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Towards Sustainable Supply Chains for Waste Plastics through Closed-Loop Recycling: A case-study for Georgia

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ABSTRACT

Sustainable and economically viable plastic recycling methodologies are vital for addressing the increasing environmental consequences of single-use plastics. In this study, we evaluate the plastic waste management value for the state of Georgia, US and investigate the potential of introducing novel depolymerization methods within the network. An equation-based formulation is developed to identify the optimum supply-chain design given the geographic location of existing facilities. Chemical recycling technologies that have received increasing attention are evaluated as candidate technologies to be integrated within the network. The optimum supply-chain design is selected based on environmental and economic objectives. The designed network of pathways uses a mix of different technologies (chemical and mechanical recycling) in a way that are both economically environmentally sound.

Keywords: recycling, supply chain, plastics, waste management, optimization

1. INTRODUCTION

Plastic materials have revolutionized our daily lives gradually replacing materials used for centuries such as wood, glass, or steel. Unfortunately, a significant amount of the plastics used ends up in landfills or marine environments with a very small percentage of them currently being recycled. For context, 35.7 MT of plastics were generated in the US in 2018 while approximately 26.9 MT ended up to landfill (75.6%) [1]. Consequently, the transition to circular economies (CE) in which waste materials will be effectively re-used stands as one of the most prevalent challenges of our times particularly in context of waste plastics [2].

The plastic waste management routes can be categorized into four categories: pre-consumer, mechanical recycling, chemical recycling, and energy recovery pathways. Currently, mechanical recycling is the primary method for recycling due to its low cost and simplicity, however, the material properties of the plastic degrade during processing (each plastic can be recycled 2-6 times during each lifetime) [3, 4]. As a result, solely depending on mechanical recycling impedes the realization of a closed-loop recycling economy [4, 5].

Chemical recycling of polymers through depolymerization pathways has garnered increased attention in the last decade as a promising alternative strategy. This is because chemical recycling enables the breakdown of polymers to constituent monomers thus, bypassing material degradation issues [3, 6]. A wide variety of methodologies have been proposed to chemically recycle waste plastics that differ considerably in terms of efficiencies, reaction pathways and maturity levels thus, ranking technologies and making decisions is nontrivial [7].

In combination to the already complex network of waste management options (e.g., landfilling, energy recovery, recycling etc.), design of economic and sustainable solutions that would maximize circularity is an open challenge. Previous studies have evaluated how to effectively manage waste systems though integrated supply-chains [8-11]. Ma et al. [4] developed a mixed integer linear program (MILP) approach to study the performance of thermochemical technologies at a regional-scale for low-density polyethylene (LDPE) and polypropylene (PP) waste. Recently, Badejo et al. [12] examined multiple technologies for managing high-density polyethylene (HDPE) waste using an MILP framework focusing on the

United States East Coast.

In this work, we model the supply chain of two types of waste plastics (i.e., polyethylene terephthalate (PET) and HDPE) through an equation-based framework using geospatial data for the state of Georgia, US. Geographic locations of the existing waste processing facilities (e.g., landfilling, mechanical recycling, etc.) are integrated within the network. Subsequently, we assess the potential of integrating novel chemical recycling methodologies into the superstructure for processing PET and HDPE waste. Literature data are incorporated into the formulation, to enable capturing the economic and emissions trade-offs between alternative technologies. Further, we employ multi-objective optimization to identify the Pareto-optimal solutions. In summary, our study presents a computational framework based on a realistic system representation that can be utilized to compare alternative pathways and enable the design of cost-effective supply-chains for PET and HDPE waste plastics.

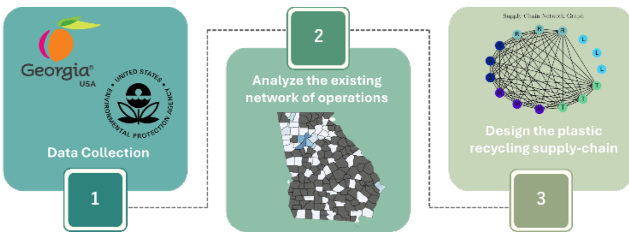

Figure 1. Overview of our analysis including data collection, formulation and optimization of the supply chain model.

