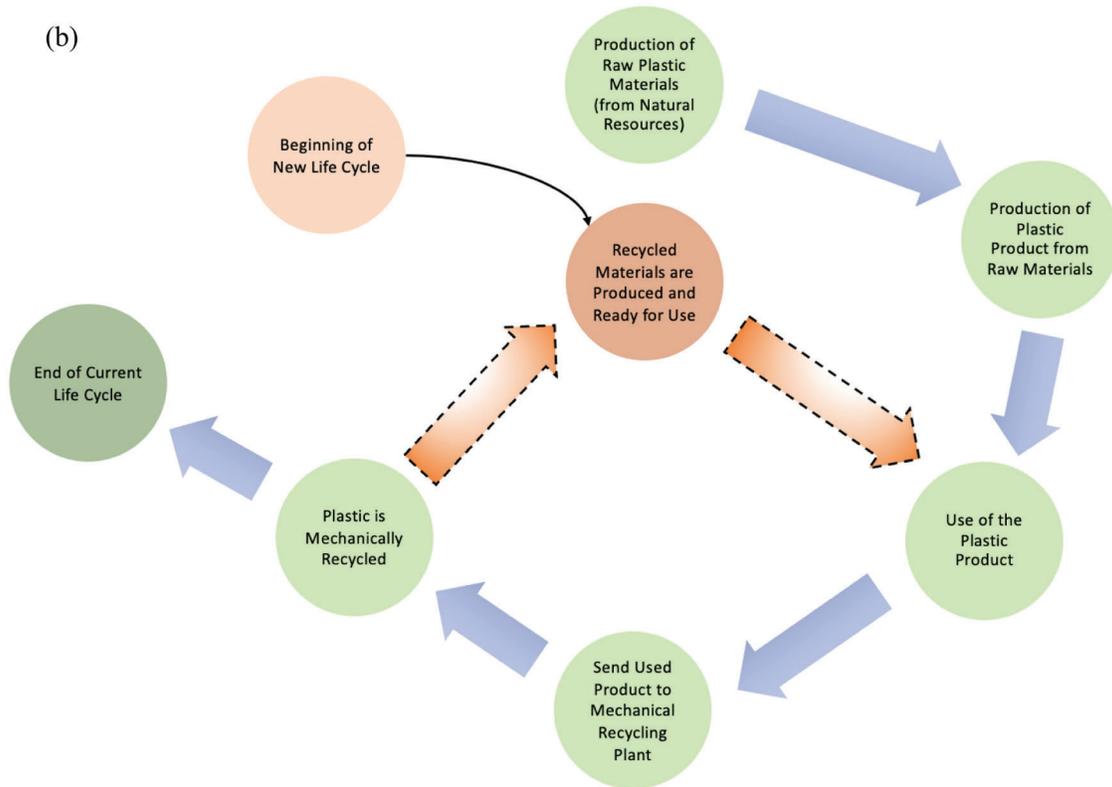


Figure 3: A general life cycle of plastic products: (a) A cradle-to-grave life cycle where disposal of plastic product is the end of the life cycle; (b) A cradle-to-cradle life cycle where recycling of plastic product is an option (the life cycle adapts to having a re-used input of materials)

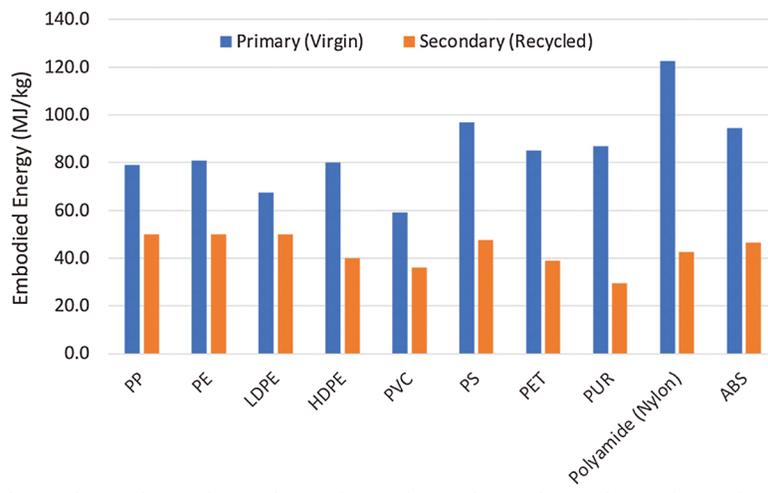


Figure 4: Various embodied energies of primary (virgin) and secondary (recycled) plastics (modified from the REMADE calculator) [20]

However, if the recycling method is used, the process changes (Fig. 3b). This cycle is modified from Fig. 3a by replacing the disposal scenario. The life cycle ends after recycling the plastic occurs, since SimaPro 7.1 includes recycling of the used plastic within the same cycle. Although the end of the life cycle occurs after the plastic is recycled, the plastic can be adapted again for another use, eliminating the need for novel production of plastic.

