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Assessing the circularity potential of plastics with a substitutability approach: A case study in Argentina

Evaluación del potencial de circularidad de los plásticos con enfoque de sustituibilidad: caso de Estudio en Argentina

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ABSTRACT

Resource depletion, greenhouse gas emissions, and pollution associated with production, consumption, and disposal of plastics demand solutions. Material circularity is presented as a key strategy to address this problem. However, a comprehensive study of these systems is needed to determine whether it is possible to completely close the material loop. When evaluating plastics recycling as a circularity strategy, it is essential to consider the conservation of mass in the cycle and the conservation of quality. In this sense, substitutability is a concept that measures the ability of the recycled material to replace virgin material. This paper presents the results of the circularity potential of six main types of plastics for five scenarios in Argentina, based on recycling rates and market shares to measure the conservation of quantity and quality in the material cycle. The results show a low circularity potential for all plastics, the best indicator being 13.6% for HDPE and the worst being 3% for PS.

Keywords: Circular economy; High-density polyethylene; Material cycle; Plastic materials; Plastic recycling.

RESUMEN

El agotamiento de recursos, las emisiones de gases de efecto invernadero y la contaminación asociada con la producción, consumo y disposición final de plásticos requieren la búsqueda de soluciones. La circularidad de los materiales se presenta como una estrategia clave para abordar este problema. Sin embargo, se necesita un estudio integral de estos sistemas para determinar si es posible cerrar completamente el ciclo de los materiales. Al evaluar el reciclaje de plásticos como una estrategia de circularidad, es esencial considerar no solo la conservación de masa en el ciclo, sino también la conservación de calidad. En este sentido, la sustituibilidad es un concepto que mide la capacidad del material reciclado para reemplazar al material virgen. Este artículo presenta los resultados del potencial de circularidad de seis tipos principales de plásticos para cinco escenarios en Argentina, basados en tasas de reciclaje y cuotas de mercado para medir la conservación de cantidad y calidad en el ciclo de materiales. Los resultados muestran un bajo potencial de circularidad para todos los plásticos, siendo el mejor indicador del 13,6 % para HDPE y el peor del 3 % para PS.

Palabras clave: Ciclo de materiales; Economía circular; Materiales plásticos; Polietileno de alta densidad; Reciclaje de plásticos.

INTRODUCTION

According to the United Nations Environment Programme, plastic production has grown faster than any other material since 1970. If historic growth trends continue, global production of primary plastic is forecasted to reach 1,100 million tons by 2050.

Since 1950, approximately 9.2 billion tons of plastic have been produced, generating some 6.9 billion tons of primary plastic waste. Over three-quarters of this plastic waste was discarded and ended up in landfills, dumps, uncontrolled or mismanaged waste streams, or the natural environment, including the oceans. Currently, it is estimated that 19-23 million tons of plastic leak into aquatic ecosystems annually – from lakes to rivers to seas – from land-based sources (UNEP-LEAP, n.d.).

The production and consumption of plastics in the Latin American region have grown significantly over the last four decades. Nowadays, the average consumption exceeds 30 kg per capita per year. Mexico and Chile, two countries with the highest per capita plastic consumption, consume more than 50 kg per capita per year, followed by Argentina and Brazil, with figures close to 40 kg per capita per year (Bianco *et al.* 2021).

A systemic change is necessary to prevent the negative impact of extracting raw materials and plastic waste from affecting the environment. The circular economy (CE) emerges as a potential solution, with "circularity of materials" referring to strategies that promote the creation of material loops - a fundamental concept in CE. The CE could be defined as a new model of economic development that promotes the maximum reuse/recycling of materials, goods, and components to minimize waste generation. It aims to innovate the entire chain of production, consumption, distribution, and recovery of materials and energy according to a "cradle to cradle" vision. (Ghisellini *et al*. 2018).

Different strategies exist for restoring material flows, such as repair, preserving the product as a whole, refurbishing, preserving the use of components, or recycling the material as a last resort. In this context, circularity is defined as the ability to conserve the quantity and the quality of the material (Bracquené *et al*. 2022)

To achieve complete closure of plastic polymer loops, it is necessary to recycle recovered plastic materials into new products of equivalent quality to the original plastic articles, essentially within applications that match those of the initial products. Commonly referred to as downcycling, when higher quality plastics are recycled into lower-quality applications. This process involves significant losses in material properties compared to virgin plastic.