2. MODEL DESCRIPTION

2.1. Model overview and problem statement

An equation-based formulation is established to systematically model the value chain of plastics. The primary objectives are: (a) to determine the most efficient path for plastic waste from various points of collections ultimately to the end-user; and (b) the mix of transformation technologies that would maximize circularity. The model is constructed as a graph where its nodes represent the source, transformation, and demand facilities. Each node is characterized by the geographic coordinates of each facility in Georgia, US (GA). The edges of the graph represent the material flowing between the nodes. This manuscript specifically studies the plastic waste management in the state of Georgia; however, the framework is generalizable and can be adapted for use in other regions that can vary in size.

The supply network in Georgia consists of distinct operations: (a) the plastic waste (HDPE and PET) is collected locally at transfer stations; (b) transported to landfills or recycling facilities; (c) transformed to usable forms through mechanical or chemical recycling; (d) mixed with virgin plastics to meet the market demands; and (e) transferred to the end-users. A simplistic graph of the route that plastics follows through the designed network is depicted in Figure 2.

Data sourced by the state of Georgia and the Environmental Protection Agency (EPA) [1, 13] are used as inputs to the model. Figure 3 visually presents the geographic locations of the system's nodes. The databases were further refined to include only those locations that process or utilize PET and HDPE. A total of 201 collection sites, 44 landfills, 29 recycling facilities (with 15 processing HDPE and 14 PET), and 30 market sites (11 and 19 sites that demand HDPE and PET, respectively) are considered.

Figure 2: Overview of the potential routes for plastic waste upcycling.

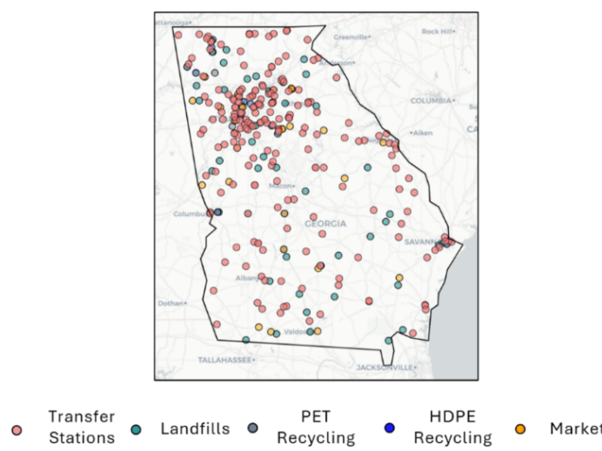

Figure 3: Map of the state of Georgia, US including all nodes of the PET and HDPE supply chain.

Figure 4 (a) and (b) depicts the spatial distribution of plastic waste generation for PET and HDPE in Georgia, respectively sourced from EPA database[1]. The amounts of HDPE and PET waste generated at each zip-code, are assigned as input rates to the closest collection site. It is assumed that the waste is already separated to HDPE and PET at each collection. The demand capacities for the each of the market locations is also assumed to be equal to the required amount of plastic at the closest zip-code [1].

At the existing geographic locations of mechanical recycling nodes, hypothetical chemical recycling facilities are introduced. It is assumed that each recycling node can process plastic waste either chemically or mechanically, provided that the capacity constraints are not exceeded. Various candidate technologies are compared for PET, including dissolution, enzymatic hydrolysis, glycolysis and methanolysis based on literature data [7]. For HDPE the investigation is focused only on dissolution as the primary chemical recycling technology.

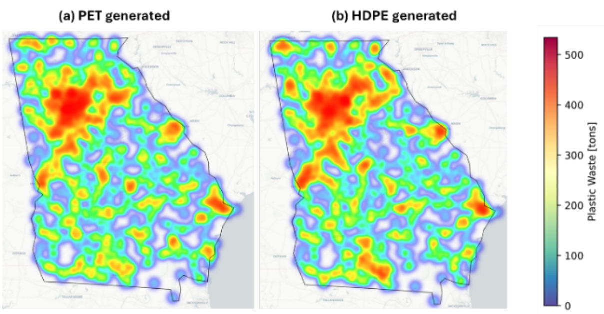

Figure 4: Heatmap of annual (a) PET (b) HDPE waste generated in Georgia, US as extracted by the EPA database.

