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Effect of Virgin PP Substitution with Recycled Plastic Caps in the Manufacture of a Product for the Telephony Sector

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Abstract: This study investigated the effects of partial and total substitutions of fossil polypropylene (PP) for recycled plastic cap equivalents in the manufacture of signage labels used by the telephone industry. Four alternative scenarios to using virgin PP were evaluated considering recycled material in flake and pellet forms based on environmental performance, degree of circularity, and technical behavior. The environmental analysis was performed by the life cycle assessment (LCA) technique, and for all impact categories evaluated, using recycled material to replace the virgin reduced adverse effects on the environment. The most significant results in this dimension, with gains of 81% in the Global Environmental Indicator, occurred when recycled PP flakes entirely replaced the fossil polymer. Once again, the highest values of the Materials Circularity Indicator (MCI) were achieved by scenarios with full recycled resin in processing the tags; however, this product must also be reused. The mechanical behavior of the tags measured technical performance, and in this case, the product made with virgin PP outperformed the recycled options except for elongation. An analysis that integrated the three dimensions into a single performance index pointed to the complete substitution of virgin material for recycled as the most balanced option.

Keywords: circular economy; environmental performance; life cycle assessment; Material Circularity Indicator; technical performance; plastic caps; recycling; waste management

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1. Introduction

Caps are elements used in plastic packaging closure systems to preserve product characteristics [1]. An inefficient closure can potentiate adverse effects on the consumer good (e.g., exposure to light, heat, gases, and humidity, and the action of microorganisms) that reduce its shelf life [2]. The cap–container set protects the product from interference caused by external agents to the packaging [3]. The caps are made of metallic or polymeric materials, which must be expanded to meet the abovementioned purposes. For this reason, polypropylene (PP) and high-density polyethylene (HDPE) are often selected as input for their processing [4].

Driven by beverages, food, and personal care industries, the world market for plastic caps achieved USD 44 billion in revenues in 2022, and for 2029 the projections point to an income of up to USD 60 billion [5]. However, even with the expansion of trade, the

manufacturers of plastic caps have been facing a severe problem: most of the packages are single-use [6]. This circumstance causes them to be discarded into the environment, resulting in harmful effects on the aquatic fauna [7], interfering with the ability to fix carbon in the oceans, intensifying global warming [8], and influencing the development of certain vegetal species when placed in the soil [9]. Because of these adverse consequences, modern society views plastics with reserve despite their benefits [10].

Mechanical recycling is the most common way of reusing post-consumer plastic caps [11], mainly because of the overall efficiency of the process [12]. Nevertheless, recycling systems should be designed considering each material's degradation mechanisms [13]. For PP and HDPE, this occurs due to successive recycling or exposure to solar radiation that causes scissions in the polymeric chains [14,15] and weakens their mechanical properties [16–18]. In addition, PP and HDPE also degrade when exposed to the natural environment [19–21].

The reuse of plastic caps corroborates the circular economy (CE) principles of eliminating waste and pollution, circulating products and materials, and regenerating nature [22]. In fact, by replacing the linear model with the circular approach, the packaging sector could reap significant results by 2040, such as (i) a reduction by more than 80% of plastics disposal in the oceans; (ii) a decrease in the production of virgin plastics by up to 55%; (iii) savings of about USD 70 billion in economic resources; (iv) 25% reduction in greenhouse gas (GHG) emissions; and (v) the creation of 700,000 jobs [23].

The plastics recycling industry is also booming [24]. In the case of PP, growth projections are around 54% for 2020–2027 [25]. In this sense, the connection between waste management systems and a robust secondary materials market is essential to promote advances in this circular logic [26]. Following this path, Gall et al. [1] investigated aspects of recycling plastic caps, seeking to establish a comprehensive product design strategy capable of activating circularity. The authors concluded that the selection of resin and additives used in manufacturing caps affects the material obtained by recycling, creating perspectives for reuse in applications with high added value.

