Systems & Control Transactions

Research Article
Foundations of Computer Aided Process Design (FOCAPD 2024)
Breckenridge, Colorado, USA. July 14-18, 2024
Peer Reviewed Conference Proceeding

PSE PRESS

Optimal Design of Food Packaging Considering Waste Management Technologies to Achieve Circular Economy

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ABSTRACT

Plastic packaging plays a fundamental role in the food industry, avoiding food waste and facilitating food access. The increasing plastic production and the lack of appropriate plastic waste management technologies represent a threat to the environmental and human welfare. Therefore, there is an urgent need to identify sustainable packaging solutions. Circular economy (CE) promotes reducing waste and increasing recycling practices to achieve sustainability. In this work, we propose a CE framework based on multi-objective optimization, considering both economic and environmental impacts, to identify optimal packaging designs and waste management technologies. Using mixed-integer linear programming (MILP), techno-economic analysis (TEA), and life cycle assessment (LCA), this work aims to build the first steps in packaging design, informing about the best packaging alternatives and the optimal technology or technologies to process packaging waste. For the economic analysis, we consider the minimum increase in price (MIP) when adding recycling to the cost of each packaging solution, while for the environmental analysis, the greenhouse gas emissions impact was considered. A case study on ground coffee packaging is used to illustrate the proposed framework. The results demonstrate that the multilayer bag option is the most convenient when considering both the chosen economic and environmental impacts.

Keywords: Optimization, Life Cycle Analysis, Technoeconomic Analysis, Supply Chain, Modelling

INTRODUCTION

Approximately 35-40% of plastics produced are discarded as waste after their first use, this percentage is expected to rise in the coming years based on current projections [1]. Containers and packaging represent around 28% of the municipal solid waste. Plastic containers account for around the 18%, and more than half of them are disposed in landfills [2]. The growing generation of plastic waste and the lack of initiatives to upcycle it, along with the irresponsible disposal of waste, threatens both marine life and humans [3].

The food industry is one of the largest manufacturing sectors contributing to the global economy. Packaging plays a crucial role in the food industry considering factors such as food quality and preservation, marketing appeal, and proper product identification. The final disposal or management of the packaging at the end of its life is a critical factor that should be incorporated during the packaging design stage, given the environmental concerns around plastic pollution. Over the past years, food packaging has evolved to increase efficiency (extend shelf-life while maintaining the freshness of the product) increasing food accessibility and reducing food waste. However, plastic food packaging is considered to follow a linear economic model, where it is designed and produced just in accordance with its intended use [4]. The need for sustainable food packaging solutions has become increasingly significant as the proportion of food packaging waste in municipal waste is on the rise.

Moreover, the increasing production of plastic implies a growing stress on resources. Materials extraction along with the processing of materials, fuels, and food contribute to water stress, biodiversity loss, and accounts for around 50% of the greenhouse gas (GHG) emissions [5. The growing production of plastics not only implicates using more virgin materials, but also the use of more resources, including energy and water, for the manufacturing of products. To tackle this, circular economy emerges as a system to promote the transition towards achieving environmental, economic, and social sustainability [6]. CE endorses, among other objectives, the closed-loop handling of natural resources to achieve minimal waste and to maintain the value of materials and products to their highest quality for as long as possible. Zhu et al notes that the design of packaging has been acknowledged as the essential initial step in moving toward CE [4]. Transitioning to more sustainable packaging solutions requires analyzing the impacts of alternative materials and their corresponding waste management technologies. Reducing the waste generated and increasing the compatibility of materials with recycling processes are fundamental to achieving recyclability targets [7].

Often, recycling complex plastic containing products can be more resource intensive than using the virgin plastic resins. For instance, PET possess a great resistance to high temperature which involves a considerable amount of energy to recycle it. Another example is multi-layer plastic films that require fewer resources given the efficient combination of materials. However, this configuration affects its recyclability. Therefore, the waste management processes for packaging should be taken into consideration during the design of the packaging.

To this end, we present a circular economy system engineering framework and decision-making tool that examines alternative food packaging design options and waste management possibilities. Using a superstructure approach, the present work employs a mixed-integer linear programming model for determining the optimal combination of packaging and recycling technologies based on economic and environmental criteria. As a case study, we have chosen coffee, which is the second largest traded commodity.