2.2. Model formulation

As mentioned earlier, the supply chain model adopts a graph network representation. The set of all nodes is denoted as N. Collection sites (T), landfill (L), mechanical recycling (MR), chemical recycling (CR), and market (M) sets are introduced to describe the sets of distinct type of facility. Therefore, the entire network is described as $N = T \cup L \cup MR \cup CR \cup M$. Furthermore, for each of the sets introduced, a subset for PET and HDPE nodes are also established such that for example $MR = MR_{PET} \cup MR_{HDPE}$. The same holds for each of the sets introduced apart from L that can accept both HDPE and PET waste. Each chemical recycling node is characterized by the candidate depolymerization technology. A binary variable $y_{i,j,tech}$ is introduced to specify the type of chemical recycling technology implemented at each CR node. Finally, every node is characterized by the material flow m_{ij}, from the starting node i to the destination node j.

The model is formulated as a MILP with the objective of minimizing the economic or environmental impact. The environmental (Equation (1)) and economic (Equation (2)) objectives are defined as follows:

$$E = \sum_{i=1}^{N}\sum_{j=1}^{N} d_{ij} m_{ij} E_{mile_{ij}} + \sum_{j=1}^{N}\sum_{i=1}^{N} m_{ij} E_{i,j} \quad (1)$$

$$C = \sum_{i=1}^{N}\sum_{j=1}^{N} d_{ij} m_{ij} C_{mile_{ij}} + \sum_{j=1}^{N}\sum_{i=1}^{N} m_{ij} C_{i,j} \quad (2)$$

Here, d_{ij} represents the distance between node i and j, while m_{ij} signifies the material flow between the nodes. E_{ij} and C_{ij} denote the CO_2-eq emitted and the cost of production at the specific node with an input flow of m_{ij}, while C_{mile} and E_{mile} the cost and the emissions of transporting plastic through the edges of the network. The first term in Equations (1) and (2) represents the impact of the transportation to the objectives while the second term the impact of processing the plastic within each node. The material balances of flows entering and exiting each node are given by Equation (3) with α_{ij} representing the conversion factors. Different conversion factors are assigned based on the technology selected, processing node and material type. Equation (3) should be satisfied for all nodes.

$$\sum_{i=N_{in}}\sum_{j=N_{in}} m_{i,j}\,\alpha_{ij} = \sum_{i=N_{out}}\sum_{j=N_{out}} m_{ij} \quad (3)$$

Furthermore, demand and source constraints are imposed through Equations (4)-(5). Equation (4) guarantees that the market needs are fulfilled. The demands are satisfied by mixing recycled with virgin, petroleum-derived plastic denoted as vPET and vHDPE, respectively. This is included because the current market requirements cannot be exclusively satisfied through recycling, even if all collected plastic is recycled. Equation (5) ensures that all waste gathered is effectively managed either through recycling or disposed at the landfills. Moreover, Equation (6) introduces a capacity constraint within the formulation, to prevent material flows from exceeding the maximum processing capacity of each facility.

$$\sum_{i=CR\cup MR}\sum_{j=M} m_{i,j} + v_{Plastic} = \sum_{i=M} Demand_i \quad (4)$$

$$\sum_{i=T}\sum_{j=L\cup CR\cup MR} m_{i,j} = \sum_{i=T} Source_i \quad (5)$$

$$\sum_{i=CR\cup MR}\sum_{j=M} m_{i,j} \leq \sum_{i=IM} Capacity_i \quad (6)$$

Equations (7) and (8) set a quality constraint for the final product. This ensures that mechanically recycled plastic can be used in the production of new materials only if blended at a maximum threshold of 50% with virgin or chemically recycled plastic. Finally, Equation (9) guarantees that at each CR node, only one technology can be active.

$$\sum_{i=R}\sum_{j=M} m_{i,j} \leq 0.5\left(\sum_{i=CR}\sum_{j=M} m_{ij} + \sum_{i=M} v_{PETi}\right) \quad (7)$$

$$\sum_{i=R}\sum_{j=M} m_{i,j} \leq 0.5\left(\sum_{i=CR}\sum_{j=M} m_{ij} + \sum_{i=M} v_{HDPEi}\right) \quad (8)$$

$$\sum_{tech}\sum_{i=CR}\sum_{j=M} y_{i,j,tech} \leq 1 \quad (9)$$

The emission and cost factors utilized in Equations (1)-(2) are depicted in Table 1. All the environmental factors apart from the chemical recycling steps were obtained from the ecoinvent database v3.10, following the ReCiPe 2016 methodology [14, 15]. The emissions and cost factors for the investigated chemical recycling technologies are taken from a recent study conducted by Uekert et al. [7] in which the authors performed rigorous simulations of various chemical recycling processes. The cost factors for the rest of the steps are taken from the literature and published industry data [7, 16, 17].