The circular model applies circularity indicators to gauge its strategies' effectiveness [27]. The Material Circularity Indicator (MCI) [28] stands out among these metrics for its ability to verify the refreshing character of material flows associated with a product, product portfolio, or even the organization itself [29].

Circularity metrics are more efficient in supporting decision-making processes when their indicators are combined with those obtained by other environmental performance assessment techniques such as life cycle assessment (LCA) [30]. LCA has been established in the business and scientific spheres as a systemic and quantitative way of estimating potential environmental impacts associated with products, processes, and services [31]. Using normative guidelines [32], their diagnoses can also identify these effects during the design of anthropic systems. There are many records of LCA applications to quantify impacts derived from the use of recycled plastics. In one of the most recent, Galve et al. [33] observed that replacing virgin PP with a recycled form could improve the global environmental performance of polymeric components by up to 30%. Following a parallel trend, Agarski et al. [34] concluded that mold manufacturing and electricity consumption were the main focuses of the lifecycle impact of HDPE caps in a study of parts manufacture in Serbia. Istrate et al. [35] found impact reductions between 20% and 80% with the exchange of virgin material for recycled material from four different sources of HDPE, one of which was plastic caps, in the manufacture of pressure tubes.

This study proposes contributing to the theme, also evaluating the environmental and technical performance of replacing virgin PP resin with an equivalent obtained from post-consumer recycled plastic caps to manufacture labels for identifying fiber optic cables in the telephony sector. Compared to existing studies in the literature, this research brings some novelties. The first refers to the way the analysis was conducted, integrating the environmental behavior of the process—jointly determined by results provided by LCA and by MCI—to its technical performance measured from the mechanical properties of

the final product. The study also evaluates the partial and total replacement rates of virgin PP by recycled PP and discusses whether the conversion of flakes into pellets causes environmental and quality losses.

Another innovation is related to the case study, Project Tampinha Legal, a socio-environmental education program in the circular economy that also adheres to the United Nations Sustainable Development Goals (SDGs) [36]. Conceived and managed by the SustenPlást Institute, Tampinha Legal encourages non-profit organizations to collect plastic bottle caps. It then sells them to registered recyclers, reverting the revenue to the collectors. The recyclers convert the caps into flakes or pellets, which are then sold to manufacturers of other plastic products. Although headquartered in Porto Alegre (RS), the program operates in eight Brazilian states and the Federal District and has collected more than 627 million plastic caps since 2017 [36].

It is expected that this study will contribute to the consolidation of recycling practices for polymeric materials, as well as provide subsidies for disseminating the circular economy concept in Brazil.

2. Material and Methods

The method established for conducting this study comprised five steps. They are as follows: (i) specification of alternatives for obtaining tags from recycled plastic caps based on the operating conditions involved in these manufacturing chains; (ii) characterization of scenarios that describe each production route; (iii) collection of data related to the performance of each procedural route (that is, specifications of raw materials and inputs, conversion efficiencies, and technical coefficients), and the consumption and emissions caused by them; (iv) preparation of diagnoses on the environmental and technical behavior of the scenarios under study; and (v) analysis of the obtained results and the proposition of recommendations that, at least at the conceptual level, may reduce the impacts generated by those systems.

2.1. Specification of Production Routes and Characterization of Scenarios

The production cycle of signaling tags from recycled PP plastic caps adopted by this study corresponds to the model practiced by the Tampinha Legal program in Rio Grande do Sul (RS), Brazil. In this arrangement, the recycled caps are collected by charities distributed throughout the region, which also perform their cleaning and separation by color. Periodically, Tampinha Legal sends the material to warehouses located in Porto Alegre to co-commercialize it with recyclers. After these agents acquire the caps, they are submitted to grinding, washing, and friction drying until they become flakes. With this format, they are then sent for tag processing, which takes place in a unit located in Estância Velha, 50 km from Porto Alegre. The recycled PP flakes receive pigment additions for color uniformity and anti-UV agent additions in this installation. They are then fed into an IDEALI Primma, model FG 90 injection molder, with an injection capacity (Ci) = 187 g and a clamping force (Ff) = 900 kN, from where labels for the telephone industry are produced.