Recycling operations incur material losses resulting from two main factors: the loss of material quantity, also known as physical material loss during the recycling process and the loss of material quality. The latter is associated with the deterioration of the physical properties of recycled materials and reduced functionality compared to virgin plastics (Cullen *et al*. 2017).

Various indicators, including the circularity potential (CP) indicator (Eriksen *et al.* 2019), have been proposed to assess both quantity and quality losses in recycling.

Material quantity losses include dynamic losses in material stock and material dissipative losses (Cullen *et al.* 2017). The material stock dynamic losses are a consequence of the product's lifespan. This is particularly relevant in the case of plastic items, which are only eligible for recycling at the end of their useful life. In contrast, dissipative losses pertain to the portion of the material that cannot be preserved as a secondary raw material (Schulte *et al.* 2023).

Assessment of material losses can be conducted indirectly through material conservation, which involves evaluating the resource recovery efficiency of the material in question. This resource recovery efficiency is expressed as the ratio of recycled material to material available for recycling (waste generated from the material), considering both dynamic and dissipative losses throughout the recovery and recycling process.

The loss of material quality is associated with the concepts of quality preservation and the notion of "substitutability". Quality conservation can partially be described through the tightness of the material cycle, which encourages maintaining products (and components) at their highest level of value for as long as possible (Bracquené *et al.* 2022).

In this context, "substitutability" refers to the ability of one material to replace another in a particular application. The life cycle assessment (LCA), according to ISO 2006, is a methodology that allows evaluating the environmental performance of a product or system, covering multiple impact categories from raw material extraction through manufacturing and distribution to use and potential end-of-life disposal alternatives, thus providing a comprehensive profile of its environmental impact. In the context of LCA and recycling, substitutability is used to evaluate the potential of recycled materials to substitute virgin materials. The calculation of substitutability can be based on material technical properties, recycling cycles, and economic factors such as market shares or price disparities. The complexity of the calculation can vary from a simple ratio to a more elaborate mathematical operation involving multiple variables. The concept of substitutability is still evolving, and there is a need for harmonization, transparency, and consideration of the application of recycled materials in its evaluation (Sanabria Garcia *et al.* 2023).

The CP indicator considers the efficiency of resource recovery and the quality of recycled materials, variables strongly influenced by local factors. These include waste separation schemes, collection systems, recycling plant technology, and social characteristics such as environmental education, recycling incentives, and regulations.

Despite global efforts to evaluate the circularity of plastics, there is a notable lack of studies focusing on the Latin American context, where unique socio-environmental and market characteristics present challenges and opportunities for circular strategies. Specifically, no prior research has comprehensively assessed the CP of plastics in Argentina.

This study addresses these gaps by applying the CP indicator for the first time in Argentina, integrating local data, and simulating alternative scenarios to explore strategies for improving material circularity. The objective is to calculate the CP based on recovery efficiencies and substitutability under Argentine local conditions for different types of plastics, including polyethylene terephthalate (PET), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), and expanded polystyrene (EPS). In addition to the baseline scenario, alternative scenarios were analyzed, modeling varying proportions of medium- and low-quality recycled materials.

MATERIALS AND METHODS

Circularity potential indicator. Eriksen *et al.* (2019) defined CP as the capability of a recovery and recycling system to close material loops under stable market conditions. As explained in the previous section, CP depends on the recovery system's efficiency and substitutability.

The resource recovery efficiency, η^{rec}, was calculated by adapting the equation described by Vadenbo *et al.* (2016) and is presented in Equation 1.

$$\eta_i^{rec} = \frac{M_i^{rec}}{U_i^{rec}} \qquad \text{equation 1}$$

Where:

η^{rec} is the resource recovery efficiency, including all physical material losses within the recycling chain.

U^{rec} [kg] is the resource potential of recovered material and expresses the amount of material in the waste stream under assessment.

M^{rec} [kg] is the amount of material recovered from the total system, which includes waste collection and recycling.

i is the type of plastic (e.g. PET, LDPE, HDPE, PVC, PP, PS, and EPS).

The term associated with quality preservation, substitutability, represents the materials with a specific quality level (Q) that have the potential to substitute virgin material and is expressed as a function of Market Share (MS). The quality of the potentially displaced virgin material is denoted as Q^{disp}, and it is always assumed to be of high quality, with $MS(Q^{disp})$ being equal to 1 for all plastics.