LITERATURE REVIEW

The state-of-the-art of sustainable packaging design consists of articles focusing on material selection, conceptual design, design development, and design validation. The material selection work focuses on reusability, biodegradable materials, and processability. The conceptual design phase involves topics such as the integration of reusing, and the abstention of a variety of impactful materials. The design development can incorporate the definition of appropriate features like size and weight, as well as the use of labels. Regarding the design validation phase, LCA tools and CE indicators are commonly used [4]. Although, the design guidelines should consider the facilitation of packaging waste management [8]. Karayilan et al [9] proposes a single-objective optimization model to evaluate environmental benefits (climate change and marine ecotoxicity) and material circularity within the packaging value chain. However, other circularity metrics and the economic aspect are not evaluated. Other studies, [10], focus on assessing the performance of different waste management systems for plastic waste, without considering the design of packaging.

Life Cycle Assessment (LCA) studies have been conducted to analyze the environmental performance of food packaging. Toniolo et al [11] performed a comparative LCA to estimate the appropriate recycling percentage for food packaging. However, most studies typically focus on evaluating metrics for the production and use of different packaging materials or designs. Siracusa et al [12] performed an environmental assessment for a single type of multilayer food packaging with a cradle to factory-gate scope. On the other hand, other LCA and techno-economic assessments evaluate various packaging options, but they concentrate on a specific recycling technology. Xie et al [13] reported an LCA on the recycling of Al-PE composite packaging. Some focus on comparing one or few alternative packaging solutions to the conventional, for example, reusable containers with single-use containers [14]. Jeswani et al [3] presented an LCA for mixed plastic waste considering pyrolysis, mechanical recycling, and energy recovery. Similarly, Munguia-Lopez et al [15] studied the environmental benefits of using solvent-based processes to recycle multilayer plastic films.

Optimization studies can enable the identification of optimal solutions for scenarios considering CE principles. Systems engineering frameworks involving multi-objective modeling can be used for the optimization of supply chains or technology allocation. Komly et al [16] presents a multi-objective optimization strategy to find the optimal allocation of PET bottles and recycling technologies to minimize environmental impacts.

However, a comprehensive economic and environmental assessment and/or optimization study considering the production, use, and waste management for different packaging designs is still lacking.

METHODOLOGY

The methodology followed will be described based on the case study for coffee packaging. Ground coffee currently comes in several packaging types, including disposable and non-disposable alternatives (refilling and reusing options). These options encompass monolayer film bags, containers, multi-layer film bags, and metal cans, that utilize materials ranging from polyethylene and/or aluminum to polyethylene terephthalate and polylactic acid (PLA). Waste management processes also offer various options, spanning traditional landfilling, incineration, and mechanical recycling, to more recent technologies like pyrolysis, and solvent-targeted recovery and precipitation (STRAP). Previous research has used LCA and multi-objective optimization to achieve a sustainable supply chain for coffee analyzing environmental and economic impacts but considering coffee production and distribution, but not its packaging [17-18]. The proposed methodology focusing on the optimal design and waste management of ground coffee packaging is divided into the four steps described below.

Packaging option identification

The first step in this analysis, is the identification of coffee packaging options currently available in the market. Between the packaging alternatives, various materials are utilized to consolidate different presentations of packaging. Among the bags considered, there are two plastic film options: monolayer and multilayer films. A multilayer film is a flexible plastic packaging that is composed of different materials that are combined to achieve specific properties that cannot be achieved with monolayer films alone. For example, in the case of coffee, a common multilayer film is composed of PE, PET, and aluminum. By combining the specific attributes of these materials, a packaging with high barrier properties and protection from light and oxygen is achieved, therefore, high-quality coffee is guaranteed. However, multilayer films are difficult to recycle using certain technologies such as mechanical recycling because of the incompatibility of the materials. Before multilayer films arose, monolayer films dominated the market, and some options are still present today.

The use of renewable resources to produce plastics arises as an alternative to avoid the dependence on fossil fuels (non-renewable energy sources) and address environmental concerns. Common plant-based feedstocks like sugarcane and corn can be processed into polymers that would have the exact same structure as the fossil fuels-derived ones. The production of these biobased materials is expected to result in a reduced carbon footprint owing to the carbon sequestration occurred during the cultivation of the plants. However, due to the various estimation methods and the conflicting results based on considerations like land use, the present study considers the carbon uptake outside of the scope.

