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Recovery pathway assessment of recycled HDPE for circular economy: Shorter-life vs longer-life products

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Abstract

High Density Polyethylene (HDPE) is a highly recyclable thermoplastic comprising 17% of all plastic produced. Yet, demand for recycled HDPE (r-HDPE) has outrun availability, partly due to manufacturers' interest in meeting sustainability goals and recycled content mandates. Given that HDPE has a variety of uses, understanding optimal allocation of the constrained r-HDPE supply across product categories and lifespans will support the challenge of addressing broader sustainability goals and establishing circular economy (CE). By utilizing systems dynamic (SD) and life cycle analysis (LCA) modeling, this work studies whether prioritizing r-HDPE for longer-life products is more environmentally beneficial, compared to shorter-life products (e.g., food-grade packaging). Specifically, this work compares the production of milk containers and drainage pipes using virgin and r-HDPE as examples of HDPE applications through three scenarios. Key findings emerged from this study including the demonstration of a slight advantage to prioritizing allocating the constrained r-HDPE supply to the longer-life product vs the shorter-life product and a distinct challenge in hitting recycled content targets with current recycling rates and 2030 goals for the United States. This highlights a need to expand current recycling infrastructure in tandem with other CE practices to reduce plastic consumption and sustain environmental health for all.

Keywords: circular economy, recycling, HDPE, system dynamics, life cycle

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1. Introduction

Today, plastics are indispensable to our lives with applications in almost every industry. The ability to fabricate products from plastics quickly and cost-effectively makes them suitable for both single-use and/or short life (e.g., packaging) applications as well as for applications that require plastic components to remain in use for decades (e.g., drainage pipes). While increasing demand continues to drive the growth of plastics production, our inability to manage end of use (EoU) plastics has led to the current plastics waste crisis. Globally, plastic waste more than doubled from 156 Mt in 2000 to 353 Mt in 2019. Yet, only about 9% of EoU plastics were recycled, 19% was incinerated, 50% was landfilled, while the remaining 22% leaked into the environment via haphazard dumping and burning [1]. The consequences of mismanaged plastic waste are enormous, including macro and microplastic leakage into the environment, freshwater contamination, and a host of human health impacts.

Circular economy (CE) practices have the potential to mitigate plastic waste concerns and dependence on virgin resources via closing the material loops. The CE manufacturing paradigm is currently limited partly due to EoU plastics being low value materials. Low economic incentive impedes the development of necessary EoU infrastructure for waste collection and plastic sorting, and limits recovery process efficiency. Furthermore, the lack of standards to align the roles of individual stakeholders (manufacturers, consumers,

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recyclers, etc.) for EoU plastic products contributes towards the current state of recovery practices and reliance on the linear economy [2].

High density polyethylene (HDPE) is of particular interest in the plastic CE as it is a highly recyclable thermoplastic and comprises 17% of all plastic produced. The demand for recycled-HDPE (r-HDPE) has increased to such an extent that the r-HDPE price at times surpasses the virgin-HDPE (v-HDPE) price, varying widely between USD 126 and USD 705 per ton in 2019, indicating that landfilled and mismanaged HDPE represents a significant missed opportunity for the US economy [3].

In the US, major causes of r-HDPE demand growth include increasing corporate pledges to reduce waste [4] and state government regulations (e.g., California (AB 793, SB 270), Washington (SB 5022, 5325), New Jersey (S2515) and Maine (LD 1467)) on category-specific minimum recycled content requirements [5]. The uncertainty associated with r-HDPE use and availability makes predicting its environmental benefits, if any, difficult. To that end, this paper explores the environmental implications of r-HDPE use in a dynamic manufacturing and recovery system. Specifically, three scenarios are considered where a constrained supply of EoU HDPE is recycled, and the resulting feedstock is allocated to the manufacture of short-term (milk containers) or long-term (drainage pipes) products. These scenarios are used to consider the potential ramifications of minimum recycled content requirements and discuss whether an environmental case for prioritizing r-HDPE for certain applications exists.