The life cycle analysis done for this study includes the quantitative effects of each part of landfill, incineration, and mechanical recycling. It should be noted that when SimaPro 7.1 refers to recycling of mixed polymers, it indicates mechanical recycling. Technically, this description is not accurate, since mechanical recycling usually requires the separation of different types of plastics before going through the mechanical recycling process. Notably, mechanical recycling can be broken down into several components. The process of mechanical recycling is shown in Fig. 5. More specifically, the processes of mechanical recycling are the following:

1. Transportation: Mixed plastic waste arrives to the mechanical recycling process facility.
2. Sorting: The mixed plastic waste is entangled with several types of plastics (e.g., HDPE, LDPE, PET, etc.). Before recycling can occur, each plastic type is separated. For example, all HDPE is grouped together.
3. Grinding: The plastic is then grinded or cut into smaller pieces to increase surface area for washing and drying. However, at this stage, the pieces are too large to undergo reprocessing.
4. Washing: Plastics are normally contaminated with waste. For instance, a milk jug would be contaminated with food waste. Thus, the plastic needs to be washed to eliminate these wastes.
5. Drying: Because the plastic is wet, it needs to be dried completely before it can be further processed.
6. Granulation: The plastics are ground into flakes to be re-molded. This process turns the smaller pieces made in the grinding process into micro-pellets for compounding [21].
7. Compounding: This process involves the polymer being melted down in an extruder, where the extrudate is cooled to a solid phase upon exiting the die and then pelletized for reprocessing.
8. Distribution: This is where the plastics are distributed to the users.

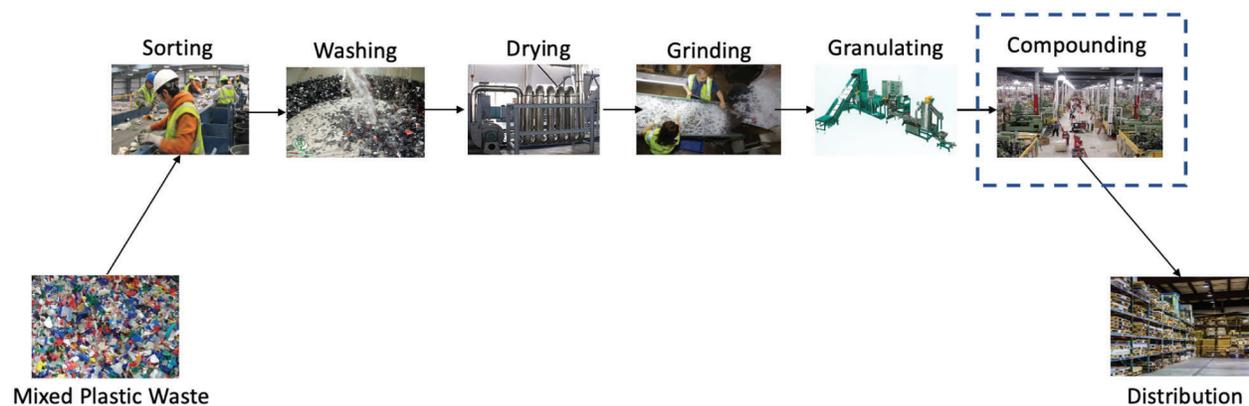


Figure 5: Network of the recycling of mixed polymers process (mechanical recycling, adapted from [22]). It should be noted that SimaPro 7.1 does not include compounding as part of the recycling of mixed polymers process; realistically, this step is included in mechanical recycling

3.2 Energy Analysis of Different Plastic Waste Management Methods

A comparison of the fossil fuel usage that assessed the treatment processes of recycling of mixed polymers (mechanical recycling), landfilling, and incineration was analyzed. Additionally, a comparison was done to Recyclbots, an emerging 3D printing method to mechanically recycle HDPE bottles (more discussion will also be provided in latter session). All four of these categories include the production of 1 kg of HDPE as well as the energy required for the process. The landfill method required 10.4 MJ whereas incineration was 10 MJ. According to Kreiger et al., the energy required to produce 1 kg of HDPE and recycle (i.e., 3D printing) was in total 8.74 MJ [14]. Fig. 6 shows that the recycling method appears to consume the most energy at 11 MJ. However, the recycling method only includes the 1 kg of HDPE being recycled once. Next, a further analysis would be carried out to assess why the recycling method consumes the most energy.

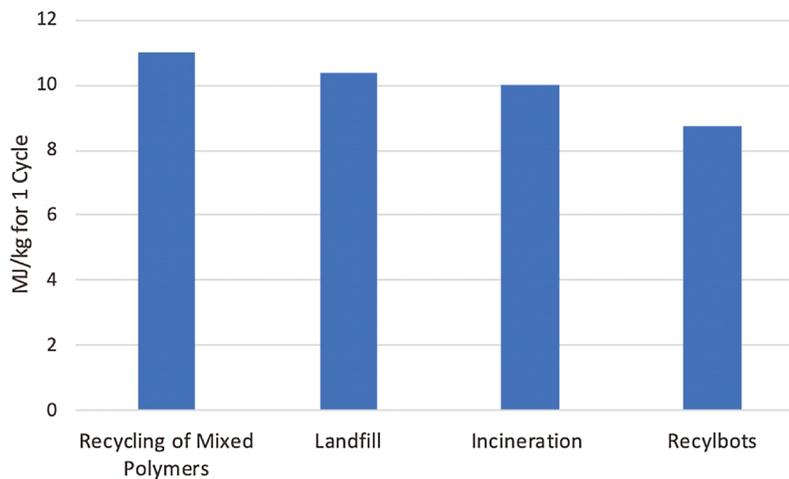


Figure 6: Energy usage for different methods. Recyclbots, another method for recycling HDPE, was examined as a variation to other disposal methods and compared in SimaPro

Fig. 7 breaks down the energy usage for the treatment processes (disposal scenarios) of recycling of mixed polymers, landfilling, and incineration methods that were all conducted using the same software (SimaPro 7.1). The blue bars represent the energy needed to manufacture 1 kg of HDPE. They are consistent throughout each treatment method at a required amount of energy at 10.4 MJ. The energy required for the treatment processes is represented by the orange bar. The method of recycling of mixed polymers requires 0.7 MJ while landfill requires 0.03 MJ and incineration generates 0.34 MJ (per kg of HDPE material burned). The amount of energy required for the landfill treatment is so low because if the plastic is disposed in the regular trash system, 1 kg of HDPE is a very small component of the trash transported to the landfill; the 0.03 MJ consists of the transportation of the plastic waste to the landfill. Incineration is used to generate energy. However, the total net energy, according to the inventory in SimaPro, produced from this process is extremely minimal. If incineration only generates such a little amount of energy while emitting tons of carbon dioxide and creating GHG emissions, it is not an efficient treatment method. Similar findings were reported and discussed in prior literature as well [1,22].