Therefore, four options for ground coffee packaging were considered in this study: i) multi-layer film bags made with PE, aluminium, and PET, ii) monolayer film bags made with PE, iii) monolayer film bags made with biobased PE, and iv) rigid HDPE containers.

Waste management options identification

The most common plastic waste management technologies consist of landfilling, incineration, and mechanical recycling. Given the limited landfill disposal and growing environmental concerns, more efforts have been put into the development of new recycling technologies. Therefore, processes like energy recovery, mechanical recycling, and chemical recycling have been proposed. Chemical recycling through pyrolysis transforms mixed plastic waste (MPW) into a chemical feedstock that can be used instead of virgin materials to remanufacture polymers. Alternatively, STRAP emerges as an alternative to recycle multilayer films by using solvents to separate the film into its different layers [19-20]. The process selectively dissolves target polymers of multicomponent waste with specific solvents.

Packaging waste management begins with the collection and sorting of municipal waste, and the subsequent production of bales from plastic waste all of which takes place at a materials recovery facility (MRF). The second stage that transforms these plastic bales into a suitable feedstock for the different upcycling technologies occurs in a plastics reprocessing facility (PRF). In PRFs, plastic bales are reduced into plastic flakes and impurities are removed from the stream.

Therefore, in this study five options for plastic packaging waste management are considered: i) mechanical recycling, ii) STRAP, iii) pyrolysis, iv) incineration, and v) landfilling. All these waste management options have as a common denominator MRFs. Pyrolysis and mechanical recycling technologies also require PRFs.

Economic and Environmental Impact Assessment

This case study assumes the coffee companies will be responsible for recycling the post-consumer waste packaging following the Extended Producer Responsibility trend. The scope considered for the TEA starts with the purchasing of the plastic packaging by the coffee company. Moreover, the fixed and variable operational costs for the recycling technologies are considered, as well as the sales of the resulting products. The packaging costs are estimated according to the price market. The recycling technologies costs are calculated based on literature data [21-23]. The products costs are defined based on the quality and the corresponding price in the market. The difference between the costs of packaging and recycling, and the revenue from sales provides the minimum increase in price, a metric that is used to quantity the economic behavior.

For the GHG emissions assessment, the production of the packaging, along with the recycling process are considered. The climate change factors contemplated to perform the LCA are obtained from the Environmental Footprint database [24-25]. The factors of climate change used for the packaging take into consideration the steps that the production of each packaging requires, such as pellets production, film extrusion, or lamination. The same applies to the climate change impact for the recycling technologies. The factors from the stages of the recycling processes, MRF and PRF, are included in the applicable scenarios. The different inputs required for the recycling technologies are collected from studies in the literature [21-23].

Previous studies have reported the economic and environmental feasibility of using STRAP to recover the constituent polymers of diverse multilayer films [19-20]. However, the multilayer film commonly used for coffee packaging (composed of PE, PET, and Al) has not been studied. Following the previous approaches, in this work, we propose a STRAP variation to treat such multilayer films. We performed STRAP experiments that showed that the recovery of all components and ink removal was feasible. The experimental yields were higher than 95 wt%. and the composition of the packaging was determined to be: 49 wt% of PE, 32 wt% of PET, 17 wt% of aluminium and 2 wt% of ink. The recovered polymers have comparable properties to the corresponding virgin resins. The collected experimental data was used to simulate the STRAP process and perform the TEA and LCA analysis [26].

Superstructure Representation and multi-objective MILP model

For each packaging, all the possible options among waste management technologies and the subsequent products are contemplated. Figure 1 illustrates the superstructure considered for this study.