Table 1: Emissions and cost factors of processing, feed, and mechanical recycling nodes

Process	Price ($/kg)	Emissions (kg CO_2-eq/kg)
Landfill HDPE	0.08	0.138
Landfill PET	0.08	0.095
MR HDPE	0.63	0.737
MR PET	0.54	1.337
Virgin HDPE	0.79	3.277
Virgin PET	1.19	4.086
Transportation	0.04/km	0.196/metric ton km

Table 2: Emissions and cost factors for chemical recycling technologies investigated

Process	Price ($/kg)	Emissions (kg CO_2-eq/kg)
Dissolution PET	0.87	4.49
Enzymatic Hydrolysis PET	2.01	3.95
Glycolysis PET	0.96	1.32
Methanolysis PET	1.05	4.19
Dissolution HDPE	1.10	2.40

2.3. Solution Strategy

The problem defined by Equations (1)-(9) is formulated as an MILP problem. The mathematical problem is solved in Pyomo with CPLEX v22.2. First, the two single-objective problems are solved independently, and the optimal network configurations and technologies of choice are obtained. In the case that the single-objective configurations are different, it indicates a conflict between the two solutions. This implies that there are trade-offs between economically sound and environmentally friendly solutions. Next, to analyze the trade-offs between the two solutions, the multi-objective optimization problem is formulated and solved using the ε-constraint methodology (Equation 10). The mathematical problem is transformed to a single-objective, bounded by an additional constraint that corresponds to the other objective [18, 19]. C_{min} and C_{max} correspond to the minimum and maximum values of the cost objectives as identified by the single-objective problems.

$$\min \ E \qquad (10a)$$

$$\text{s.t. } C < \varepsilon \text{, where } C_{min} \leq \varepsilon \leq C_{max} \qquad (10b)$$

3. RESULTS AND DISCUSSION

To evaluate the potential of integrating chemical recycling within the existing network we analyze: (a) the environmental impacts (Section 3.1), (b) the economic implications (Section 3.2), and (c) both objectives simultaneously (Section 3.3).

3.1. Environmental considerations of the GA recycling network

The spatial solution considering the environmental objective is depicted in Figure 5 (a). This solution is representative of the Business-As-Usual (BAU) scenario, where 10% of the plastic waste is recycled. A very small portion of the generated waste plastic are directed to recycling facilities. For PET, mechanical recycling nodes remain inactive and all of plastics are processed through chemical recycling. This is because of the higher conversion rates and relatively similar emissions rates between mechanical recycling and glycolysis (e.g., candidate technology with lower emission factor). Strictly only considering emissions, chemical recycling is favored in the BAU case (e.g., 90% landfill). The opposite is true for HDPE, where all plastics that is not landfilled are mechanically processed. This is attributed to the relatively lower emissions of MR as compared to CR for HDPE. It is worth acknowledging that the emission data for chemical recycling processes are based on experiments and simulations hence, the results may change as closed loop depolymerization recycling methods are further explored and optimized at larger scales.

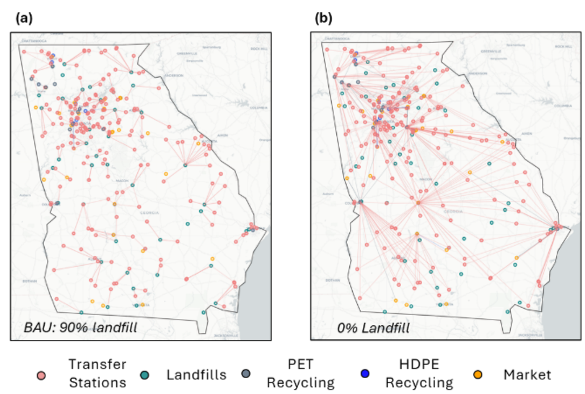

Figure 5: Solution for (a) 90% landfill scenario; (b) 0% landfill scenario under the environemntal objective.

To further explore the potential of recycling, sensitivity analyses are carried out to investigate the scenarios in which more plastic waste is recycled. The percentage of waste directed to landfills is changed to represent hypothetical scenarios. As landfilling is increasingly banned across Europe and some US states, those scenarios are important to consider. The network configuration for the zero-waste scenario is depicted in Figure 5 (b). The solution showcases an interconnected network of nodes with both chemical and mechanical recycling facilities activated.