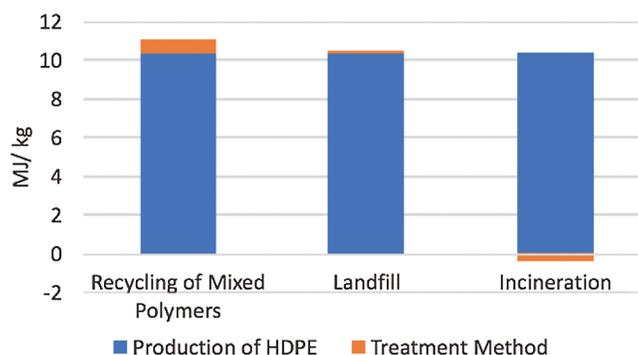


Figure 7: Additional energy uses for the three disposal methods on top of the production of 1 kg of HDPE

The energy for each of the steps in mechanical recycling (total 10.4 MJ/kg) is summarized in Fig. 8, which indicates that drying and granulation require the most energy. The drying process requires 57% of the energy needed to treat the plastic. Drying is needed in the mechanical energy process because the plastic needs to be dried after it is washed (Fig. 5). Particularly, drying is extremely important for plastic processing. If any moisture is within the recycled plastic, the quality and appearance of the plastic product would not be consistent [23,24]. An advanced mechanical recycler can remove the moisture or other volatile contents by implementing a degassing (i.e., devolatilization) process, but the amount is still very small, likely within 1%–5%. Similar phenomena have also been reported on research projects compounding hygroscopic biomass into polymers or mechanically recycling hydrolytic polymers such as poly (L-lactic acid) (i.e., PLA) [23,25].

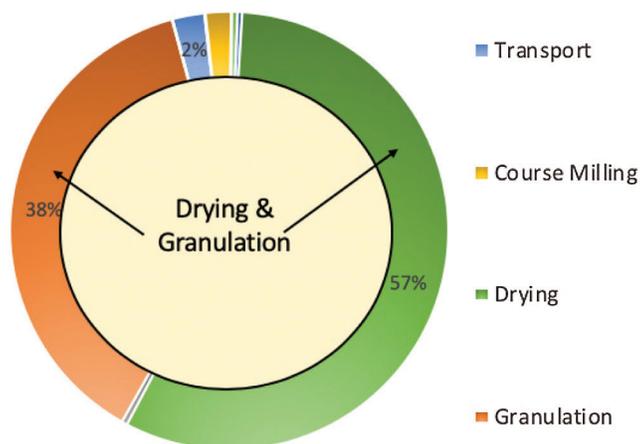


Figure 8: Breakdown of fossil fuel usage for mechanical recycling of mixed polymers. Drying and granulation use the most energy in the 11-step process. Other steps include transport (2.35%), shredding (0.093%), course milling (1.86%), separation in fluid tank (0.028%), fine separation in hydrocyclon (0.037%), water separation in spin drier (0.42%), fine milling (0.33%), ultra-fine cyclone separation (0.42%), and internal transport (0.046%)

The drying process takes place at a temperature of 100°C and involves the phase change of water. The high latent heat of vaporization of water leads to a high energy consumption [26]. Similar phenomena are also observed in the biofuel industry, where removing water from biomass is also a key step [27,28]. Granulation requires around 38% of the energy required to mechanically recycle the plastic and is another

key step in reprocessing recycled material. This step may include melt filtration, where contaminants are essentially melted off and the throughput is pushed through various sieves to filter the product [22]. A granulator used by plastic industry usually is oversized and over-powered so that it can handle different applications within a plant [29,30]. Possible ways to improve the energy efficiency of the granulation step of a mechanical recycling includes 1) Increasing the throughput, 2) Improving the motor and controls, and 3) Multiple-stage size reduction [29,30].

Now that the breakdown of the energy usage for the treatment of recycling plastic is understood, an analysis can be conducted that expands the recycling method. There are approximately 350 million tons of plastic waste produced annually, of which 17% is HDPE. An analysis was conducted assuming that all the HDPE produced annually has undergone three life cycles (because HDPE typically can be reprocessed for 3–10 times) [31]. For the recycling process, Fig. 9 calculated the effects of recycling the HDPE three times. This is compared to three life cycles for the accumulated HDPE being sent to landfill and incineration. As Fig. 9 suggests, the more life cycles that occur, the use of energy exponentially increases. We can see that if all the plastic was recycled and re-used (for three times in this analysis), the difference would be very large. Because recycling processes eliminate the need to produce new plastic from raw materials such as petroleum, large amounts of energy are saved. In fact, the difference in the amount of energy between mechanical recycling of all the plastic and sending all the plastic to the landfill is enough to power over 146 billion iPhones for life instead. This analysis provides an insight to the amount of HDPE from post-consumer waste, which is currently sent to either landfills or incinerators, so-called “graves”, all which could instead be recycled (Fig. 9).