Some local manufacturers choose to produce tags using recycled PP in pellet form. To acquire this configuration, the flakes are taken to another recycler, established in Novo Hamburgo, 41 km from Porto Alegre, to be dried until total elimination of moisture, extruded, and cut. The recycled PP pellets are converted into tags after the transformations described above. Given its characteristics and potential to generate impacts, we also decided to include this variant among the alternatives evaluated by the study. Figure 1 depicts the manufacturing chain (including logistical operations) established for processing sign tags from recycled PP flakes and pellets. According to statistics from the Tampinha Legal program based on estimates of overall process yields, the collection of 1.0 kg of plastic caps results, on average, in the recycling of 556 units of material [36].

The strategy established to evaluate the effect of virgin PP substitution with recycled post-consumer plastic caps in manufacturing signal tags was the comparison of environmental and technical performances.

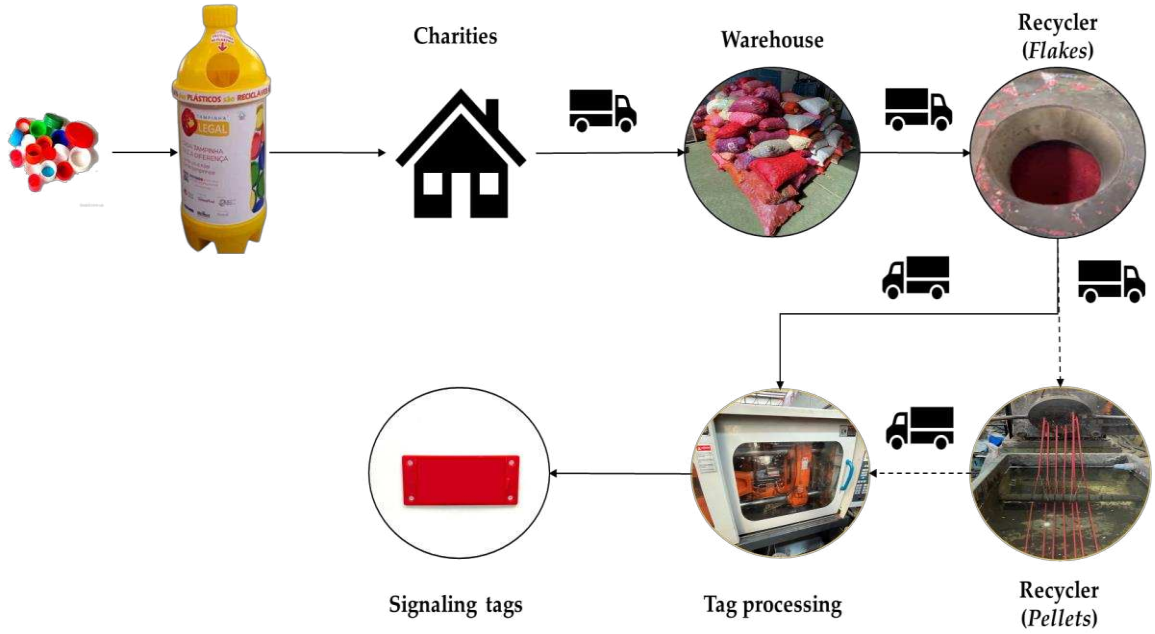


Figure 1. General diagram of the manufacturing cycle and logistics operations involved in the production of signage labels from recycled PP caps.

Therefore, five different analysis scenarios were elaborated regarding the substitution rate, partial or complete, of virgin material for recycling and the appearance of flakes or pellets of the material submitted for injection. As part of the test to verify the effect of partial replacement on environmental and technical performance, the proportion chosen was 50%, which was intermediate between the two sources of materials. These options are detailed in Table 1, S1, in which the tags made from virgin PP pellets were considered to comprise the reference scenario for comparisons at different moments of the analysis. This is because virgin PP pellets are the most frequently used raw material for processing that product.