The total CO_2-eq emissions of the different scenarios are highlighted in Figure 6. It is observed that as landfill is reduced, the total emitted CO_2-eq are also reduced, even though the emissions of landfilling are minimal. This is outweighed by the fact that plastics diverted from landfills are transformed into usable forms which, consequently, reduces the virgin plastic amount required to satisfy the market demands. Moreover, this is supported by the relatively small emission factors of glycolysis as compared to fossil production. The total emissions reported for HDPE are far lower than those of PET only because the input waste amount of PET is approximately double that of HDPE waste.

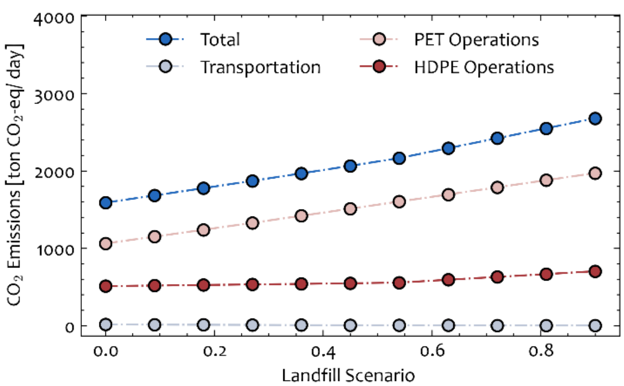

Figure 6: Emmited CO_2-eq for different landfilling scenarios categorized by distinct operations

Furthermore, more recycling nodes are activated as landfilling is reduced since more waste needs to be processed while virgin requirements are reduced. The mix of technologies utilized to fulfill the market demands are visually represented in Figure 7 for the BAU and zero-waste scenarios. In the BAU scenario, the demand of new plastic is fulfilled mainly through the production of virgin materials while, in the zero-waste case, mainly through the transformation of waste to useful products. The different solutions can be attributed to quality requirements set by Equations (7) and (8), the capacity constraints set for recycling as well as the amount of plastic diverted from the landfills to processing nodes.

In terms of the investigated technologies, glycolysis outperforms all the other candidate methods and is chosen as the most promising recycling solution in all the investigated scenarios. This is highly correlated with the fact that emissions of glycolysis are considerably lower compared to all others and very similar to those of mechanical recycling. The trade-off is that glycolysis has lower conversion than some of the other candidate technologies, however, this does not outweigh the higher environmental impact. Moreover, the use of plastic sourced from fossil resources is reduced in all those hypothetical cases, as highlighted in Figure 7. As more plastic waste is available for re-processing, the market demands do not have to be met with virgin quantities and the emissions are reduced. However, even under the zero-waste scenario, some virgin plastic is still required to meet the demands due to material losses occurring at intermediate nodes within the value-chain.

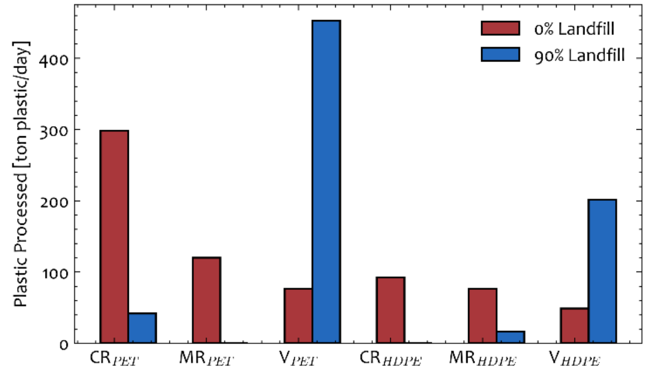

Figure 7: Amount of plastic processed through chemical and mechanical recycling compared with virgin requirements for 0% and 90% landfill scenarios.

3.2. Economic considerations of the GA recycling network

The spatial solution when considering the economic implications of the network are highlighted for the BAU and the zero-waste cases in Figure 8 (a)-(b). The effect of the same circularity scenarios to the economic objective are depicted in Figure 9.