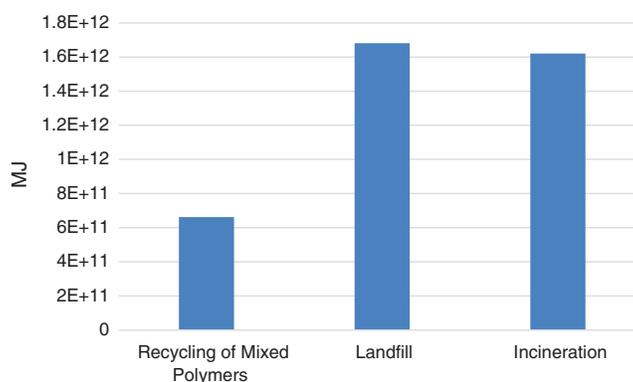


Figure 9: Analysis of the energy requirements for all the HDPE (59.5 million tons) that is produced annually to undergo three life cycles for each respective disposal scenario

3.3 Environmental Loadings of Different Plastic Waste Management Methods

Currently, 9.56 million metric tons of HDPE are produced annually in the United States, with almost 60 million metric tons produced globally [32,33]. To understand the effect of the production of HDPE on the environment, LCA was conducted for 1 kg of HDPE and scaled to the annual production for analysis. The disposal scenarios were also scaled to handle the total annual amount of HDPE through one cycle (i.e., to recycle 9.56 million metric tons for one time). Fig. 10 evaluates the different factors used in conducting an LCA. Because each of the impact categories are in different units, the following figure separates each factor for a comprehensive comparison. A positive axis indicates that the production or the process contributes to that category (e.g., the production of HDPE contributes 1.37×10^4 DALY to respiratory inorganics) and a negative axis indicates this process removes/generates some of the effects the production caused (e.g., incineration of HDPE can prevent effects of ecotoxicity).

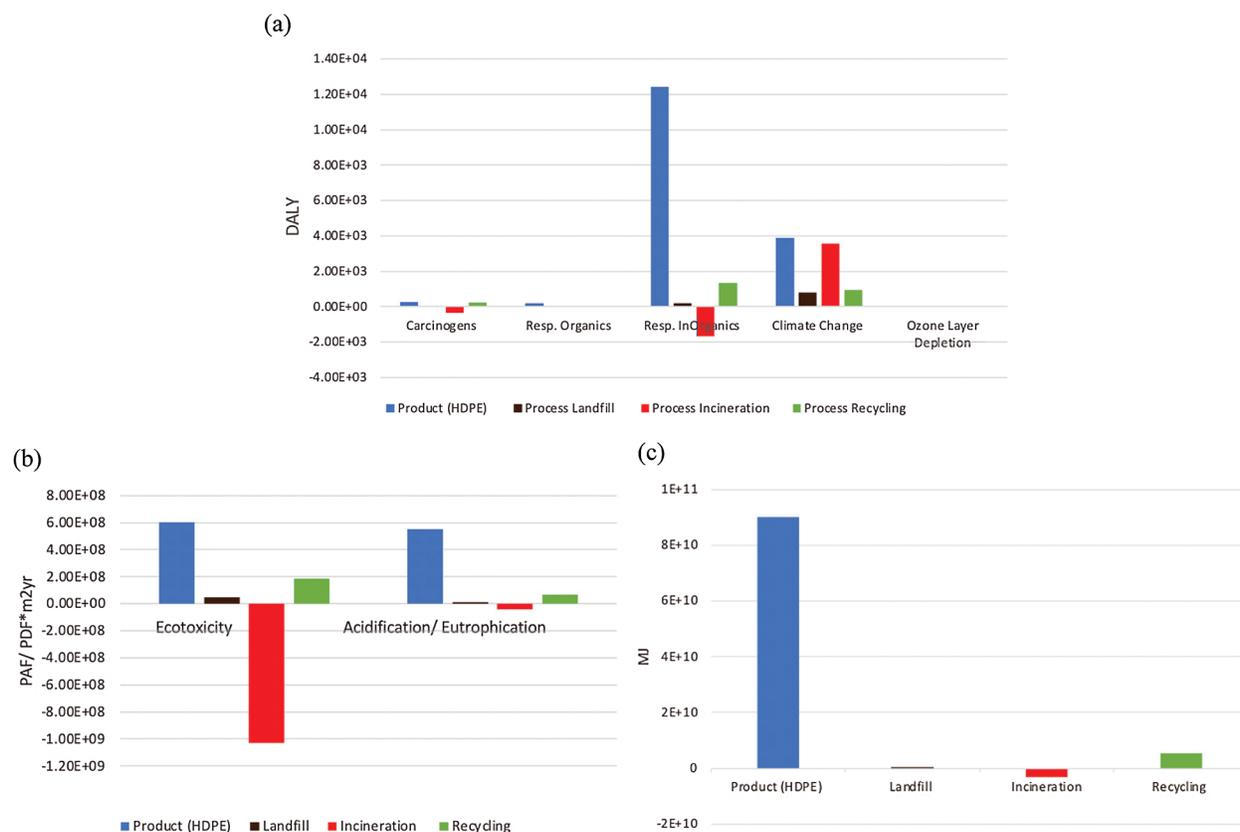


Figure 10: Life cycle burdens for all processes against the annual production of HDPE (i.e., 9.56 million metric tons of HDPE): (a) Carcinogens, respiratory organics, respiratory inorganics, climate change, and ozone layer depletion (unit: DALY); (b) Ecotoxicity and acidification/eutrophication (unit: PAF/PDF·m²·year); (c) Fossil fuel usage (unit: MJ)

