A FRAMEWORK FOR THE EVALUATION OF THE CIRCULARITY OF PLASTIC WASTE MANAGEMENT SYSTEMS: A CASE STUDY ON MECHANICAL RECYCLING OF HDPE

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Abstract

Circular Economy aims to solve resource, waste, and emission challenges by creating a production-to-consumption supply chain that is restorative and environmentally benign. In the case of plastics, this corresponds to keeping plastics at their higher quality in the economy, without any degradation or leakage into the natural environment. This is a very challenging task, although a first step towards such a model of plastics is to evaluate the circularity of alternative plastic waste management processes. This work introduces a Circular Economy assessment framework based on our previous work that provides i) a set of indicators and metrics for plastic recycling processes, ii) quantitative and holistic Circular Economy overall and category-based metrics, and iii) media for data visualization and analysis of Circular Economy indicators. Using this quantitative tool, areas of improvement for plastic waste processing technologies and facilities can be identified, and the performance of new technologies can be benchmarked against industrial standards. The applicability and the capabilities of the developed Circular Economy assessment framework is demonstrated through a case study on mechanical recycling of High Density Poly Ethylene. Results illustrated that areas for improvement of the mechanical recycling of High Density Poly Ethylene include the Energy dimension, that can be improved through the use of renewable energy sources, while at the same time improving the Emissions & Spillages dimension. Although, it is concluded that the mechanical recycling of High Density Poly Ethylene is inevitably constrained by contamination and complications arising from material separation and degradation that resulted in the low scores calculated that cannot be improved. The need to explore other methods of plastic waste management is highlighted at the end of the study.

1   Introduction

The production and use of plastic in the world has continued to significantly increase over the past decades, outpacing any other manufactured material, and leading to plastic pollution (Geyer et al., 2017). The durability and resistance to degradation of plastics make them so versatile in innumerable applications but at the same time make it very difficult for nature to assimilate leading to a significant need for efficient and effective plastic end-of-life management.

There are different types of plastics produced for the market, although only two are consistently recycled, Polyethylene terephthalate (PET) and High Density Poly Ethylene (HDPE), also known as plastics number 1 and 2 based on the Resin Identification Codes (RIC). The remaining plastics tend to end up as waste in landfills, damps, or our waterways.The recycling rate of plastics in the United Sates fell from 8.7% in 2018 to 5-6% in 2021, according to the U.S. Environmental Protection Agency (U.S. EPA). As the United States are trying to expand the plastic waste management infrastructure to increase the rate of plastic recycling, tools for informed decision making are becoming eminent.

Plastic recycling can be energy and water intensive, having adverse effects on the environment (Milios et al., 2018). Even though there have been recent advances in plastic recycling, there is still much to be done to make sure that plastic waste does not end up in the environment and, at the same time, that the plastic management processes do not harm the environment. A proposed approach for the transition towards sustainable plastic supply chains is Circular Economy (CE).

CE supply chain systems are systems that are restorative, regenerative and environmentally benign by design (Kirchherr et al., 2017). This can be achieved through the re-utilization of materials, the usage of renewable energy sources, and ultimately by closing any open material loops (Baratsas et al., 2021b). In the case of plastics, this corresponds to keeping plastics at their higher quality in the economy, without any degradation or leakage into the natural environment, using renewable energy sources, and eliminating the use of natural resources. This is a very challenging task, although a first step towards such a model of plastic supply chains is to evaluate the circularity of alternative plastic waste management processes (Paletta et al., 2019; Baratsas et al., 2021a).

The most common type of plastic recycling is mechanical recycling, where plastic is ground up and melted to then be reformed (Schyns and Shaver, 2021). Other types of plastic waste processing include chemical recycling (Thiounn and Smith, 2020) and energy recovery processes (Sharuddin et al., 2017). Recently, a process called solvent-targeted recovery and precipitation (STRAP) has been proposed for recycling multilayer plastic films (Walker et al., 2020). Each layer of these films is composed of a different polymer, which makes their recycling challenging. However, the STRAP process enables recovering the constituent polymers of the multilayer films using a series of solvent washes, and it is economically feasible (Sánchez-Rivera et al., 2021). The pyrolysis process is an energy recycling process that converts waste plastic into liquid oil (Li et al., 2022). These are just two examples of advancing methods of plastic recycling.