Following the alternatives previously described, seven scenarios are considered for the four most common coffee packaging options. Pyrolysis, landfill, and incineration are contemplated for all the packaging, as shown in the superstructure in Figure 1. Pyrolysis is divided into two scenarios: one that extends to the production of the pyrolysis oil and another that additionally involves the polymerization of new polymers from the pyrolysis oil. Mechanical recycling can process only monolayer packaging (films or rigid containers) and STRAP, only multilayer films. Two scenarios were defined for STRAP: one with ink removal that separates all the layers of the packaging using: one solvent to remove the PE layer, a second solvent to separate the aluminum and PET leftover along with the ink, and an eddy current separator to separate the metal from the polymer. The second scenario with no ink removal just removes the initial layer of PE (which constitutes the largest portion following the common composition of coffee packaging [27]) and directs the remaining residue to landfill. The use of more solvents conveys a larger use of resources that generate more emissions, then a scenario considering STRAP and landfill is analyzed as an additional alternative. The basis for the study is defined as 1000 containers.

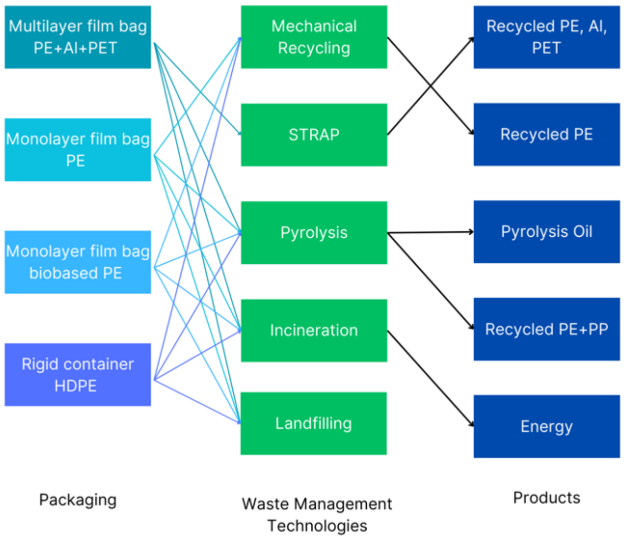

Figure 1. Superstructure considered in the study.

Under the economic criteria, the goal is to find the minimum increase in price that the company or the customer will have to cover. On the other hand, for the environmental criteria, the objective is to select the process that would generate the least GHG emissions. Given these two competing objectives, this work proposes the use of a multi-objective optimization to evaluate the trade-offs between the different packaging designs and waste management technologies. Hence, the resulting pareto front of this circular economy framework serves as a decision-making tool.

The basis for the study was defined based on a typical 500-gram ground coffee container, and the model was defined using the following nomenclature.

Nomenclature

Sets and Index

P, p	set of packaging, packaging index
R, r	set of recycling technologies, recycling technology index
m	Individual materials index
mt	multilayer packaging
mn	monolayer packaging
bm	biobased monolayer packaging
hp	HDPE rigid container
po	pyrolysis with oil production
pp	pyrolysis with polymerization
sr	STRAP with ink removal
sn	STRAP with no ink removal and landfill
mr	mechanical recycling
lf	landfill

we	waste to energy
Decision Variables	
I_p	total input of packaging
B_P	number of bags for packaging p
$F_{p,r}$	flow from packaging p to technology r
C_p	total cost for purchasing packaging p
$CR_{p,r}$	total cost for recycling packaging p through technology r
$S_{p,r}$	sales of products obtained from processing packaging p through technology r
$D_{p,r}$	difference between cost of recycling and sales for packaging p and recycling technology r
EP_p	CO_2 eq. emissions from the production of packaging p
$ER_{p,r}$	CO_2 eq. emissions from the recycling of packaging p with technology r
Constants	
M_p	material per bag for packaging p
W_p	weight of packaging p
W_m	weight of individual material
X_p	cost of packaging p per ton
X_m	cost of individual material
$Cost_r$	cost of waste management technology r per ton
$Cost_{MRc}$	cost for mechanical recycling for an hdpe rigid container
$n_{p,r}$	yield of processing packaging p with technology r
$nl_{p,pp}$	yield of the polymerization of LDPE
$np_{p,pp}$	yield of the polymerization of PP
$X_{p,r}$	cost of product from packaging p processed through technology r
X_{PP}	cost of PP
X_{bp}	cost of polymerization by-products
G_p	Climate change factor for packaging p or material
G_m	Climate change factor for individual material
$G_{p,r}$	Climate change factor for packaging p processed through technology r

The packaging alternatives have a set of possible recycling technologies r available. The set of packaging is: $P = \{mt, mn, bm, hp\}$. The set of technologies is: $R = \{po, pp, sr, sn, mr, lf, we\}$. Additionally, a set of materials is defined to refer to the components present in the multilayer film: $M = \{PET, Al, PE\}$.