Amongst this analysis, recycling contributes more to some of the categories, most notably the fossil fuel usage, than incineration and landfill. However, the fossil fuel usage of mechanical recycling is much smaller than that needed to produce HDPE. The energy required for mechanical recycling is largely due to drying for the pretreatment of used plastics and granulation for re-making the virgin-like polymers. Incineration has smaller impacts on ecotoxicity and acidification/eutrophication (Fig. 10b), but it has a significant impact on climate change (Fig. 10a). The latter would be considered more detrimental to the environment than the effects of ecotoxicity from recycling. In fact, our analysis indicates that the environmental burdens due to the recycling process are negligible compared to those of the production of HDPE. Furthermore, among all the plastic waste management methods considered, only mechanical recycling can produce secondary plastics that could replace virgin plastics, thereby eliminating the environmental burdens generated due to the production of virgin plastics. Notably, only one-time recycling of HDPE was considered in Fig. 10. Typically, HDPE resin can be recycled at least 10 times [34]. Therefore, mechanical recycling has the potential to reduce even more environmental burdens caused by the production of virgin HDPE.

HDPE varies from other types of polyolefins due to its sturdy character and presence in multiple plastic items. For instance, milk jugs are created from HDPE. Because of its rigid structure, HDPE is much easier to recycle. In fact, as Fig. 11 shows, HDPE has the second highest recycling rate among the six types of plastics in the United States [35]. In contrast, low-density polyethylene (LDPE) and polypropylene (PP), accounting

for 46% of the plastics, have very low recycling rates. In fact, only 5.3% of LDPE and 0.6% of PP are recycled in the United States. LDPE and PP are mostly used for packaging films, which cannot be handled by most of the current mechanical recycling facilities due to the limited feeding capability (flexible films vs. rigid plastics). About 50% of these packaging films are used for food, which may contaminate LDPE and PP that cannot be easily washed by water. Food components can penetrate into the polymeric matrix and make the current washing process ineffective [36,37]. Due to regulation reasons and/or customers' concerns, these packaging films are rarely recycled. And even if they are, the recycled plastics have to be approved by the FDA to determine if they can be used again in food containers. In addition, LDPE and PP are commonly used in multilayer packaging materials [38,39], which also contains non-plastic components such as foil, paper labels, and adhesives. These versatile pollutants make recycling LDPE and PP even more challenging. Because of the mixture of the polyolefins, sorting, as required for the mechanical recycling process, becomes intangible, sending these products directly to a different disposal scenario, like landfill or incineration. The complexity of production of these other polyolefins contributes to the downcycling, or difficulty in sending products with these plastics to mechanical recycling, thus, contributing negatively to the plastic accumulation problem and requiring further research to improve their recycling rates.

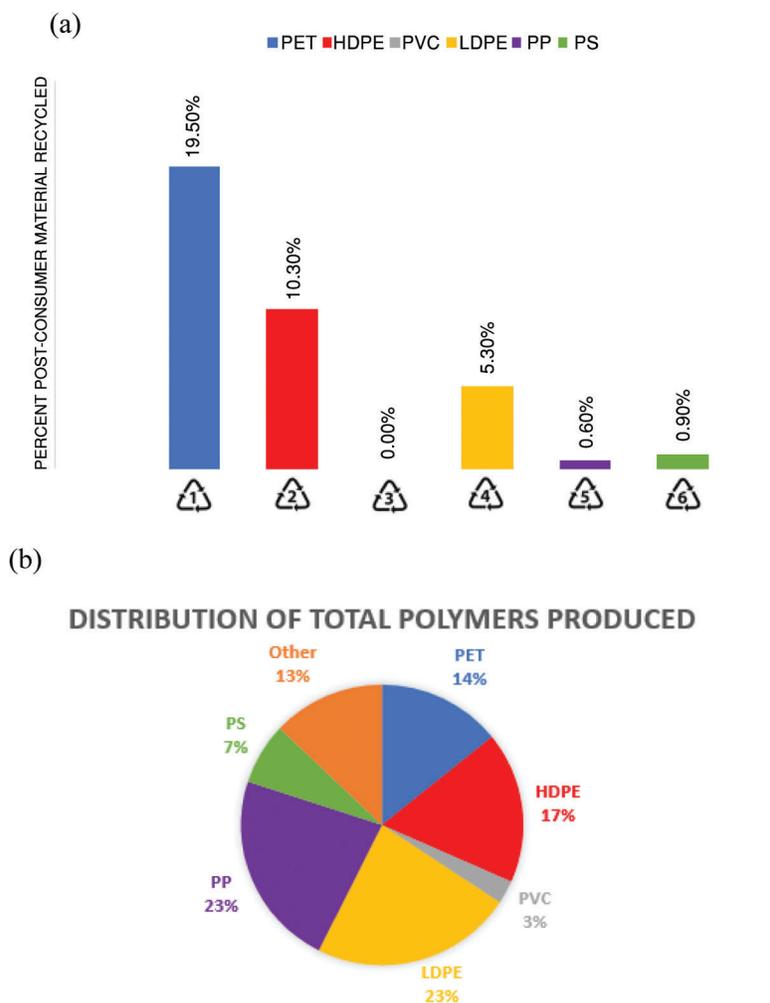


Figure 11: Statistics about plastic production and recycling rates: (a) The recycling rates of different plastics in the United States and (b) Distribution of total polymers produced globally (adapted from [4,35])