Table 1. Scenarios established for conducting the study.

Scenario	Material Utilization Rate (%)		Material Appearance
	Recycled Plastic Caps	Virgin PP Resin	
S1	0	100	Virgin PP
S2	50	50	Flake Recycled PP/Virgin PP
S3	100	0	Recycled PP flake
S4	50	50	Recycled PP pellet/Virgin PP
S5	100	0	Recycled PP pellet

2.2. Analysis Dimensions

2.2.1. Environmental Performance Based on LCA Diagnosis

The environmental performances of the scenarios constituted for this study were determined through the LCA in the attributional modality and with a "cradle-to-gate" approach. In addition, applying the technique followed the guidelines in the ISO 14044 standard [32]. The Functional Unit (FU) used in the analysis was "producing 100 tags for use in telephony services". Considering that each tag had an average mass of 5.0 g, its corresponding reference flow (RF) = 500 g material/FU described this parameter in operational terms.

Figure 2 depicts a generic product system diagram of telephony tag production. The scheme highlights specific route variations for each evaluated scenario and the consumption and emissions typically associated with each situation, even if qualitatively.

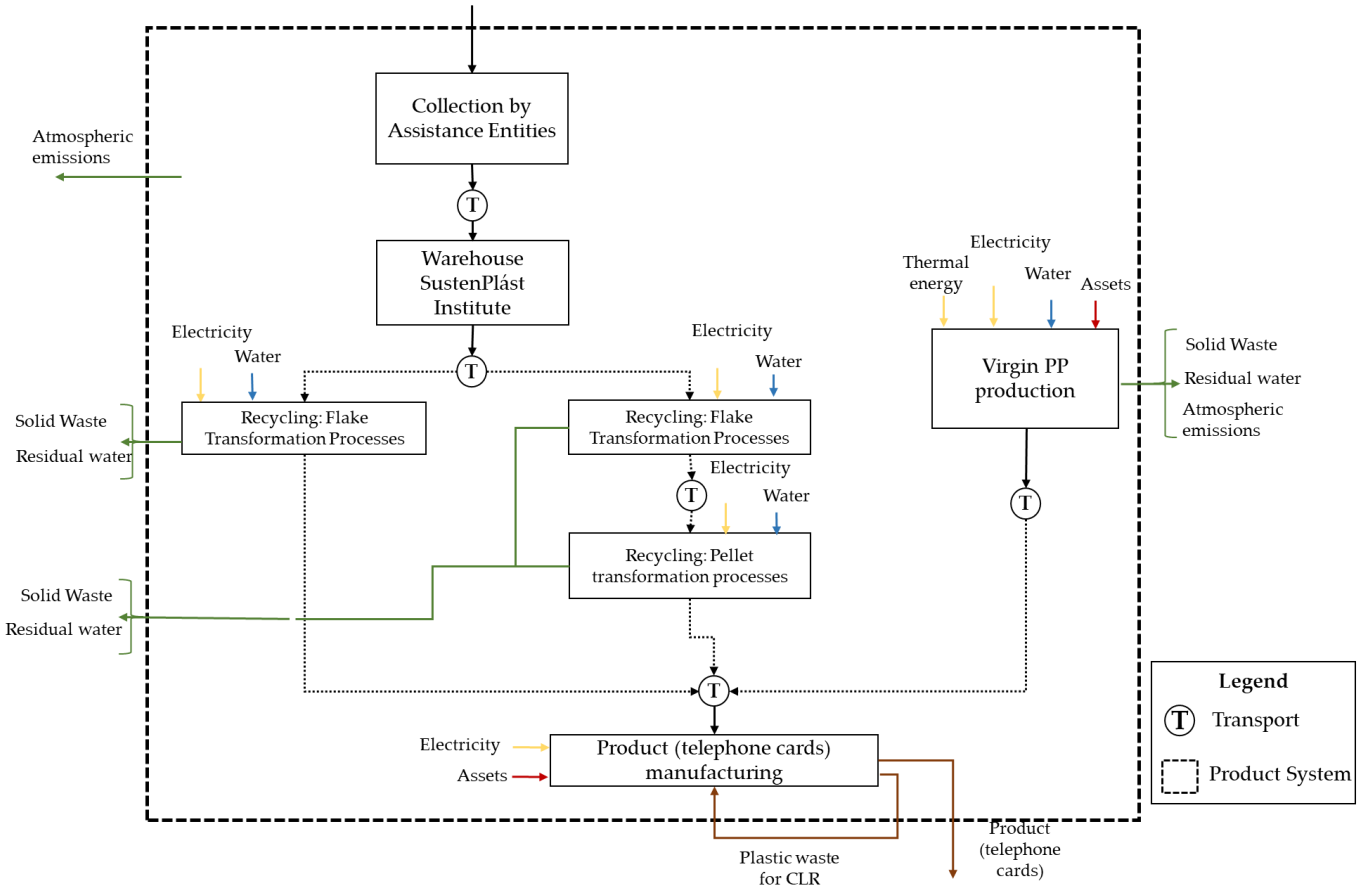


Figure 2. Generic product system highlighting different tag processing cycle alternatives for the telephone segment from virgin resin and recycled plastic caps in flake and pellet formats.

Primary data were used to specify logistical aspects and operational conditions exercised in each stage of the productive arrangements. These data were collected during the 2nd half of 2022 (time coverage). The sampling was conducted by completing exploratory questionnaires, technical visits to the production units, and interviews with employees there. The values describe yields, technical coefficients, consumption, and emissions in plastic cap recycling processes, flakes and pellets production, and tag manufacturing.

The environmental loads associated with utilities (e.g., heat generation: "*Heat, central or small-scale, natural gas {BR}| propane extraction, from liquefied petroleum gas | APOS, U*", and water treatment: "*Tap water {BR}| tap water production, conventional treatment | APOS, U*") were modeled according to the average conditions practiced in Brazil for providing these services. However, electricity generation and transmission operations were treated