2. Background

In CE, evaluation of environmental and sustainability performance should address the dynamic nature of CE systems [6]. As literature suggests, system dynamics is a valuable method to assess the impacts of material recovery strategies. Guzzo et al. developed a system dynamics (SD)-based framework for examining decisions at different levels of CE transitions [7]. In recent work Mathur et al. used SD simulations for analyzing environmental impacts of product recovery pathways [8]. Moloney studied the impacts of municipal solid waste recycling rates plateauing with SD models [9]. Additionally, using an analytical- instead of SD-approach, Shen et al. modeled a recycling system where PET bottles were recycled into new bottles or fibers and compared the environmental impact of varying the number of recycling cycles, plastic allocation strategies, and demand profiles for each stream [10]. Integration of SD with life cycle approaches provides a more comprehensive view of systems with materials circulation.

Prior literature discussed the use of r-HDPE in variety of applications, including milk containers and drainage pipes. Several studies focused on the mechanical properties of r-HDPE resins made from milk containers [11], [12] and the environmental impacts of EoU recovery of this resource via life cycle assessment (LCA) [13], [14], [15]. These studies primarily served to provide proof of concept of the value of recycling for this waste stream and to aid in design stage decision-making for the containers. Also with the drainage pipe case, the environmental impacts of the substitution of r-HDPE for v-HDPE and other traditional materials has been investigated for r-HDPE sourced from mixed post-consumer waste [16] or dedicated homogeneous waste streams [17]. While these studies demonstrate the feasibility of use and environmental impacts reduction of r-HDPE for these streams individually, the work presented herein builds upon these findings to quantify the environmental impacts of two products with different processing needs, life spans and demands, when competing for limited streams of a recycled feedstock.

3. Methodology

This paper compares the potential environmental impacts of using r-HDPE in plastic milk containers "MC" that have a use life of several months vs. drainage pipes "DP" that have a use life of 50 to 100 years. Since plastic MC are food grade material, use of r-HDPE leads to stricter and extra processing requirements (e.g., "super-clean" process) that can increase environmental impacts [18], [19], [20]. Since r-HDPE is supply constrained, any diversion of the available supply of r-HDPE to a product category that currently does not use it will displace its use from a sector that uses it now. Typically, the diversion will come from a product category most sensitive to r-HDPE price. However, the modeling of price sensitivity and the resulting market dynamics are beyond the scope of this work. Given MC and DP are at the extreme ends of HDPE applications in terms of product use life and recycle-processing needs, these two product categories were chosen to highlight possible deviation of material needs and environmental impacts.

3.1. Case study

This case study focuses on the potential displacement of r-HDPE (portion currently sourced from recycled MC) going into DP products and the associated environmental impacts. All other r-HDPE recovery pathways (i.e., r-HDPE going into other product categories) are assumed to be intact. In the US, the total annual HDPE resin demand for MC production is estimated at 284 525 000 kg [13]. Since the fraction of recovered translucent HDPE bottles (used in applications such as MC) going into piping applications is 33% [21], the same fraction is assumed for recovered MC. Therefore, the annual MC production of interest to this case study is 93 893 250 kg. Using the collection rate of translucent HDPE bottles (27.2% for 2019 [22]) and the loss rate of materials in reclaiming (5% [10]), r-HDPE portion available for DP sourced from MC is 24 262 016 kg. Average HDPE DP with recycled material has

Table 1. Scenarios modeled and how the available r-HDPE is allocated.

Scenarios	r-HDPE to MC	r-HDPE to DP
Scenario 1 (Current case; DP priority)	0%*	100%*
Scenario 2 (50:50 sharing)	50%*	50%*
Scenario 3 (MC priority)	100%*	0%*

*Allocation percentages are the initial r-HDPE stream allocations. If the recycled content percentage for each product exceeds its feasible value (50% for MC, 90% for DP), excess r-HDPE is dynamically allocated to the other.