The substitutability is defined by Vadenbo *et al*. (2016), where the functionality of the recovered material is divided by the functionality of the displaced material. In this case, when considering circularity potential in a hypothetical market scenario with closed polymer loops operating under steady-state conditions, the functionality is represented by the fraction of the total polymer market within which the recovered plastic with a specific quality is applicable and can fulfill the material requirements. As explained in the previous section, this concept signifies that functionality now denotes the potential of a recovered material fraction to satisfy demands within a steady-state market, aligning with the vision of a circular economy.

Therefore, the equation for CP is presented in Equation 2.

$$CP_i = \eta_i^{rec} \times \frac{MS\ (Q^{rec})_i}{MS\ (Q^{disp})_i} \qquad \text{equation 2}$$

Where:

CP_i is the Circular Potential for plastic *i*.

MS The market share represents the mass percentage of each plastic, used within each application group, categorized as high, medium, and low for each respective quality level (high, medium, and low).

Application groups and quality classification. Understanding that there are different types of recycling and qualities of recycled plastic. Eriksen *et al.* (2019), based on existing literature and legislation related to the use of plastics, identify eight application groups. These application groups are further classified into three quality levels, as defined by the authors: 1) high quality, assigned to materials approved for food contact, representing the strictest legal requirements for materials; 2) medium quality, assigned to materials that can be used in toys, electrical and electronic products, representing lower and variable legal requirements, and 3) low quality, assigned to materials with minimal legal requirements such as construction, non-food packaging, automotive industry, and others.

For Argentina, a modification has been made according to local regulations; the pharmaceutical and medical industry has high legal standards, so this application is considered high quality. The "Agro" category has also been added to the low-quality application group. Information of Table 1 provides more details of the normative used for classification.

The methodology establishes that a material is considered high quality if it can meet all the demands of the plastic market across all defined application groups. In contrast, recovered medium or low-quality polymers can only fulfill specific application fields.

In terms of definition, virgin plastic is classified as high quality since its composition can be controlled during production to tailor it to the corresponding application. Only those recovered polymers of high quality have the potential to replace virgin plastic completely throughout the entire cycle. The CP exposes that even if all plastic waste were recycled, it would not be enough to close the material loop due to the quality required in the different fields of application, generating dependence on virgin material.

The Market shares are shown in Table 2; values were estimated based on information from IPA (2019) and CAIP (2021). These percentages represent virgin materials. This information is used to determine the market share that the recycled material could replace according to its quality, as seen in Table 2.

Table 1. Argentine legislation on the quality of plastics required for their use in applications.

Application	Requirements	Legislation
Food packaging	The regulations include a positive listing of materials and impose a ban on reusing plastic food containers. However, this prohibition has three exceptions: returnable PET containers for carbonated soft drinks, three-layer PET containers for the same purpose, and single-layer PET containers containing a mix of virgin and recycled material.	Argentine Food Code (CAA) (Chapter IV - Packaging) Article 200 bis - (Joint Resolution N° 32/03 and N° 287/03), Article 212, as well as the MERCOSUR Legislation in force (Resolution GMC (Common Market Group) 56/92). https://alimentosargentinos.magyp.gob.ar/contenido/marco/CAA/Capitulo_04.htm
Pharmaceutical and medical	The accepted additives are indicated for each type of material described in FA8 Chapter 420.	Law Nº 16.463. Law Nº 2724. File Nº 1-47-1110-2283-02-0 of the registry of the National Administration of Medicines, Food and Medical Technology (A.N.M.A.T.). FARMACOPEA Argentina Decree 202/2003 https://servicios.infoleg.gob.ar/infolegInternet/anexos/85000-89999/86181/norma.htm
Household items (within this group, toys are included)	The presence of THREE (3) phthalates (DBP, BBP, and DEHP) is restricted for articles, or parts thereof, of flexible material, and the presence of THREE (3) others (DNOP, DINP, and DIDP) is restricted for articles, or parts thereof, of flexible material that can be put in the mouth by children.	Resolution No. 583/08 of the Ministry of Health establishes the safety requirements for the manufacture, import, export, marketing, or delivery free of charge of childcare articles and toys. https://servicios.infoleg.gob.ar/infolegInternet/anexos/155000-159999/158549/norma.htm
Electricity and electronics	The producers of EEE shall have the following obligations. To design the appliances, as well as the spare parts for their repair, it shall be prohibited in the EEE placed in the market the presence of polybrominated biphenyls (PBB), polybromodiphenyl ethers (PBDE), and other substances that (PBDE) and other substances determined to be hazardous.	National law 23992-urban waste-technological-environmental impact-waste-specific. Each province establishes its own law, for example, Provincial Law Buenos Aires 14321 https://normas.gba.gob.ar/documentos/Bj7QDiyV.html#:~:text=La%20presente%20Ley%20fomenta%20un,RAEEs%2C%20sus%20componentes%20y%20materiales.
Building	No specific legal requirements	-
Non-food contact packaging	No specific legal requirements	-
Automotive	No specific legal requirements	-
Furniture and decoration	No specific legal requirements	-
Agro	No specific legal requirements	-
Others	No specific legal requirements	-

Table 2. Percentage distribution of market share by type of plastic and application group in Argentina.