differently. The fact that these production cycles are installed in greater Porto Alegre (RS), regardless of the specific transformations of each scenario, led to the elaboration of an energy grid with contours particular to the region. For this, the datasets "*Electricity, medium voltage {BR-Southern grid}| electricity voltage transformation from high to medium voltage | APOS, U*", and "*Electricity, high voltage {BR-Southern grid}| electricity, high voltage, production mix | APOS, U*" were adapted using data and information obtained from the Brazilian Energy Balance for the year 2021 [37].

The transport of plastic caps from collection to the recycling plant was modeled in a stratified way. The assistance entities that collect this material were brought together in a

single distribution center representative of their region according to the average distances to the warehouse (expressed in km) and quantities delivered at the destination (kg). The model considered two types of transport vehicles: "*Transport, freight 3.5–7.5 metric ton Euro 3*" for quantities of material delivered M $\leq$ 310 kg; and "*Transport, freight 7.5–16 metric ton Euro 3*" for loads M > 310 kg.

Almost all the material and energy flows that circulate (in and out) across product system boundaries under analysis were included to prepare the environmental diagnoses of each scenario. Exceptions occurred for the pigment used in the color standardization and the anti-UV material added to the injectors to produce the tags. Aspects such as the unavailability of data on their manufacturing cycles and low cumulative contribution to the total mass introduced in this process stage (<1.0% in both cases) meant these assets were disregarded from environmental performance analysis.

The life cycle of virgin PP resin—with a scope from crude oil extraction to resin production—was specified in terms of consumption and emissions based on secondary data collected from the Ecoinvent® Database version 3.8 [38].

The recycling of plastic caps—whose original function was to make the containers that contained substances and materials watertight—to make tags suitable for recording information typical of the telephone sector was configured in an *open loop recycling* (OLR)-type system. Due to this characteristic, the OLR arrangements should be classified in methodological terms as multifunctional processes [39].