Measuring the circularity of plastic waste management processes can aid in decision making and help to minimize adverse effects recycling processes can have on the environment (Avraamidou et al., 2020). By keeping track of important circular economy metrics (such as greenhouse gas (GHG) emissions, water consumed, energy needed, etc.), waste plastic processing facilities can see how well they are doing in each category and in what categories they could improve on. Facilities and researchers can also use the circularity metric to compare different waste plastic processing technologies to each other or different types of recycling methods to each other. These comparisons can help to determine which recycling facilities or technologies are most efficient and least harmful to the environment.

The circular economy metric continues to be reshaped and redefined by researchers since its inception. This had led to varying depictions, applications, and purposes of the CE as seen in various research papers and definitions (Kirchherr et al., 2017). In addition, the majority of CE research has been focused at the macro level (city, region, nation, globe). With CE growing in its use and popularity there has been recent development of CE on the micro level (product, individual enterprises, consumers) (Elia et al., 2017). However, the indicators used at the macro level that are being applied to the micro level are too broad to give an accurate CE analysis at the level of a company or process (Vinante et al., 2021). A shift towards specific industry level indicators is what might be necessary to fully convey the CE for companies. There is currently no literature using the CE metric to analyze plastic waste management processes.

This work focuses on the development of a CE metric for plastic waste management processes. Using the CE assessment framework developed by Baratsas et al. (2022, 2021) as a basis, plastic waste management specific indicators were used to develop the proposed CE metric. The next section describes in more detail the development of the CE metric, while the third section is focusing on a case study on the mechanical recycling of HDPE.

2 Circular Economy Metric

The developed circular economy metric for waste plastic processing incorporates all CE goals along with their associated dimensions, indicators and metrics. Some of the indicators and metrics can be applied to a wide array of different companies at the micro level, although some were specifically derived for plastic waste management processes. The CE dimensions, indicators, and metrics that are used can be seen in Figure 1.

Table 1 of Baratsas et al. (2022) explains why each category was chosen due to the circular economy goal it is addressing. Figure 1 also shows what indicators or data is needed for each category and then how it is normalized to calculate a sub index score that can be compared to other plastic management methods. The linear average of the sub index scores is then taken to calculate the overall circularity of the process. A score of 0 indicates that the process is completely linear while a score of 1 indicates that the process has fully achieved all the goals of a circular economy.

The components of the metric that are specific to plastic recycling fall under the durability category. A big issue with many plastic recycling technologies is that they can degrade the plastic, which makes it difficult to reuse for its original purpose. The quality of plastic, in terms of mechanical properties and color, after it is recycled is the most important factor in deciding its new product use. Plastics can have many different properties (strength, viscosity, ductility, etc.) and different applications have different property requirements (for example packaging film requires a low value for stiffness while pipes require high values), therefore it is challenging to determine how to quantify durability under the CE metric.

Demets et al. (2021) were able to develop a metric to quantify the substitutability of recycled plastics using a scale of 0 (unsuitable substitution) to 1 (excellent substitution). Demets et al. (2021) took into account how different applications of the plastic warranted different necessary property values. Therefore, they split the substitutability scores into different categories based on the intended use of the plastic. To calculate these scores Demets et al. (2021) considered the plastics mechanical properties (strength, stiffness, toughness, ductility, and impact strength) and the plastics processibility, which can be determined by its ease of flow. A score was calculated for both mechanical properties and processibility and the smaller of the two was used as the overall substitutability score.