3.4 Review of Recycling Techniques on Other Petro-Based Polymers

The results reported above were conducted for an analysis on HDPE. Scenarios for other types of plastic can be simulated, but the results from HDPE 1) Show that there are significant and beneficial results of mechanical recycling, as compared to landfill and incineration, and 2) Provide an insight on how LCA can perform a holistic evaluation of different disposal methods. Effects of recycling can vary amongst the types of plastics. However, results from HDPE can help visualize the general trend of energy savings developed by sending plastics through this mechanical recycling method instead. As other handling methods, such as chemical recycling (e.g., gasification, pyrolysis, chemolysis, solvolysis, and hydrothermal processes), the use of biodegradable or bio-based polymers, supercritical fluid extraction, and solvent dissolution/precipitation, are being developed and refined, LCA can help perform a comparative analysis of the energy expenditures and environmental effects from production and disposal to determine which is preferred [40].

Other plastics such as PET, PS, and PP face similar problems on the most efficient way to recycle. Mechanical recycling is the most common method for reusing plastics, but the quantitative effects of this handling process on other plastics is unknown. Tab. 3 provides an overview of different types of recycling methods that have been investigated and reported for three other common plastics. The literature suggests that potential research gaps lie in developing tailorable technologies for plastics with different polymeric structures, but it remains consistent with the LCA results that recycling in some form is preferred over landfill and incineration to reduce the amount of toxins released via degradation of the plastics. Chemical recycling, or tertiary recycling, has become a potential handling method in lieu of mechanical recycling due to its ability to return the polymers to a virgin-like form [2,40]. Additionally, various other methods, such as incorporation of petrochemical based polymers with bio-based polymers or blends of polymers, are becoming potential handling methods.

Table 3: Literature review of recycling methods of PET, PS, and PP

Type	Reason for new disposal method	Reported results of mechanical recycling	Reported results of chemical recycling	Reported results of other methods	References
PET	Emits harmful toxins into the environment when sent to landfill, and can be easily re-used.	The polymer does not degrade and can easily be re-used however, process is complex usually due to contamination of PET prior to undergoing mechanical recycling.	Various types of chemical recycling are adaptable to PET and can convert back to virgin-like product and respective monomers, but very expensive process where cost of chemical recycling outweighs novel production.	Blends of <i>bio-based PET</i> (most commonly produced biopolymer) are showing promise, as it can easily undergo mechanical recycling and does not sustain degradation. Bio-based materials can also reduce the use of petrochemicals.	[41–43]
PS	PS foams can occupy large volumes (95% air), creating a problem in limited landfill space and consuming transportation energy for disposal.	High impact PS (i.e., HIPS) can sustain up to 9 cycles of recycling before properties are significantly altered.	Selectivity of catalysts needs to be heavily considered. However, PS can sustain 3 recycling cycles (via solvent dissolution) without degradation.	For a desired identical product, <i>thermal</i> methods are not recommended but potential opportunity exists for wastes to be used to make PHA.	[44–46]
PP	Sufficient process needs to be developed to reduce the release of harmful substances via landfill, since PP is hard to recycle due to weakness intrinsic properties.	After the second cycle, the properties are significantly destroyed due to the high temperatures used in the recycling process.	High recovery is seen; however, the structural components are altered, leading to changes in crystallinity and thermal stability	<i>Blends</i> of tougher polymers are being incorporated to reduce the inherent weak properties of PP (e.g., thermoplastic polyurethane, TPU).	[47–49]

3.5 Improvement of Current LCA Methods

Although LCA can provide a framework for understanding the effects of different disposal scenarios on plastic waste, more data must be collected for further analysis. In LCA for mechanical recycling, any scenario involving this disposal goes through the same 8-step process. However, if each step in the mechanical recycling process was evaluated independently, there would be a better understanding of the effects of the technology as well as the effects of using such a disposal scenario on the item. Because mechanical recycling is the most commonly utilized and most adaptive method currently used in the world, further improvements need to be conducted in this technology before exploring other recycling methods. With more efforts towards mechanical recycling, more data could be collected for a better analysis on how this process can become a better solution for reducing plastic accumulation.

3.5.1 Comparison of Various Recycling Methods for Reclaiming Polymer Structures

Herein, various recycling methods that can reclaim polymer structures back from plastic waste would be compared and their benefits and drawbacks would be discussed. As the plastic accumulation problem exponentially increases, technologies are being developed to resolve the issue and provide an alternative to mechanical recycling. These solutions tend to focus on greater adaptability of handling used plastics and work to restore them to the virgin-like state. Although technologies have had positive results in the laboratories, the potential for large-scale application can vary and may not be feasible.

From the results presented earlier, landfill and incineration are versatile methods of handling various types of plastic waste. However, each has significant issues. Sending plastic waste to a landfill rather than an incinerator does not initially cause significant emissions of greenhouse gases, other than the CO₂ emitted during the transportation of the waste to landfills. Over time, however, landfilled plastic waste could release harmful microplastics or organic wastes into the air, soil, or groundwater. The impacts of this pollution are difficult to quantify and could have long-lasting and serious effects on our food and water supplies as well as human health. Incineration on the other hand could generate a small amount of energy. Sending potential fuel for incinerators to a landfill, the potential source of energy is wasted and lost. In addition to the issues caused by transportation, incineration emits large amounts of CO₂ and other greenhouse gases or pollutants in a relatively short amount of time, and it could accelerate climate change, ozone layer depletion, and associated environmental problems. [Fig. 11b](#) shows that although incineration can save some harmful effects of ecotoxicity, the generation of GHG emissions and impacts on climate change present a poor trade-off. Overall, incineration and landfill should be discouraged as major methods of plastic waste disposal.