The most usual way of dealing with this problem consisted of applying the "*cut-off*" approach, from which the environmental loads associated with each function were restricted exclusively to it [40]. As a result, consumption and emissions generated during the life cycle of plastic caps were only attributed to the sealing of the respective containers. In this way, these materials began manufacturing the tags—used for the second function of recording information—as elementary flows, devoid of any environmental load.

Another multifunctional situation identified in the production cycle, common to all analyzed scenarios, occurs during the tags manufacturing stage. In addition to this consumer good, the injection of polymeric material also generates a by-product that can be used to prepare other items of interest to the telephony sector itself. To address this situation, we applied the *surplus method*, which assigns all environmental loads to the flow that continues inside the product system, i.e., the tag stream. The adoption of the surplus method, therefore, evaluates the worst possible scenario in terms of the environmental effects attributed to a given function. Furthermore, a sensitivity analysis was also carried out to modulate the impact caused by this decision. In this case, the multifunctionality situation was treated by *allocation* using the amount of mass of each co-product as a criterion for distributing the environmental loads.

Based on this principle, the following were selected to compose the environmental performance profiles of the scenarios under analysis: Global Warming Potential (GWP), Primary Energy Demand (PED), Water Scarcity (WS), Formation of Particulate Matter (PMF), and Terrestrial Acidification (TAc). The GWP was estimated using a variant of the Intergovernmental Panel on Climate Change (IPCC) method (2021), GWP with CO_2 uptake-v 1.03 [41]. In addition to emissions of the various Greenhouse Effect Gases that are contemplated by the conventional approach proposed by the IPCC, the GWP with CO_2 uptake also considers releases of carbon dioxide into the air of biogenic origin ($CO_{2,b}$) and the capture of CO_2 as a result of photosynthetic activity ($CO_{2\ upk}$) for global warming quantification [42]. Global Warming Potential is the environmental impact that most concern modern society. This fear is justified by the increasing concentration of GHG in the atmosphere, mainly CO_2 and CH_4 of fossil origin. Such characteristics would be enough for the study to consider the GWP among the dimensions that define the environmental performance of the arrangements under analysis. As if that were not enough, the transformation and logistics chains of the manufacture of signaling tags comprise activities whose implementation results in releasing these compounds into the

atmosphere. Because they are also common to other impact categories, such activities are detailed below.

Primary Energy Demand (PED) impacts were determined by the Cumulative Energy Demand (CED) method, v.1.09. The PED of a product comprises the direct and indirect energy consumption that occurs throughout the considered life cycle; that is, the accumulated consumption of primary energy from the extraction of natural resources to the final disposal of the consumer good, as well as its raw materials and auxiliary materials [43]. The choice of PED to integrate the environmental impact profile of the systems under analysis is due to two factors. The first refers to the fact that almost all processes involved in transforming resin (virgin or recycled) into tags are energy-intensive, both in electricity and heat. Regarding electricity, this aspect is relevant because the Rio Grande do Sul matrix has significant contributions from coal and natural gas. The second factor is related to a comprehensive logistics network, fundamentally road and diesel-powered, for the circulation of inputs (plastic caps) and intermediaries (virgin and recycled resins in the form of flakes and only recycled resin with presentation of pellets). The CED method expresses PED in terms of non-renewable (NRF: fossil; NRN: nuclear; and RB: biomass) and renewable (RB: biomass; RWSG: wind, solar, geothermal; and RW: water) energy resources [44].