We adapted the substitutability metric developed by Demets et al. (2021) as an indicator and index for the Dura-
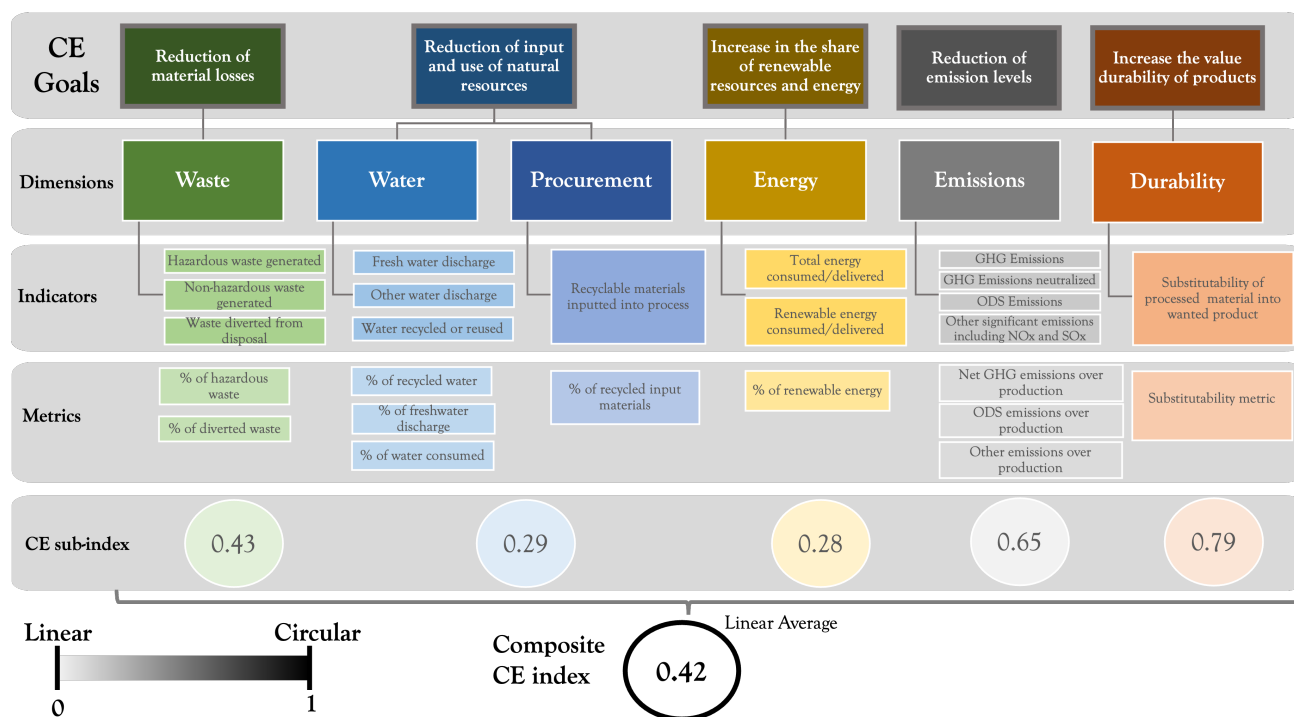
Figure 1: Representation of the development of the proposed CE metric calculator (Adapted from Baratsas et al. (2022)). GHG: greenhouse gas, ODS: ozone depletion substances

bility dimension of our CE metric for plastic waste management processes that produce plastic resins as their product. A third element, the color change, was added to the Durability dimension along with the substitutability metric, since for a subset of plastic uses discoloration of the plastic can lead to the recycled plastic deemed unsuitable for substitution even if mechanical properties and processability are determined to be good.

To calculate the Durability metric, a score for mechanical properties, processability, and color change are calculated, and the smaller of the three is used as the overall Durability sub-index. For more details regarding the derivation and calculations for the rest of the sub-indexes, the reader is referred to Baratsas et al. (2022).

Finally, to calculate the single composite CE index for plastic waste management, the linear average of all five sub-indexes is calculated, as seen in the illustrative example in Figure 3.

3 Case Study: Measuring the Circularity of Mechanical Recycling for HDPE

Mechanical recycling is a process where plastic waste (sorted by material type) is milled and washed, passes a flotation separation, and is then dried. The plastic flakes produced can either be used to produce new plastic materials or further processed into granulates. Mechanical recycling is the most common approach used for recycling polyethylene tereph-

thalate (PET) and high-density polyethylene (HDPE). This section will focus on the mechanical recycling of HDPE, and describes the process to evaluate its circularity.

The overall circularity and sub index scores for mechanical recycling of HDPE are calculated here. The data used in the calculations was found from Bataineh (2020) and Demets et al. (2021). The system boundary for this case study is only the processing of HDPE at a waste processing center. These numbers do not include the work that is done to the plastic at the material recovery facility, plastic reclamation facility, or the transportation needed through out. The mechanical recycling process, which is inside the boundary, includes the additional sorting and cleaning of material (that is done once received at the plastic waste processing facility), granulation, and extrusion into post-consumer pellets.

After defining our system boundary, data from literature was collected for all indicators listed in Figure 3. This data is presented in Table 1. The data for the waste, water, procurement, energy and emissions dimensions where obtained from Bataineh (2020); while the data for the durability dimension was obtained from Demets et al. (2021).