Sequential dissolution-precipitation by various solvents followed by adsorption for removal of impurities is another potential method of plastic recycling [50–52]. Various solvent mixtures are effective for selectively dissolving or precipitating polyolefins and other plastics. Legacy additives such as colorants and flame retardants can be removed to restore the plastics close to its original polymers for reuse. This method can be operated at ambient conditions and thus does not require significant amounts of energy nor emit a large quantity of greenhouse gases. However, detailed LCA and cost analyses are needed to evaluate this new technique. Certain types of solvents are required and the costs to process the various types of plastic would need to be examined before this method could be scaled up. Moreover, some organic solvents are refined from petroleum and thus a detailed LCA would be needed to evaluate the environmental burdens to manufacture the solvents.

In the laboratory setting, there has been a proposed technique that builds upon using 3D printing [14]. Recyclebots were developed to take used plastics and create a filament through the material that could be used for 3D printing. This method greatly saves fossil fuel usage and could be a potential solution by limiting novel production of plastics. However, in the analysis, there are some unreasonable assumptions regarding this method. For instance, one assumption in the analysis requires everyone (in the city of

Detroit, for their analysis) to have a 3D printer in their house and use the printer continuously as well as following specific recycling guidelines. This would not be feasible to expand across the United States. Alternatively, 3D printing could be an option for remote areas or mobile bases (e.g., army bases or space stations) to carry out onsite recycling.

3.5.2 Data Gap in the Current LCA Database

Data gaps in current LCA databases remain as major challenges to further LCA studies and comparisons. In particular, no database in any updated software has any values for chemical recycling and limited knowledge on mechanical recycling. Hopefully, data from chemical recycling or other advanced recycling methods can be attained and inputted into major LCA software such as SimaPro for a full analysis on these methods of treating plastics.

In terms of evaluating the best technique for dealing with the plastic accumulation problem, mechanical recycling would be the best solution. From the aforementioned analysis, mechanical recycling greatly decreases the need for fossil fuels in producing virgin plastic materials. If all plastic waste was mechanically recycled for 10 times or more, this would significantly reduce the need to produce virgin plastic. Additionally, this method does not produce any significant harmful emissions. This eliminates the contribution to GHG emissions and ozone depletion. Unfortunately, the collection rate within the United States for recycling has remained low (~10% for HDPE). Although the blue collection bins indicating recycling are provided, the majority of plastic waste is thrown into the landfill/garbage bins. The mixed plastic wastes collected in the blue bins contain mixtures of all types of plastics, which have to be sorted at materials recovery facilities (MRFs) to produce HDPE waste prior to mechanical recycling. The sorted waste is usually dirty, resulting in the need for washing and drying in mechanical recycling. Some plastic waste collected in the blue bins is too contaminated to be recycled and is also sent to landfills. To increase the collection and recycling rates of HDPE for recycling, separate bins labeled for HDPE recycling and specific instructions on how to properly clean and dispose the waste should be provided. This new method for collecting sorted HDPE waste will require additional designated bins and space for waste collection, and most importantly, a change in consumer behavior.

Several solutions exist or are being further developed to eliminate or reduce the plastic accumulation problem [2]. So far, mechanical recycling proves to be the most efficient and most widely used amongst the technology that has been developed. If mechanical recycling is more widely adopted throughout society, this would begin to help reduce waste accumulation. As for the future, chemical recycling could prove to be even more efficient [40]. More analysis on this technique needs to be conducted to prove if this method could also help reduce plastic waste accumulation.

3.6 Policy Discussion in Progress

Plastic regulation is becoming a more important topic of discussion in policies throughout the United States and the rest of the world. The European Union has been proactive in creating policies regarding the plastic accumulation problem. Recently, the European Parliament has passed a bill banning the use of single-use plastic items (e.g., straws) by 2021. Single-use plastics is the majority of litter on lands or in oceans as well as in landfills. Although Europe has already adopted a strict recycling policy, this recent bill also allows the increase of the plastic waste to be halted. Additionally, the policy that was passed in March 2019 requires the collection of 90% of the plastic bottles to prevent these items from making their way into the environment. In an effort to enforce this policy, the bill has also indicated that polluters will face harsh consequences to ensure compliance of this policy. The EU provides an example of the positive effects of these regulations. Data suggest that in 2016, plastic recovering rate was increased to 72.7%, up nearly 3.5% from 2014 [53]. The limitation of production and the enforcement of correct handling of

plastics, which are ready to be sent to recycling, is enabling EU countries to effectively tackle the plastic accumulation problem.

The EU can serve as an example for what the United States can achieve. On June 16, 2020, Reps. Haley Stevens (D-Michigan) and Anthony Gonzalez (R-Ohio) introduced a bipartisan bill, The Plastic Waste Reduction and Recycling Act, to the House of Representatives in support of plastic recycling [54]. The purpose of the bill is to ensure that the United States competes in the plastic recycling realm and contributes to solving the accumulation problem, alongside other nations. The bill would not only develop strategies to enforce and build plastic recycling within the United States, but also would encourage research and funding to develop solutions to the problem. For instance, the bill would require the United States Environmental Protection Agency (U.S. EPA) to support research into innovative plastic waste management and research the effects of the waste on the environment. The US EPA is just one factor of the bill; the United States Department of Energy (U.S. DOE), National Science Foundation (NSF), and United States Department of Transportation (U.S. DOT) would all be required to actively take part in finding solutions and funding different research projects to tackle the problem [38,54]. The bill is just a start for developing a more focused approach to increase recycling and establish needed infrastructure. Ultimately, more R&D efforts to develop innovative plastic recycling methods and effective policies to reduce use of plastics and increase rates of waste collection and recycling would be needed to address this plastic accumulation issue.