The WS indicator brings together the direct and indirect use of water by a consumer (or producer) based on the regional availability of this resource. WS became a relevant impact for the study due to the water consumption associated with cleaning the plastic caps and generating heat (in the form of steam) to support endothermic processes. The values used in this study to describe impacts of this nature were determined by the method elaborated by Boulay et al. [45]. The PMF and TAc impact categories were evaluated using the ReCiPe 2016 Midpoint (H) v.1.01 [46]. Contributions to PMF were expressed in kg $PM_{2.5\ eq}$. These results came from emission-concentration sensitivity matrices for precursors such as NH_3, NO_x, SO_2, and $PM_{2.5}$ emitted from the global source–receptor model TM5-FASST [47]. The TAc evaluates the loss of plant species due to decreased soil pH. The impact factors used in these estimates seek to quantify the influence of $[H^+]$ on fractions of potentially extinct species of vascular plants located in mixed temperate broadleaf forests, tundra, and (sub)tropical moist broadleaf forests [48]. Impacts associated with PMF and TAc also refer to asset transport operations by vehicles that consume diesel oil, whose combustion emits precursors common to both categories, such as NO_x, SO_2, and $PM_{2.5}$.

It is worth noting that the calculations performed to determine the environmental performance of the scenarios were carried out using SimaPro® Software, v. 9.3.0.3, distributed by PreSustainability.

2.2.2. Circularity Performance: MCI Index

As already anticipated by the Introduction section, the performance regarding the circularity of the manufacturing scenarios of signaling tags from virgin and recycled PP was evaluated by the MCI. As for the composition, this index results from the combination of three product particularities; they are (i) the mass of virgin raw material used in its manufacture; (ii) the mass of non-recoverable waste attributed to the product, and (iii) a utilization factor, which considers the duration and intensity of use of the consumer good under analysis [28].

The analyses conducted by the MCI are always based on two extremes. The first of these, the *Linear Economic Model*, is characterized by considering products manufactured from virgin materials, whose final disposal occurs in landfills. The other extreme, qualified as the *Circular Economic Model*, admits products that do not originate from virgin materials, which, when no longer able to fulfill their original functions, will be recycled (or reused) with complete (100%) efficiency. The MCI scale of variation, between 0.0 and 1.0, is designed to examine the degree of transition between the linear and circular models.

The MCI makes certain assumptions that can become limitations because they are far from reality. Examples are the assumption that post-consumer-recovered material can be processed to a similar quality as virgin material, or that there will be no material

loss during the preparation of the collected products for reuse/recycling [27]. Despite this, the combination of MCI with other environmental performance indicators, such as those generated by applying the LCA technique, enables favorable strategic choices for CE projects and guides the search for better product and process performance in more than one perspective of the environmental dimension [49]. Successful examples of this integration are the studies by Loca et al. for plastic bottle closed-loop recycling in the USA PET market [50], and Rigamonti and Mancini [51], who discussed the potential roles of circularity indicators and LCA in improving circular decision-making.

This study evaluated the circularity of the scenarios under investigation according to two perspectives. The first of them, specified as MCI-A, assumed that after fulfilling their intended function (signaling), the tags would be disposed of in landfills. In the second perspective, the MCI-B, these materials would be sent for recycling to produce a consumption good with a different function from the previous ones contemplated by the OLR system. As a result of this hypothesis, we also admitted that since they are products made up of only one material (i.e., mono materials), the tags could be fully used, that is, in their total available quantities, in the manufacture of the product that would be derived from them.

2.2.3. Technical Performance

The technical performances of the tags obtained according to each analysis scenario (Table 1) were determined by tensile strength and impact strength tests. To this end, test specimens were produced in an Arburg thermoplastic injection molding machine, model Allrounder 520S. During injection, the heating zones were kept at 210–215–220–225 °C, while the exit at the nozzle reached 230 °C. The performance characterizations were based on mechanical tests performed before and after exposure of the test specimens to weathering (accelerated weathering test) in a UV chamber. The polypropylene H 301, supplied by Braskem S.A. [52], with a flow index FI = 10 g/10 min (measured at 230 °C/2.16 kg according to ASTM D1238 method) was adopted as the reference standard for the determination.

The traction test was guided by the procedures described in ASTM D638 [53], using type I specimens, in an INSTRON model 23–30 universal testing machine with a claw separation speed of 50 mm min^{-1}, a load cell of 5.0 kN, and a conventional extensometer. The impact test followed the guidelines specified in the ASTM D256-10-method A [54]. For the case under analysis, the hammer had a capacity of 1.0 J, and the notched samples were conditioned for 40 h before the test.