Application group	PET	HDPE	PVC	LDPE	PP	PS	EPS
High Quality	**57**	**27**	**0**	**36**	**10**	**28**	**19**
Food and pharmaceutical packaging	57	27	0	36	10	28	19
Medium Quality	**0**	**16**	**20**	**5**	**26**	**13**	**0**
Household goods	0	10	8	0	5	0	0
Electronics and electrical	0	6	12	5	21	13	0
Low Quality	**43**	**57**	**80**	**59**	**64**	**59**	**81**
Construction	0	18	53	0	13	11	60
Non-food packaging	43	20	10	22	9	23	19
Automotive	0	6	6	2	22	5	0
Furniture & Decoration	0	6	4	1	7	1	0
Agro	0	3	3	8	6	0	0
Other	0	4	4	26	7	19	2
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**
Recycled	**PET**	**HDPE**	**PVC**	**LDPE**	**PP**	**PS**	**EPS**
Q= high	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Q=medium	**0,43**	**0,73**	**1,00**	**0,64**	**0,90**	**0,72**	**0,81**
Q=low	**0,43**	**0,57**	**0,80**	**0,59**	**0,64**	**0,59**	**0,81**

polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and expanded polystyrene (EPS).

Currently, there is no recycled plastic of high quality in the world except for PET. This means that although high quality recycled plastic theoretically has MS(high Q) equal to 1, in reality the recovery efficiency (η rec) is 0.

Case Study. Five hypothetical scenarios were developed to explore the CP plastic in Argentina. These scenarios model different proportions of high, medium, and low-quality plastic recovery.

Scenario 1 is the most representative of the current reality in Argentina for PET, LDPE, HDPE, PVC, PP, PS, and EPS. The other four proposed scenarios consider the current proportion of high-quality PET recycling, which remains constant at 5%, and model the proportion of medium and low-quality recycling, assuming ratios of 0:100, 0:100, 25:75, and 75:25 for the remaining plastics. In other words, the effect of changing the recovery efficiency was evaluated by modeling the proportion of plastics recovered as a function of their quality in the different scenarios. This work takes into account only the influence of the quality of the recovery without considering, for example, whether the full installed capacity of the recycling plants would be used, thus increasing the amount of recycling.

Additionally, two secondary scenarios were simulated by modeling the amount of high-quality recycled PET. In secondary scenario 1, a maximum value of 7% was considered, based on theoretical values according to global literature (World Economic Forum, 2016), while in secondary scenario 2, a minimum value of 0% for high-quality recycling was established. These scenarios are summarized in Table 3 .

Table 3. Case study scenarios: percentage distribution by quality of recycled plastics in Argentina.

Scenario	% High Quality	% Medium Quality	% Low Quality
1. LDPE, HDPE, PP, PS, PSE, PVC	0	50	50
1. PET	5	47,5	47,5
1.1. PET max	7	46,5	46,5
1.2. PET min	0	50	50
2. LDPE, HDPE, PP, PS, PSE, PVC	0	0	100
2. PET	5	0	95
2.1. PET max	7	0	93
2.2. PET min	0	0	100
3. LDPE, HDPE, PP, PS, PSE, PVC	0	100	0
3. PET	5	95	0
3.1. PET max	7	93	0
3.2. PET min	0	100	0
4. LDPE, HDPE, PP, PS, PSE, PVC	0	25	75
4. PET	5	24	71
4.1. PET max	7	23,25	69,75
4.2. PET min	0	25	75
5. LDPE, HDPE, PP, PS, PSE, PVC	0	75	25
5. PET	5	71	24
5.1. PET max	7	69,75	23,25
5.2. PET min	0	75	25

polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and expanded polystyrene (EPS).

The choice to model only the quality in CP and not the quantity was made to highlight this crucial aspect, which is often overlooked when measuring recycling or circularity. This approach acknowledges that not all plastics have the same requirements; while higher-quality recycling can open up more markets, for plastics consistently used in low—and medium-quality markets, investing in high-quality recycling might not be justified due to the lack of market demand.