The selection or not of the packaging and the technology is given by the following two binary variables:

$$y_p \ \forall\, p \in P \tag{1}$$

$$z_r \ \forall\, r \in RT \tag{2}$$

The decision variables depend on the following continuous variables:

$$\mathrm{B_p} \leq 1000\, y_p \quad \forall\, p \in P \tag{3}$$

$$\textstyle\sum_p B_p = 1000 \ \forall\, p \in P \tag{4}$$

$$\mathrm{I_p} = B_p \mathrm{M_p} \qquad \forall\, p \in P \tag{5}$$

The amount that should come from packaging p to recycling technology rt is given by the continuous variable:

$$\textstyle\sum_r F_{p,r} = \mathrm{I_p} \ \forall\, r \in R, \forall\, p \in P \tag{6}$$

The following equations are general constraints considered for the model:

$$F_{p,sr} = 0 \,, \forall\ \mathrm{p} \in \{\mathrm{mn, bm, hp}\} \ \forall\ \mathrm{r} \in \{\mathrm{sr, sn}\} \tag{7}$$

$$F_{mt,mr} = 0 \tag{8}$$

$$\textstyle\sum_p y_p \geq 1 \ \forall\, p \in P \tag{9}$$

$$\textstyle\sum_r z_r \geq 1 \ \forall\, r \in R \tag{10}$$

$$F_{p,r} \leq 100000 z_r \ \forall\, r \in R, \forall\, p \in P \tag{11}$$

$$F_{p,r} \leq 100000 y_p \ \ \forall\, p \in P, \forall\, r \in R \tag{12}$$

The packaging cost, the recycling cost and the products sales considered for the economic assessment are given by equations 13-22:

$$C_p = W_p\, X_p B_p \ \ \forall\, p \neq mt \tag{13}$$

$$C_{mt} = (W_{Al} X_{Al} + W_{PET} X_{PET} + W_{PE} X_{PE})\, B_{mt} \tag{14}$$

$$CR_{p,r} = F_{p,r}\ Cost_r \ \forall\, p \in P, \forall\, r \in R - \{i = hp, j = mr\} \tag{15}$$

$$CR_{hp,mr} = F_{hp,mr}\ Cost_{MRc} \tag{16}$$

$$S_{p,r} = F_{p,r} n_{p,r} X_{p,r} \ \ \forall\, p \in P, \quad \forall\, r \in rt : r \neq pp, lf, sr, sn \tag{17}$$

$$S_{p,pp} = F_{p,pp}(\, nl_{p,pp}\, X_{PE} + np_{p,pp} X_{PP} + n_{p,po} + X_{bp}) \tag{18}$$

$$S_{p,sr} = (F_{p,sr} n_{p,sr})(0.49 X_{PE} + 0.32 X_{Al} + 0.17 X_{PET}) \tag{19}$$

$$S_{p,sn} = F_{p,sn} n_{p,sn} 0.49 X_{PE} \tag{20}$$

$$S_{p,lf} = 0 \tag{21}$$

$$D_{p,r} = S_{p,r} - CR_{p,r} \ \ \forall\, p \in P, \forall\, r \in R \tag{22}$$

$$Profit = \textstyle\sum_p \sum_r D_{p,r} - \sum_p C_p \tag{23}$$

The computation of the emissions used for the analysis of the environmental impact follow equations 24-27:

$$EP_p = W_p G_p B_p \ \forall\, p \in P \colon p \neq mt \tag{24}$$

$$EP_{mt} = (W_{Al}G_{Al} + W_{PET}G_{PET} + W_{PE}G_{PE}) + M_{mt}G_{mt}B_{mt} \quad (25)$$

$$ER_{p,r} = G_{p,r}F_{p,r} \; \forall \, p \in P, \forall \, r \in R : p \neq mt \quad (26)$$

$$ER_{p,sn} = G_{p,sn}F_{p,sn} + (F_{p,sn}0.22)(0.65G_{lf} + 0.35G_{ldA}) \quad (27)$$

$$Emissions = \textstyle\sum_p EP_p + \sum_p \sum_r ER_{p,r} \quad (28)$$

The model objective functions are given by the maximization of profit and the minimization of emissions, as shown in equations 23 and 28.