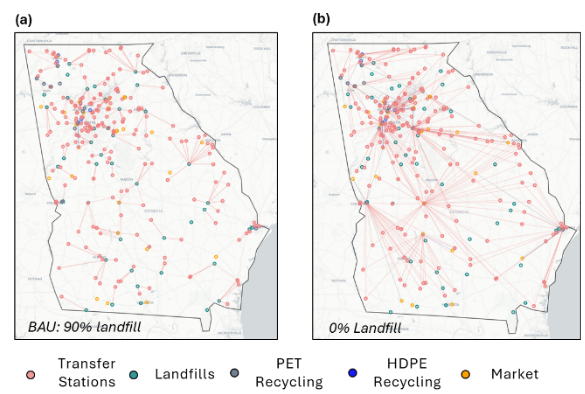

Figure 8: Optimal network configuration under the (a) BAU; and (b) zero-waste scenario considering the economic objective.

It is observed that the evaluated cost objective is relatively constant throughout the different scenarios because of the similar cost factors in the competing scenarios (e.g., fossil production compared to recycling). The use of recycling technologies in the zero-waste scenarios does not reduce the cost relatively to the BAU that needs fossil – derived plastic to meet the market demands. More specifically, the cost of virgin PET is set at

$1.19/kg compared to $0.87/kg for the dissolution that has the lowest cost factors amongst the competing technologies, while the cost of landfill is minimal. These two relatively close values in conjunction with the zero-waste constraint, drive the cost of recycling up, and even though recycling is selected, the cost is not substantially reduced. Moreover, the HDPE operation costs increase as the share of landfilling is reduced due to the higher costs of chemical recycling when compared to virgin or MR production. This trend is influenced by the quality constraints set by Equation (8) which enforces a certain amount of HDPE waste to be processed through CR, because otherwise the quality of the final product will be inadequate.

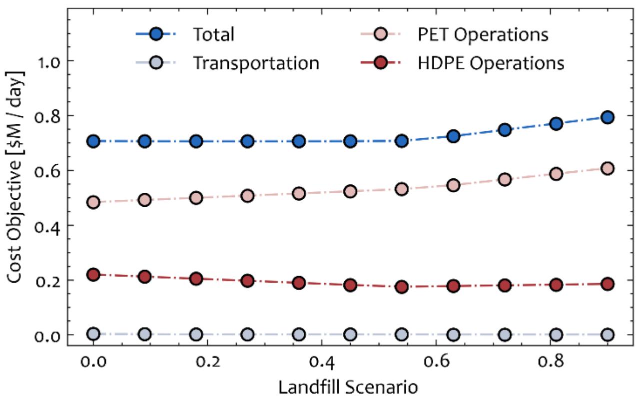

Figure 9: Cost objective for different landfilling scenarios as identified for the different technologies.

In terms of the competing technologies for PET, dissolution outperforms all the other options, being different from the environmentally favorable recycling methodology (i.e., glycolysis). This result is attributed to the relatively low-cost factors used for dissolution. In addition, the virgin requirements follow similar trends with the environmentally friendly solution discussed earlier with less fossil-derived plastic required, as landfilling is reduced. All in all, the solution identified for the cost minimization scenario corresponds to a different network with different chemical recycling technologies activated compared to the green-house gas (GHG) minimization scenario, as depicted in Figure 10. This shows that the solutions are in fact in contrast.

3.3. Identifying trade-offs between environmentally friendly and cost-effective solutions.

In this section, we investigate the trade-offs between the economically friendly and environmentally sound solutions. The values of the two objectives are depicted in Table 3 for the two distinct landfilling scenarios (0%, 90%). This, along with the recommended technologies (e.g., glycolysis is chosen as the best environmental case, dissolution for the most economical solution) indicates that the two objectives are in conflict meaning that different value chain networks are optimal. Moreover, the amounts of PET processed through chemical and mechanical recycling are very different for the two single-objective problems as illustrated in Figure 10.

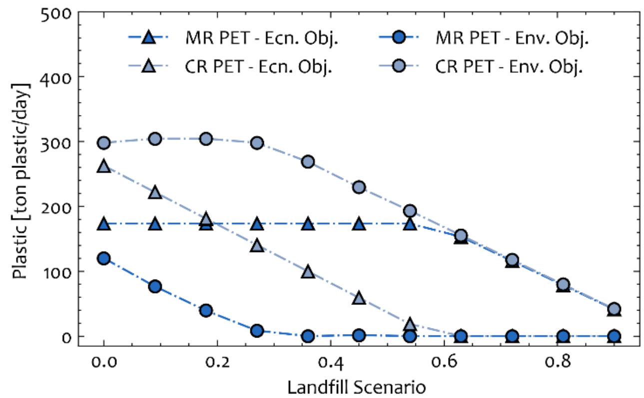

Figure 10: vPET required for different landfilling scenarios and technologies to meet the market demands.