Figure 3 and Table 2 show the calculated sub-index values for the mechanical recycling of HDPE process and how they compare to one another. The durability category has multiple sub-index values because Demets et al. (2021) chose these as the applications recycled polyester would be made into for their study. The two applications that were used in this study are bottle and film. Both the closed loop and open loop processes for bottle and film are calculated and shown. Both closed loop processes (film to film and bottle to bottle) score significantly better than the open loop processes (film to bot-
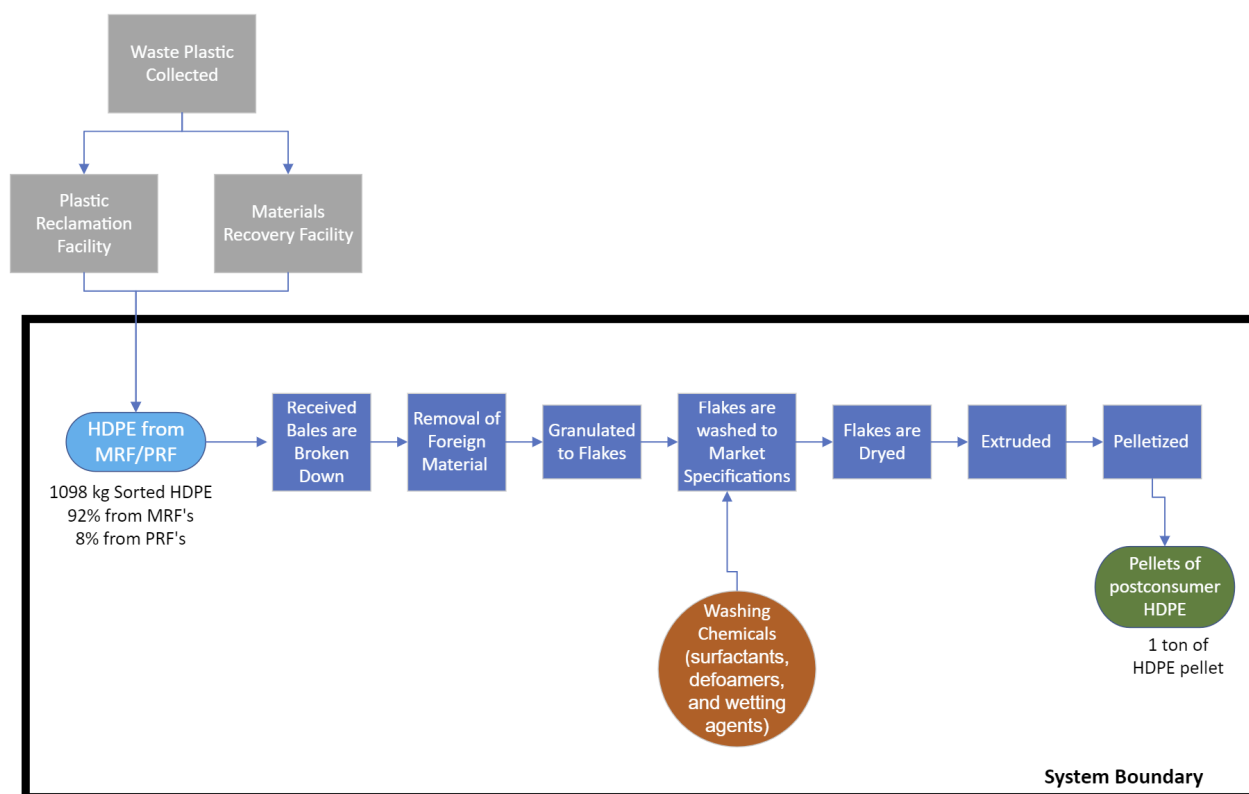
Figure 2: Mechanical Recycling Process of HDPE and System Boundary

tle and bottle to film). Disregarding durability, emissions and spillages is the most circular sub catergory, while water usage and energy are most linear. The data found from literature did not specify if any of the water used to clean the plastic was reused so we assumed it was being withdrawn every time. If the processing plant is treating and reusing the water, or if they began doing this, their circularity score for water and procurement would increase. In addition, the literature did not specify how much renewable energy the plant was using. We approximated the amount of renewable energy used based on how much is used in Wisconsin according to EIA (2022). If the amount of renewable energy the processing plant used increased, then the energy sub index score would also increase.

Table 3 shows the overall circularity scores for the mechanical recycling process of HDPE based on the intended application. The linear and bi-linear average scores are given for comparison. As shown, the bi-linear average scores are lower because they are more effected by low sub index scores. Overall, closed loop recycling (bottle to bottle and film to film) score higher than the open loop recycling processes (film to bottle and bottle to film).

Even though mechanical recycling can be improved by using renewable energy (increasing the Energy and Emissions & Spillages Sub-Index scores), is inevitably constrained by contamination and complications arising from material separation and degradation that resulted in the low scores calculated for the Waste and Durability Sub-Indexes

and the low overall circularity index scores seen in Tables 2 and 3. The proposed assessment tool can be used to evaluate chemical recycling process, such as the STRAP process described in the introduction section, that are not constraint by material separation or degradation issues.