Regarding the current scenario, the integrated solid waste management (ISWM) system in Argentina is regulated by the Law of Minimum Standards for Environmental Protection, Law 25,916, enacted in 2004. This law establishes that municipalities are responsible for the collection, transportation, treatment, and final disposal of municipal solid waste (MSW). There are no systematic bases and statistics on each municipality's management in the country.

The calculated recovery efficiencies were estimated using waste generation and recycling production at the national level. However, to characterize the waste by type of plastic and to generalize the ISWM scheme, data were taken from the CEAMSE. This company provides services to a population of approximately 17,000,000 inhabitants, representing 37.1% of the total population of Argentina, according to the results of INDEC (2023). In other words, the metropolitan area of Buenos Aires (AMBA) is considered a central point of research due to its wide access to information and data, as well as the convergence of different jurisdictions, including the Nation, the Province of Buenos Aires, the Autonomous City of Buenos Aires (CABA) and the municipalities. Its significant population concentration and position as the epicenter of MSW generation in Argentina stand out. The AMBA also has the largest number of waste pickers, formal (cooperatives) and informal (waste picker collectors), and the most significant presence of plastics industries. (Cittadino *et al.* 2020).

Waste collection strategies characterization. Regarding waste collection strategies, according to the official website of the Gobierno de la Ciudad Autónoma De Buenos Aires (n.d), waste collection strategies in CABA can be classified as formal and informal. Within the first group, waste is collected through municipal solid waste containers, macro-generators (companies and industries), and green points. MSW containers are the main formal waste collection points in CABA. These containers are in different parts of the city and are designed to receive recyclable and non-recyclable waste from citizens. The municipality collects waste from the MSW containers using compactor trucks. Recyclable waste is taken to green centers for sorting and treatment, while non-recyclable waste is taken to landfills. Waste from MSW containers has the highest percentage of rejection (30 to 35%) due to poor sorting at the source. For the rest of the strategies, the rejection is in the order of 10 to 20 %.

Macro generators are large waste producers like businesses, industries, and public institutions. These generators are required to contract private companies to collect their waste. These companies that collect waste from macro-generators must comply with the requirements established by the municipality, such as separating waste into recyclable and non-recyclable and delivering recyclable waste to green centers.

The green points are collection centers for recyclable waste located in different parts of the city. Municipal personnel or volunteers staff these points. Neighbors can bring their recyclable waste to the green points for free delivery. The recyclable waste received at the green points is taken to the green centers for sorting and treatment.

In the informal circuit, waste picker collectors were found, people dedicated to waste collection in urban environments. These waste pickers sell the materials collected to companies specializing in recycling, making this activity a significant source of income as a job.

Green Centers are categorized into A, B, C and D levels based on their infrastructure and technology. Type A centers are characterized by their advanced technology, using facilities called material recovery facilities (MRF), semi-automated processes that achieve high productivity.

On the other hand, type B centers have manual sorting belts and balers, and five centers have these characteristics. Both type A and B centers receive a variety of waste, including waste from containers, macro-generators, waste picker collectors, and green points.

Type C centers do not have sorting belts but do have balers. Type D centers, on the other hand, carry out all their processes manually. These centers are designed to receive better-sorted waste, such as waste from macro-generators, waste picker collect, and green points.

Characterization of waste generation and recycling: Quantities and types. Cittadino *et al.* (2020) estimate that the per capita generation of municipal solid waste in Argentina is 1.03 kg/day, translating to approximately 40,490 to 47,500 tons/day. Of this, 46% is managed by CEAMSE. The a uthors s uggest t hat w hen p rojecting t he a mount of plastics discarded nationally, it is most prudent to consider a range where plastics represent between 10 and 20%, with an average of 13% by weight of MSW. The c omposition o f M SW f ractions i n A rgentina reveals a diverse distribution of materials, each contributing to the overall waste stream. Among these fractions, organic matter, primarily food waste, constitutes the largest proportion at 44%. Plastics account for 13% of the waste, followed by paper and cardboard at 18%. Glass, metals, and textiles collectively represent smaller shares, with glass comprising 4%, metals 3%, and textiles 4%. Additionally, pruning, gardening, and aggregates contribute 6% to the waste composition, while pathogens and miscellaneous materials comprise 8%.