The recognition of the plastic accumulation problem has been brought to the attention of the public. Already, local governments in the United States have begun to tackle the issue by regulating plastic in most cities. For example, the District of Columbia (D.C.) has passed a tax on plastic bags. A customer will pay 5 cents for every plastic bag in all retail stores that sell food or alcohol. This law was passed in hopes to reduce the use and accumulation of waste plastic bags and encourage the use of reusable bags. D.C. is just one city that has implemented laws to regulate plastic bags. Currently, 349 cities in the United States have some law regarding plastic bags. Additionally, California and Hawaii are two states that have a statewide plastic bag ban. The amount of tax varies across the United States but has become increasingly higher in effect in the last decade. The United States is further behind other countries in handling the plastic accumulation problem. However, the initial laws passed in local governments have increased the possibility of passing laws at the federal level.

In light of the results from this LCA, some suggestions for the policies on plastics disposal in the United States can be made. First, HDPE is a material which is fairly easy to isolate from other plastics at recycling facilities. Additionally, HDPE can be recycled more than 3 times before any significant loss of properties is observed and serves as a much more sustainable supply of HDPE than virgin resin. Therefore, policy makers should enforce strict rules on the recycling of single-use HDPE packaging (e.g., water/milk gallon jugs). One suggestion would be to install a nationwide deposit on HDPE gallon jugs, and community recycle-bins for milk jugs. Some states already enforce a tax on PET 2-liter bottles and aluminum cans. Adding HDPE gallon jugs to a nationwide policy would likely be a simple modification to an already existing infrastructure. To make this solution even more sustainable, HDPE bottles can be transferred as whole bottles for granulation at a centralized, regional recycling plant. This would make the recycling process far more energy efficient, as granulation accounts for approximately 40% of the energy consumed in the mechanical recycling process. In continuation with this step, granulation of all plastic bottles returned for their deposit should be granulated after they have been received at the recycling plant, as some bottle deposits at grocery stores actually granulate the bottles using small granulators in the machine, which is not energy efficient.

As an alternative to mechanical recycling, chemical recycling receives a lot of attention as it can deal with plastic mixtures. Since this method is still relatively new, the policy makers in the United States will have to make significant investments in R&D in this area. There are currently several methods for the chemical recycling of different polymers as well as isolating and recovering polymer structures from

polymer blends and multilayer packaging. Two examples of chemical recycling methods which have been developed and are still under improvement by several institutions world-wide are thermolysis (including pyrolysis, gasification, and hydrothermal processes) and solvent dissolution/precipitation (including supercritical fluid extraction) [1–3,40,51]. Notably, reclaiming polymer structures back from plastic waste will lead to the highest energy efficiency [10,41]. Therefore, the authors would suggest the policymakers to invest more R&D funding on research that can recover polymer structures. Up-front, these methods involve a significant investment, but in the long run the polymers recovered using these methods could display unparalleled purity compared to polymers recovered using mechanical recycling. In addition, the LCA results presented in this study also suggest that incineration is not recommended as a plastic recycling method as it has poor decarbonization efficiency, releasing the highest amount of greenhouse gases among the three recycling methods compared (Fig. 10).

In 2020, our world has been severely impacted by the COVID-19 pandemic. The rates of sickness, hospitalizations, and downturns of economies have impacted almost every nation. The severity of the illness has led to increased efforts in prevention and medical care in order to “flatten the curve.” However, the plastic waste accumulation problem has become worse as a result. To keep the general public and the medical staff and patients safe, single-use plastic masks, shields, gloves, protective gowns, test kits, sanitation supplies, and other plastic products are essential. The spent supplies are sent to landfills and incinerators without being recycled or managed because of rules for preventing contamination. Since all these prevention and treatment activities are important, as the COVID-19 pandemic continues, the accumulation of plastic waste will continue to rise as well. Finding new solutions to reduce plastic waste accumulation has become increasingly urgent.

4 Conclusion

The plastic waste accumulation problem is becoming a more urgent issue for societies and nations across the world. In the United States, the collection/recycling rate of plastic waste is alarmingly low, as most of the waste is sent to landfills and incinerators or ultimately ends up as litters on land or in the oceans causing contamination of the environment. LCA has shown that mechanical recycling can provide significant positive impacts in reducing the amount of fossil fuel usage as well as reducing the negative impacts on the environment. If implemented, the plastic production could significantly decrease to slow the exponential rise in plastic accumulation. Although LCA can provide some quantitative analysis on different disposal methods, there is still a data gap to fully analyze all the disposal methods accurately. This could depend on the location, the technology, and the ability to collect such data. New methods have been in development to address the plastic accumulation problem. Some solutions show promise for commercial application. LCA can provide an initial analysis on the new technology. With further investigation on the effects of plastic accumulation and efforts to encourage recycling and to limit production, policies to solve this problem can be implemented to encourage the general public to become actively involved in the solutions of the problem. Much more analysis and research are needed to fully tackle the plastic accumulation issue. Understanding the effects of plastic waste accumulation and potential impacts of recycling on the environment is an important first step.

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