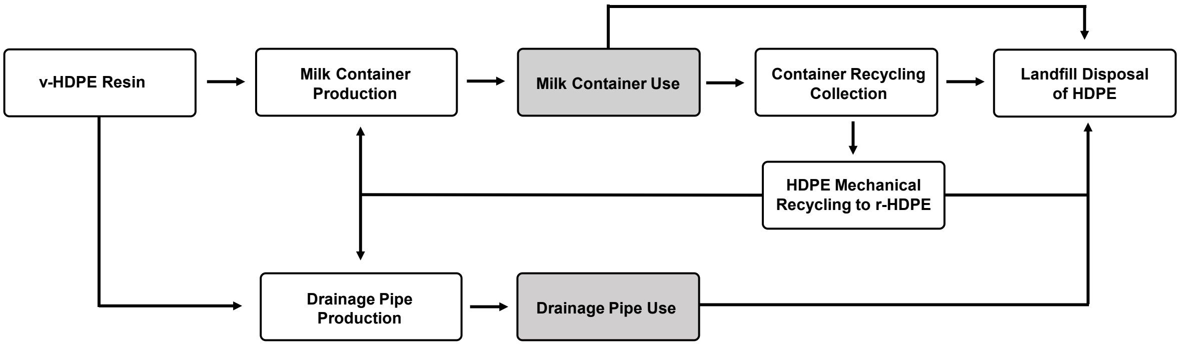

Fig. 1. Process steps and v-HDPE and r-HDPE resin flows in the system dynamics model.

50% recycled content [23]. Therefore, the total HDPE resin (both virgin and recycled) demand for DP applications sourced from recovered MC is estimated to be 48 524 032 kg.

In the above system, currently, all r-HDPE goes to DP (Scenario 1). In the other scenarios simulated (Table 1), the available r-HDPE is allocated to the MC pathway. Such diversion is likely with minimum recycled content requirements for MC, if the limited availability persists. Simulations are completed for two collection rates of HDPE – the 2019 value of 27.2% (rounded to 27% subsequently) [22] and EPA's national 2030 recycling goal of 50% [24].

Figure 1 visualizes the basic materials flows in the MC and DP product systems chosen for the case study where the three scenarios are tested to allocate the limited available r-HDPE.

In this work, the computational SD model was built using the *AnyLogic 8* software package* to simulate the HDPE resin production and recycling for MC and DP product streams. The v-HDPE stock provides virgin resin to both product streams. In the MC stream, flow is initiated by the annual resin demand for MC. Then, on average, MC stock remains in the path for 3 months. This timespan captures the average time from resin production to recycling of used bottles or landfill pathways. Material collected from material recovery facilities (MRFs) then goes through recycling processing, ending up in r-HDPE stock. This r-HDPE stock will be allocated between the MC and DP pathways according to the assignments defined in Table 1. DP's average use life (50 to 100 years) goes beyond the time horizon of simulation. EoU landfilling of DPs in use during that period is included in the LCA.

The simulation has a time horizon of 30 years to collect both the dynamic and cumulative values for information of interest such as v-HDPE produced, r-HDPE used in each pathway, HDPE landfilled due to non-collection and rejection during sorting and recycling. The 30-year period was chosen for the simulation as a long-term forecast. A longer time horizon may add further unknowns and variability in the system (e.g., recycling technologies and material use practices), leading to limited usefulness of such forecast. Market growth rates for the two product types are assumed to be same and therefore not modeled.