The BAU solution is an exception since the identified configuration is very similar for the two problems. This is because very small amounts of plastic waste are recycled and almost all of it is diverted to landfills. The difference between the two cases is how the 10% of waste will be processed. For the zero-waste case studied, the spatial solution and the selected technologies are different, as highlighted in Table (3). Therefore, the trade-offs between the two objectives for this scenario are evaluated by following the procedure outlined in the Solution Strategy section.

Table 3: Values of the environmental and economic for the two extreme landfilling scenarios

Objectives	Economics (M$/day)	Emissions (ton-CO_2-eq/ day)
90% Landfill		
min Env	0.82	2679
min Ecn	0.79	2682
0% Landfill		
min Env	0.79	1590
min Ecn	0.71	2561

The Pareto front is depicted in Figure 11 for the case of 0% landfilling. Point A represents the optimal configuration corresponding to the minimum cost objective, regardless of the environmental impact. Similarly, point B represents the optimal configuration from an environmental perspective. The exact values of the objectives are presented in Table 3. All other Pareto solutions that lie in between points A and B signify the trade-offs between the two objectives based on the level of importance between the values.

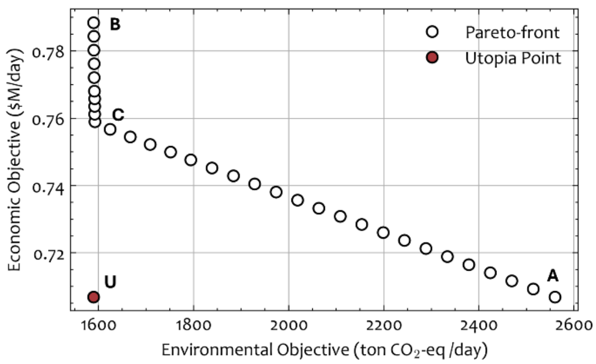

Figure 11: Pareto front and utopia point for the multi-obejctive optimization problem for the zero-waste case.

Point U, also referred to as Utopia point, reflects an ideal solution, in which the values obtained from the two single-objective problems are plotted. This is a hypothetical scenario that can never be reached for those two conflicting scenarios. The different solutions observed as we move along the Pareto-front stem from changes in the configuration of the optimal waste management network in the studied region and the technology chosen. The most significant difference between the two configurations is that the economically friendly solution only dissolution is chosen as a candidate technology, while in the environmentally sound value chain glycolysis is favored. Glycolysis and dissolution technologies are activated with different quantities processed as we move between points A and C. After point C, the cost objective increases at a different rate than the environmental objective. This is attributed to fact that after this point, only glycolysis is the active CR technology with some amounts processed through MR. As we move between point C to B, waste is diverted from MR to CR which increases the processing costs but has minimal impact to the emissions. This is because the emissions of MR and glycolysis for PET are very similar, while the opposite is true for the cost factors.

4. CONCLUSIONS

In this work, we discuss the design of optimal value chains of plastic recycling for a specific set of collection sites, transformation facilities and market. A superstructure network model was formulated to describe the existing recycling chain in the state of Georgia in the US. Our analysis evaluates the potential of integrating different depolymerization recycling technologies for PET and HDPE waste within the existing network. Different spatial arrangements and technologies are selected and designed for environmentally and economically friendly solutions. This contribution focuses only on the comparison of different depolymerization methods. However, to holistically evaluate the supply-chain of plastic recycling, it is essential to compare other technologies not solely based on depolymerization, such as energy recovery or feedstock recycling. The landscape of plastic waste management is highly dynamic and as new technologies are advanced and new research is conducted, the emission and cost factors used in this analysis may change. In terms of the HDPE feedstock, this assessment only accounted for the use of dissolution as a chemical recycling technology. Future work will delve deeper into the integration of additional chemical recycling technologies beyond PET and HDPE. We anticipate that this approach will allow for the evaluation and comparison of multiple waste management pathways along with more realistic feedstocks.

ACKNOWLEDGEMENTS

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