DISCUSSION AND RESULTS

The mixed-integer optimization model was implemented in Julia 1.8.5 and solved with Gurobi v1.0.1. For the multi-objective problem, the ε-constraint method was utilized [28]. The resulting pareto front is illustrated in Figure 2, with the details of each pareto solution presented in Table 1.

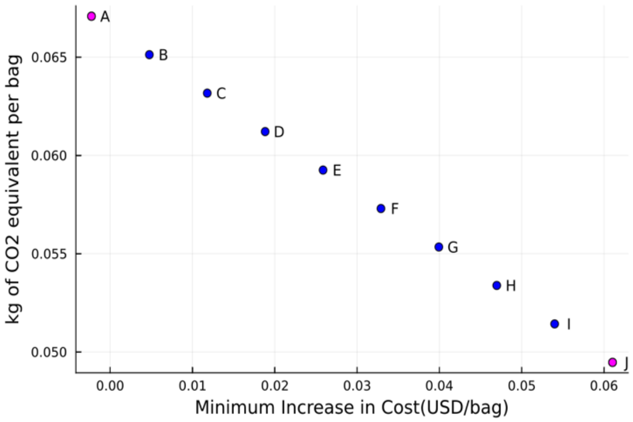

Figure 2. Superstructure considered in the study.

Table 1: Percentage of multilayer film bags processed by the selected technologies for the points of the obtained pareto front.

Points	Technology	Bags Allocation
● A	STRAP with ink removal	100%
● B	STRAP with ink removal Landfilling	89% 11%
● C	STRAP with ink removal Landfilling	78% 22%
● D	STRAP with ink removal Landfilling	67% 33%
● E	STRAP with ink removal Landfilling	56% 44%
● F	STRAP with ink removal Landfilling	44% 56%
● G	STRAP with ink removal Landfilling	33% 67%
● H	STRAP with ink removal Landfilling	22% 78%
● I	STRAP with ink removal Landfilling	11% 89%
● J	Landfilling	100%

The results indicate that the most profitable scenario is STRAP with ink removal for a multilayer film with an increase in price of approximately zero per bag due to the high selling price of the recycled polymers. However, its emissions reach 0.067 kg of CO_2eq. per bag. The minimum increase in price shows a negative value in the pareto front due to a minimum profit of 0.0018 $ per bag that for simplicity is approximated to zero. On the other hand, the least GHG-emitting alternative is the landfilling of multilayer packaging with the lowest emissions of 0.05 kg CO_2eq. per bag. Nevertheless, the extra cost reaches $0.06 per bag.

The packaging type selected in all pareto points is the multilayer PE-Al-PET bag. The set of solutions show possibilities for: a combination of two technologies (blue points) or just one technology (pink points). The technologies contemplated are STRAP with ink removal and landfilling. Given the set of solutions found, it is shown that the reduction of materials together with the proper feasible recycling technology are key to sustainable packaging solutions.

The costs and emissions for processing different packaging types even when using the same technology differ due to the different amounts of material present in each type of container. A trade-off between the amount of material needed and the desired performance of the packaging is highlighted. Multilayer films require less amount of material than monolayer packaging to achieve a high performance. However, the multilayer films characterize by greater complexity that results in a challenge for traditional recycling technologies. Therefore, the recently proposed process STRAP represents a breakthrough technology. It would solve the recyclability limitation generally attributed to multilayer films, while promoting a packaging solution that is less resource intensive. Furthermore, multilayer films represent a substantial advantage as the light weight leads to decreased energy consumption during transportation and consequently lower emissions.

The integration of environmental and economic considerations is suitable to determine the most convenient sustainable solutions. The LCA takes into consideration the emissions generated from the resources used in each of the technologies, like solvents, water withdrawal and energy requirements. Then, the CO_2 equivalent emissions obtained from the LCA, enables an appropriate comparison of the environmental impact of the different processes. However, there are other environmental impacts that should be considered. While landfilling has been selected as the most environmentally convenient alternative when considering the GHG emissions, there are other potential impacts of landfills to the environment including: soil contamination, water and air pollution, and loss of resources. Landfilling is recognized to have long-lasting environmental impacts. Even after closure treatment and some years, landfills can still release gases and leach contaminants within the surrounding area [29].