4 Conclusion

A circular economy metric for plastic waste processing has been introduced in this paper. It includes components specific to plastic recycling and also the general categories used to analyze circularity at the micro level. The capabilities and applicability of the subject framework are demonstrated through the presented case study of mechanical recycling for HDPE. The results can quantitatively and visually show how mechanical recycling is scoring at different sustainability categories.

However, the non-availability or non-reporting of data complicates the evaluation process, potentially routing to misleading results or misrepresentation of the recycling processes. Also, social aspects are not directly captured in the current form of the framework, but can be incorporated in the future through the addition of new dimensions and indicators of interest.

It is the hope that in the future, a waste processing facility can use their results from this metric to compare to past years data, other processing facilities data, or different waste processing methods data. The comparisons that this metric

Table 1: Data collected for the waste, water, procurement, energy and emissions dimensions

| Data description	Unit	Value
Total Recycled Product	metric tons	1.00
Total Energy Consumed	GJ	1.637
Total Renewable Energy Consumed	GJ	0.162
Total Indirect GHG Emissions from Energy	metric tons	0.224
Nitrogen oxides, sulfur oxides, and other significant air emissions	metric tons	0.000114
Water Withdrawal	m^3	0.24
Solid Non-Hazardous Waste Generated	metric tons	0.14
Non-Renewable Materials Used	metric tons	0.0033
Total Waste Plastic Input	metric tons	1.098
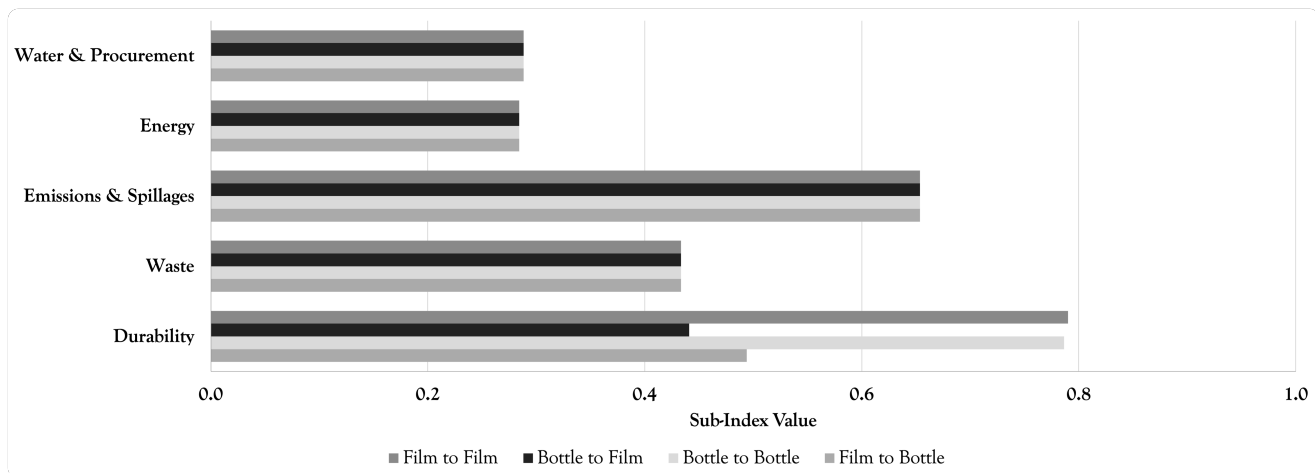
Figure 3: Mechanical Recycling of HDPE Circularity Sub-Indices

can produce will help companies make optimal decisions in regards to the environment and supply chain. To this end, we are developing a web-based platform to host the proposed CE index framework that will be accessible to both industry and academia.

Acknowledgments

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Table 2: CE Sub-Index scores

Sub-Index Category	Raw material to Product Use	Score
Water and Procurement	All	0.2882
Energy	All	0.2833
Emissions and Spillages	All	0.6535
Waste	All	0.4333
Durability	Film to Film	0.7900
	Bottle to Film	0.4408
	Bottle to Bottle	0.7863
	Film to Bottle	0.4940

Table 3: Overall Circularity Index for HDPE Mechanical Recycling

	Linear Average	Bilinear Average
Film to Film	0.49	0.23
Bottle to Film	0.42	0.17
Bottle to Bottle	0.49	0.23
Film to Bottle	0.43	0.18

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