Regarding the composition of the plastic fraction in Table 4, PEDB is the most prevalent plastic, about 40% of the total characterized. It is used to manufacture various containers, but its main use is in disposable bags. PET is another important component of waste, although its share has fluctuated between 15% and 10% in recent years. This decrease could be related to the adoption of recycling practices and the reintroduction of returnable glass bottles in certain periods. On the other hand, PVC has had a lower presence in waste, possibly due to restrictions on its use in food packaging (Cittadino *et al.* 2020).

In 2021, about 286,000 tons of plastic were recycled in the country from all types of recyclable plastic waste: domestic, agricultural, and industrial, with a growing trend. The installed plastic recycling capacity is estimated to have still an unused capacity of 60% (Ministerio de Ambiente y Desarrollo Sostenible, 2022).

The tons of plastic recovered for each type were obtained from IPA (2019). This information was used to calculate the mass percentage of recovery for each type of plastic relative to the total recovered in 2019.

RESULTS AND DISCUSSION

Recovery efficiencies. As described in the methodology section case study, using the data for total plastic recovered in 2021 and the percentage of recovery for each type of plastic in 2019, the projected tons of recycled material by type for 2021 were estimated. With the values in Table 4, the tons of waste for each type of plastic were calculated for 2021, assuming they remained the same as in 2020.

Table 4. Percentage of plastic-type in the plastic fraction of municipal solid waste in Argentina.

Plastic-type	Percentage (%)
PET	15,6
HDPE	12,1
PVC	3,9
LDPE	39,5
PP	17,1
PS	9,9
Otros	1,9

polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and expanded polystyrene (EPS).

Figure 1 shows the recovery efficiencies for each plastic type according to Equation 1 for the year 2021.

Circularity potential for each type of plastic. Using the results of the recovery efficiencies (Figure 1) and the values of MS (Table 2), CP was calculated for each plastic and each grade. The results are shown in Figure 2.

The recovery efficiencies (Figure 1) show relatively low values. The plastics with the highest recovery efficiency are HDPE and LDPE, with 20.96 %, which means that 79.04 % of the material is lost in the cycle. On the other hand, the plastics with the lowest efficiency are PS and EPS, with 3.59 % and 3.60 %, respectively. The values are related to the amount of waste generated, as HDPE and LDPE represent 12.1 % and 39.5 % of the plastic waste generated.

Regarding recycling potential (Figure 2), it is logical that the plastics with the highest recycling efficiencies have the highest CP: HDPE has the highest CP with 13.6 %, followed by LDPE and PP with 12.9 % and 8.8 %, respectively. Once again, PS and EPS have the lowest CP, with only 3 % and 4 %, respectively.

The influence of the quality of the recovered material and the markets suitable for this quality can be observed; for this reason, HDPE has a higher recycling potential than LDPE, although both have the same recovery efficiency.

In the most favorable scenario simulated, scenario 3, where all the recovered material is recycled at medium quality, an improvement in the CP is observed for all plastics except PET and PSE due to the fact that these plastics do not have a significant market in medium quality applications. The plastics that show the greatest increase in CP when the quality of the recycled material is improved are HDPE, with an increase of 1.68 %, and PP, with a 1.49 % increase. This is relevant when it comes to taking measures such as determining which type of green center each material should be treated in or making investments to improve the circularity of the material.

The most unfavorable scenario is the one in which all the recovered material is recycled with low quality, represented in scenario 2.

These results can be complemented by the findings of the study conducted by the Asociación Sustentar (2022), which proposes a recyclability index, defined as the capacity of materials to effectively fulfill the entire recycling chain. A material with high recyclability can be used as raw material to manufacture other containers. This index quantifies, on a scale from 1 to 5, the effective recovery of materials and is mainly based on the commercialization potential of materials in the city's green centers. Its methodology, based on interviews, obtains for each green center and each material a qualitative response to which a numerical value between 1 and 5 is assigned. Where 5 means the material is recovered and commercialized without issues, and 1 means the material is not recovered and sent to final disposal. Materials with high scores are widely commercialized by cooperatives working in green centers. Generally, they have stable buyers and manage to reinsert the waste into the productive circuit without issues. Among the plastic materials with the highest recyclability value in the city (equal to 5) are PET plastic bottles, HDPE plastic containers (also known as blown plastic), plastic bags (LDPE), and film-type wrappers, as long as they are clean and dry. On the other hand, there are other materials with high recyclability but with a slightly lower value of 5 points, among which are white PET, printed bags (such as those for sugar, sliced bread, and napkins), and plastic dairy containers (PS).