The model enables the quantification of alternatives that, while initially deemed beneficial, were ultimately excluded from the set of chosen solutions. A packaging choice anticipated as a green alternative, yet not selected was the biobased polyethylene bag. Despite biobased polyethylene being an environmentally friendly alternative due to its origin, it involves higher prices than fossil-fuel derived polymers and accounts for the same disposal issue (recycling requirement) as fossil-based plastics. The emissions for the biobased packaging (based on the system boundaries) with the landfill alternative increase to 0.29 kg CO_2eq. per bag. Another packaging option that was not selected as solution is the HDPE rigid container. Even though the packaging facilitates the recycling of the plastic waste, the amount of material required makes it less environmentally friendly. For this alternative, the emissions increase to 0.23 kg CO_2eq per bag considering landfill.

Besides recycling, the scope of the study takes into consideration the resulting products of the process. The outputs for the different scenarios are analyzed given that the products (and even the quality of the pellets) might vary. Depending on the products, the sales can be altered. Some LCA studies that compare mechanical with chemical recycling, don't take into consideration important factors such as the quality of the outputs of the process, affecting the alternatives that provide a higher quality recycled product. The ideal case would be to obtain the most valuable product, like in the case of pyrolysis with polymerization, however, that would imply higher costs and emissions for the further processing of the material. The output of STRAP for the coffee packaging is of high quality and is obtained at a low cost, providing an economically feasible scenario.

As previously noted, certain recycling technologies may degrade the plastic's quality because they affect its mechanical properties [31]. Others instead produce a virgin-like quality plastic without deterioration and application restrictions [3]. Moreover, some processes might produce more waste or consume more resources than others. Consequently, the next logical step involves implementing a comprehensive circularity assessment framework to holistically explore environmental impacts [32].

CONCLUSIONS

Plastic packaging plays a significant role in modern society given its multiple benefits; however, a responsible management is required. Global efforts are put into the development of sustainable alternatives to reduce environmental impacts, such initiatives highlight the need to evaluate the required recycling infrastructure. The CE framework proposed in this work contributes to literature by analyzing the optimal packaging configuration based on the recycling technologies available to process it and materials used for packaging. Packaging solutions that are environmentally and economically viable are required. Both objectives are evaluated individually and as competing objectives. The use of multi-objective optimization generates a set of solutions valuable for decision-making. The case study of coffee provides an insight into the minimum increase in price if coffee companies were responsible for the packaging recycling. The prices are obtained for a combination of technologies with the best packaging resulting in different levels of emissions.

Despite their initial classification as environmentally unfriendly, multilayer films prove to be the most convenient option when equipped with a recycling technology to process it like STRAP. The technologies that are part of the solution encompass STRAP with ink removal and landfilling. The most economically viable technology is STRAP with a zero-price increase, but emissions of 0.07 kgCO_2 eq. per bag. Conversely, the most environmentally friendly alternative is landfill with 0.05 kgCO_2eq. per bag, but an extra cost of 0.06 USD per bag. However, given the multiple environmental impacts caused by landfilling, further analysis is required. The toxicity of the leachate is one of the principal sources of contamination. Therefore, an analysis of their composition and their related impacts can provide insights in the environmental and human health effects [29,33]. This can be quantified under a metric that considers toxicity or the impact on water, air, land quality and human health. An alternative to assign a monetary value to environmental goods is to use an economic valuation technique [34]. Additionally, for future work a further analysis for biobased packaging can be explored taking into account carbon uptake with different system boundaries and considerations.

Regardless, the environmental and economic assessment is a good approximation and first approach, a holistic evaluation of circularity needs to be developed. For that reason, the future work will focus on applying a circularity calculator to the different management technologies to extend the analysis and visualize the trade-off between circular and economically feasible scenarios. The ultimate goal would be to provide insights to design more sustainable packaging and supply chains. Furthermore, there are a few biodegradable packaging options emerging today. However, it will be considered in the future study together with reusing practices and alternative disposal technologies such as composting and home-composting.

ACKNOWLEDGEMENTS

This material is based upon work supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office under Award Number DEEE0009285, and the University of Wisconsin-Madison.

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