3.2. Life cycle impact analysis approach

LCA is used to derive the environmental impacts based on the material flows and production quantity from the SD simulation. In performing an LCA, one must determine both a functional unit by which to measure associated emissions and choose an allocation method for the industrial processes in the materials' life cycle. For the impact calculations, the functional unit will be 1 kg HDPE to allow a fair comparison between the use of v-HDPE and r-HDPE in feedstock for products with heterogeneous life spans. The SD model will be used to accommodate the different use life lengths and processing needs of the MC and DP, so that total environmental impacts can be estimated (see Section 4). Recycling allocation will be conducted using the "cut-off" method where the burdens associated with the v-HDPE will conclude at the end of its first use, i.e., disposal, and the burdens assigned to r-HDPE will start with recovery of the post-consumer material and include its reprocessing (sorting, granularization and cleaning) [25], [26]. As this work was focused solely on the emissions associated with production of the HDPE feedstock for two different product streams and not the products themselves, emissions associated with the use phase of the products were not included in this analysis. Forming of MC and DP are not modeled assuming processing is same whether using v-HDPE or r-HDPE. Additionally, while the MC are assumed to be recycled at the end of their lives in this study, the DP remains in place at the EoU and is assumed to have the same impacts as if that material was landfilled, which is consistent with similar LCA studies [23]. Transportation needs for collection are assumed same for both MC and DP. Outgoing transportation of resin to product manufacturers was not included in industry reports and is assumed to be within 500 km, by combination diesel truck.

Data on the processes to produce the v-HDPE and r-HDPE resin as well as transportation distances and methods were collected from industry specific LCA studies [13], [19], [25], *ecoinvent Version 3* database and USLCI. Environmental impacts were assessed using the SimaPro software and TRACI 2.1 method, which provides a host of indicators to holistically evaluate environmental impact. To determine which indicators and inventory elements to report, this work considered which

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*The commercial products and terms identified in this paper does not imply recommendation or endorsement by NIST. Nor does it imply that they are necessarily the best available for the purpose.

indicators were most impacted with the addition of the "Super-clean" process step to the conventional recycling process. For example, the addition of the Super-clean process step resulted in an 11% increase in water use and 27% increase in electricity required. Thus, energy demand and water use were considered key factors when examining the scaled impacts of the scenarios outlined in section 3.1. Global warming potential (GWP) and Ecotoxicity were also considered due to the differences in the impact of the unit process (26% increase in kgCO2e and 42% increase in CTUe, respectively) and provided a comparison to similar LCA studies on r-HDPE and r-polymers in literature.

4. Results

4.1. Environmental impacts of different allocation scenarios

The environmental impacts from the production volume and allotment achieved through SD modeling are highlighted in Table 2 and Table 4. The results given in this section are provided as cumulative values for the 30-year simulation time horizon. Table 2 focuses on the GWP of the v-HDPE and r-HDPE production and disposal for the two products modeled in this study. As expected, the largest contributor from these two feedstocks is the v-HDPE. There is a decrease in both overall GWP and in the v-HDPE contribution to the total with an increase of the recycling collection rate to 50%. However, the difference between the 3 scenarios is minimal (1 to 5%), with the current practice (i.e., DP priory) performing slightly but not significantly better.

Table 2. Global Warming Potential (GWP) from the production and disposal of HDPE resins for the 30-year time horizon (given in MMtCO2e).

		Sc. 1: DP priority	Sc. 2: 50:50 sharing	Sc. 3: MC priority
Collection rate of 27%	v-HDPE production	6.85	6.88	6.90
	MC r-HDPE	0*	0.24	0.49
	DP r-HDPE	0.39	0.2	0*
	Disposal	2.06	2.06	2.06
	Total GWP	**9.31**	**9.38**	**9.45**
Collection rate of 50%	v-HDPE production	5.83	5.87	5.91
	MC r-HDPE	0.02	0.45	0.9
	DP r-HDPE	0.71	0.36	0*
	Disposal	1.71	1.71	1.71
	Total GWP	**8.26**	**8.39**	**8.52**

*Zero means that given the available supply of r-HDPE material and the study parameters, there was no available material left for this product.