Materials with medium recyclability are found, such as the case of caps and labels are baled together with the bottles, and it is the buyer who is responsible for utilizing or not these materials. Another material with medium recyclability but less frequently commercialized is small plastics, smaller than 10 cm. In many centers with sorting belts, they are difficult to grasp.

Materials with low recyclability are multilayer wrappers, plastic wrappers corresponding to the other category (plastic number 7), and/or PP, EPS, plastic sachets, and various types of plastic trays. A lack of buyers was detected for those wrappers composed of other plastics or PP but with some optimism for recovering this material soon. Regarding plastic sachets, the lack of buyers, low prices, and lack of material and space to store were highlighted.

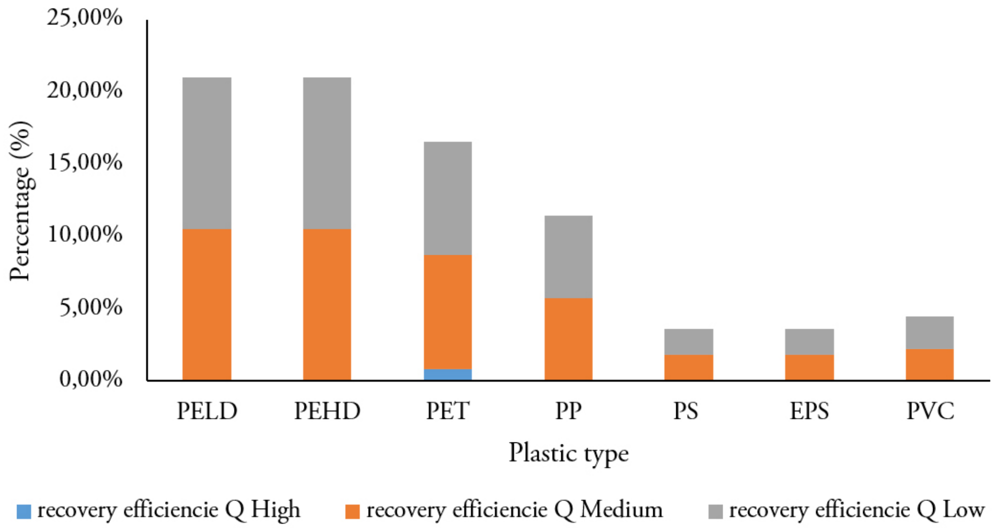

Figure 1. Recovery efficiencies for plastic type in Argentina. polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and expanded polystyrene (EPS).

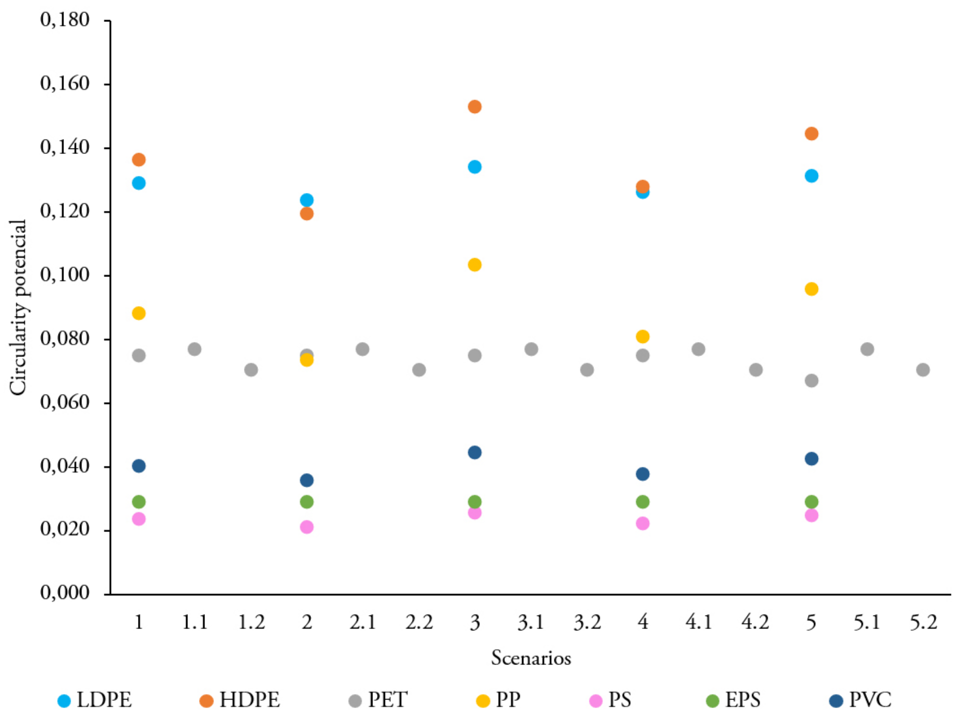

Figure 2. Circularity potential (CP) by plastic types for each scenario. polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and expanded polystyrene (EPS).

PS also proves to be a material with particular difficulties for commercialization. The main reasons are related to technical issues such as lack of densifier or logistics. Due to its low weight and large volume, it is difficult to store for sale not only because of the lack of space but also because of its low price. The only center with a densifier generally receives this material from large generators and also receives material from other centers. To carry out the densification process, around eight people and a lot of materials are required to make it profitable. Plastic trays are also usually not recovered for various reasons, including the lack of buyers, the inability to identify the plastic they are made of, their cleanliness, their low weight and density, and their low price. Finally, regarding multilayer wrappers, all green centers reported a lack of market for their commercialization.

It can be observed that the high CP rates of HDPE and LDPE align with the results of this study, where the dominant packaging of these materials, such as bags and bottles, show high recyclability in green centers. It can also be observed, for example, that EPS and EP are among the plastics with the most recycling difficulties, and this is reflected both in the recyclability index of the Observatory of Urban Hygiene of The City (Asociación Sustentar, 2022) and in the CP. However, there is a discrepancy regarding the data obtained for PP, which may be because the products evaluated by the Observatory of Urban Hygiene of The City (Asociación Sustentar, 2022) are mainly general containers. As is shown in Table 2 of plastic MS, the container market for this plastic is low. Therefore, it is possible that its recycling comes from the markets where it is more prevalent. Another curious finding is that PET is a highly recyclable material for green centers and the only plastic with high-quality recycling technology. Yet, it shows a low CP, so specific strategies for this material must be evaluated. Once again, the criticality of market demand for a material and its quality, as well as its ability to transform into raw material again instead of waste, can be observed.

The article by Eriksen *et al.* (2019) aims to analyze waste separation strategies and schemes in Europe and assess their impact on the CP of materials. Due to this different focus, the results are not directly comparable, as the study provides an overall CP for plastics based on each separation scheme.

However, similar conclusions can be drawn between the two studies. For example, it is highlighted that the scenarios that include the recovery of high-quality PET and HDPE have the highest circularity potential. This is because these high-quality plastics can substitute virgin plastics in all possible applications within their respective markets. In contrast, in some applications, medium- and low-quality PET and HDPE can only replace virgin plastic. Since more than half of the PET market relies on high-grade PET for food packaging, the reduction in circularity potential when moving from high to medium or low-grade is particularly significant for PET.

The study by Eriksen *et al.* (2019) also shows that the most efficient plastics recovery system is the one that includes sorting schemes covering both rigid and flexible plastics, with a higher number of target polymer fractions and high source separation efficiency. This system has the potential to close 42% of the material loop, suggesting that with current technology, Europe is still far from achieving a fully closed plastic loop, which would require a theoretical recycling potential of 1.

The results obtained highlight the complexity of achieving effective plastics circularity in the Argentine context. In addition to the need to improve the efficiency of recovery and recycling, it is fundamental to consider the limitation of the quality of recycled plastic as a key obstacle to be addressed to close the material loop fully. Considering both aspects in the circularity allows a more objective and comprehensive approach, allowing to identify the processes that depend on the virgin material and to evaluate the optimal recovery and recycling strategy for each type of plastic.

Regarding the limitations of this methodology, it is important to point out that it is based on market shares, which may vary over time. Although it provides a general assessment of the material, it does not consider aspects related to specific applications that limit the use of recycled plastic. An illustrative example would be the production of paint containers, which require low quality, where technical limitations of the process may prevent the use of 100 % recycled material in their production. An important limitation of this study is the lack of systematic data collection in Argentina, which introduces inaccuracies in the results. Many data had to be estimated based on the available information and projected to 2021, as more up-to-date data are unavailable. This lack of precise and updated information poses an additional challenge to the accuracy and validity of the results obtained in this analysis. Furthermore, this study could be expanded to thoroughly evaluate various waste separation strategies and their impact on CP.

Obtaining values for substitutability and circularity at the local level is of significant importance in the search for indicators and strategies to address the challenges associated with resource depletion and pollution from the use of plastics. These data are essential in their own right but are also fundamental to making more accurate allocations in LCAs.

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