Table 3 compares between the current feasible goals (i.e., achievable targets with current manufacturing technology) for recycling content of each product type, and the final percentages the system settled to at steady state (after about 10 years). Only current practice, where the DP was given priority, combined with the higher recycling rate, achieved a product's recycling content goal. Otherwise, there was an insufficient amount of r-HDPE. This could forecast continued issues manufacturers may have in sourcing enough recycled resin even as recycling infrastructure improves. This will be discussed further in section 5.

Table 4 provides the cumulative values of other environmental impact indicators (energy demand, water use, and ecotoxicity) examined in this study. Similar trends as stated previously can be found. The recycling rate is a much bigger factor in the reduction of environmental impacts than the individual scenarios themselves. The minimal benefit gained is primarily through the less processing of plastics needed for DP.

Table 3. Recycling content percentages achieved for milk container (MC) and drainage pipes (DP) production compared to manufacturing goals.

	Product	Goal %	Sc. 1: DP priority	Sc. 2: 50:50 sharing	Sc. 3: MC priority
Collection rate of 27%	MC	50%	0%	13%	26%
	DP	90%	50%	25%	0%
Collection rate of 50%	MC	50%	1%	24%	48%
	DP	90%	90%	46%	0%

Table 4. Summary of total values (all resin production and disposal in study) for selected environmental indicators for 30-year time horizon.

		Sc. 1: DP priority	Sc. 2: 50:50 sharing	Sc. 3: MC priority
Collection rate of 27%	Energy Demand (GJ)	9.70×10^{10}	9.76×10^{10}	9.83×10^{10}
	Water Use (m^3)	3.24×10^{10}	3.28×10^{10}	3.32×10^{10}
	Ecotoxicity (CTUe)	3.22×10^{11}	3.23×10^{11}	3.24×10^{11}
Collection rate of 50%	Energy Demand (GJ)	8.81×10^{10}	8.92×10^{10}	9.03×10^{10}
	Water Use (m^3)	2.98×10^{10}	3.05×10^{10}	3.12×10^{10}
	Ecotoxicity (CTUe)	2.71×10^{11}	2.72×10^{11}	2.73×10^{11}

4.2. Additional variations in the results

In addition to the food-grade recycling processing requirement (i.e., "Super-clean" process) modeled in the LCA, there are additional steps compared to regular recycling. For MC, bales need to be inspected more rigorously (typically manually). Food-grade recycling streams need to avoid contamination from toxic chemicals, including from similar HDPE containers of pesticides and other chemicals. Even when the EoU material stream comes from food applications, a risk of toxic contaminants is still present [27]. Additionally, a risk exists that end-users store other chemicals in these containers and then return those through typical recycling streams. For the PET food-applications recycling, EU limits the sourcing to a maximum of 5% postconsumer material from materials that were in contact with non-food materials or substances [27]. Therefore, the actual rejection rate of material and processing environmental burdens may be higher than the data used in prior results. When availability of recycled material is limited, allocating that material to a product stream that requires less intensive processing (e.g., in this case DP) could be more beneficial.

As an approximation of these possibilities, the model was tested with additional rejection rate of 25% for MC path [28], along with additional processing related environmental impacts 50% higher than the reclaimer processing estimate used in section 4.1 to get an idea of the additional range of possible environmental impacts. Table 5 shows that with these changes, the differences between the base case (i.e., scenario 1) and scenarios 2 and 3 further widen. For 27% collection rate, these differences range from 2.5% to 7.5%, and for 50% collection rate the range goes to 5.3% to 14.8%.

5. Discussion

Without significant improvement in collection and recycling, r-HDPE will continue to be a supply-constrained resource. Any "new" product category starting to use r-HDPE will lead to displacement of the material from a current category. According to the Table 3, even if the collection rate increases to the 50% target, the potential still exists that individual product categories will not achieve recycled-content goals. This illustrates that these goals should not be set in a vacuum and can benefit from modeling efforts that consider current recycling infrastructure, efforts for its improvement and expansion, as well as market demand. This also highlights that recycled-content goals by themselves may not reduce the environmental impacts of plastic production. Other research and actions should be pursued in parallel such as planning in the product design phase to reduce plastic content overall or to promote improved EoU circularity.

The comparative environmental impact value percentages between scenarios in the results may seem minor at first. However, given the volume of materials involved, the magnitude of environmental impact differences between these scenarios are more considerable. According to Table 3, at the collection rate of 50%, prioritizing r-HDPE for DP instead of MC has the potential to decrease the overall emissions by 0.25 MMtCO$_2$e. For context, this is similar to avoiding 28 million gallons of gasoline consumption over the time horizon [29]. Likewise, the results also show consistency in that prioritizing allocation to DP did have lower impacts across all scenarios.

For the short-life product, this case study focused on MC only. However, there are plenty of HDPE product streams that could be considered with this framework. Expanding this analysis to a wider array of product category types with differing levels of processing needs (i.e., different magnitude of environmental impacts associated) will add richness to the analysis. Additionally, introducing other competitors for r-HDPE in the system may exacerbate the challenge of hitting recycled-content targets, and increase overall environmental impacts due to limited r-HDPE supply.

Table 5. Cumulative environmental impact summary with additional rejection and reclaimer processing burdens, for 30-year time horizon.

		Sc. 1: DP priority	Sc. 2: 50:50 sharing	Sc. 3: MC priority
Collection rate of 27%	GWP (MMtCO2e)	9.31	9.61	9.90
	Energy Demand (GJ)	9.70 x 10^{10}	9.76 x 10^{10}	9.83 x 10^{10}
	Water Use (m^3)	3.24 x 10^{10}	3.28 x 10^{10}	3.32 x 10^{10}
	Ecotoxicity (CTUe)	3.22 x 10^{11}	3.23 x 10^{11}	3.24 x 10^{11}
Collection rate of 50%	GWP (MMtCO2e)	8.28	8.80	9.34
	Energy Demand (GJ)	8.81 x 10^{10}	8.92 x 10^{10}	9.03 x 10^{10}
	Water Use (m^3)	2.98 x 10^{10}	3.05 x 10^{10}	3.12 x 10^{10}
	Ecotoxicity (CTUe)	2.71 x 10^{11}	2.72 x 10^{11}	2.73 x 10^{11}

Sourcing data on specific processes was challenging and errors relating to that is a limitation of this study. Section 4.2 provides an update to the results in case the environmental burdens are larger than originally estimated. Further modeling is also needed to understand the r-HDPE price due to increased demand, and how that may cause MRFs to improve their recovery activities. Improvements in recovery efficiency will also be a factor in being able to meet demand and reduce environmental impacts.

6. Conclusions and Future Work

Policies and regulations are being set across different regions related to minimum levels for postconsumer recycled content in plastic-based products [22], [30]. These policies can be useful to incentivize manufacturers' use of recycled content and thereby raise demand incentivizing collection and recycling infrastructure improvements. However, the overall environmental and sustainability impacts of these policies and goals needs the type of rigorous analysis that is presented here to identify priorities and the limitations of the economic system. If policies drive up the price of recycled material, manufacturers without any policy targets for recycled content (such as those that do not fall into a given product category or region) could unintentionally be incentivized to reduce their recycling efforts through market signals (i.e., price). Additionally, material may be transported to specific regions from outside the region to fulfill the higher demand presumably at a higher price point, thereby increasing the transportation-related environmental impacts. All other factors being the same, the result is an overall greater environmental impact with little to no added benefit to the region in terms of GHG emissions and contrary to the intension of the policy.

There are other recycled materials with similar use cases, where the supply is limited, and it is used in product categories with variety of use life lengths and recycling processing needs. The considerations and take-aways found in this study on HDPE pathways may be applicable to those other materials. We plan to expand this study to such materials in future work. With CE's focus on circular material flows, it is important to also consider environmental impacts of different circular pathways available. Furthermore, understanding the "dynamics" of the material pathways and the resulting environmental impacts is important, especially when making decisions in CE systems.

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