Finally, the accelerated weathering test was conducted by the protocol provided in ASTM G154-cycle 1 [55] for the following conditions: test time, t = 1000 h; UVA lamp, irradiation rate J = 0.89 W/m^2/nm; wavelength, λ = 340 nm; and radiation exposure time, t_e = 8 h (under black panel temperature T_p = 60 ± 3.0 °C) followed by a condensation time, t_c = 4 h (T_p = 50 ± 3.0 °C).

3. Results and Discussion

3.1. Environmental Performance

Tables 2 and 3 present the environmental performance results of scenarios S1–S5 obtained from applying LCA to produce 100 signaling tags (=RF). These diagnostics were generated considering that the multifunctionality situation identified during the injection stage, between the tags and another polymeric product, could be treated either by the surplus method (Table 2) or by applying the allocation procedure (Table 3), in this case, using mass-market criteria.

Regardless of the solution adopted to deal with the multifunctional situation familiar to all scenarios, S1—which uses virgin PP to manufacture the signaling devices—obtained the worst results of all the options analyzed for any impact category considered in the evaluation. Such performance can be attributed to two factors: (i) the fossil origin of the polypropylene resin used by this arrangement; and (ii) the energy consumption, in the form of electricity and heat, of the process, which also comes from non-renewable resources.

At the other end of the scale were S5 and S3. The proximity of performances between both, and, consequently, their distance from S1, suggest that the use of recycled plastic caps to replace virgin PP resin considerably reduces the adverse effects on the environment of these arrangements, regardless of the appearance of the material used for injection (flake or pellet). Adopting the cut-off approach to solve the typical multifunctionality of OLRs established in scenarios S2–S5 consists of a third factor that explains the same disparity. This is because this methodological procedure assigns exclusively, compulsorily, and automatically all environmental loads (and consequently, their derived impacts) of the production cycle of closures to their original function, which is to close the package. Thus, the life cycle established to meet the role of signaling performed by the tags starts treating the caps, a valued waste, in the same way, it would do with a resource extracted from the environment, without environmental load. Despite this simplistic way of distributing impacts among the functions contemplated by an OLR, many specialists in conceptual aspects of LCA see in the cut-off approach the least discretionary and, at the same time, value-neutral procedure to perform that partition [39,40,56].

Table 2. The environmental performance generated by LCA of tag production from scenarios S1–S5, applying the surplus method for multifunctionality treatment.

Scenario	GWP_{upk} (kg $CO_{2\ eq}$/RF)	PED (MJ/RF)	PMF (g $PM_{2.5\ eq}$/RF)	TAc (g $SO_{2\ eq}$/RF)	WS (L/RF)
S1	2.21	98.1	2.14	6.27	45.4
S2	1.30	58.9	1.40	4.11	36.2
S3	0.11	7.40	0.38	1.16	21.8
S4	1.10	50.3	1.26	3.73	36.9
S5	0.19	11.3	0.61	1.83	33.9

Table 3. The environmental performance generated by LCA of tag production from scenarios S1–S5, applying the allocation method with the mass criterion for multifunctionality treatment.

Scenario	GWP_{upk} (kg $CO_{2\ eq}$/RF)	PED (MJ/RF)	PMF (g $PM_{2.5\ eq}$/RF)	TAc (g $SO_{2\ eq}$/RF)	WS (L/RF)
S1	1.00	45.8	1.10	3.26	30.3
S2	0.54	27.4	0.76	2.25	25.9
S3	0.10	6.81	0.37	1.11	21.0
S4	0.59	28.1	0.79	2.35	27.9
S5	0.12	8.04	0.43	1.31	24.8

Looking in more detail at Table 2 and retrieving data applied in the product system modeling, it was possible to conclude that the production of PP became the unit process of the most significant contribution to the impacts caused by S1 concerning GWP_{upk} (80%), PED (79%), PMF (57%), and TAc (60%). It was followed by the production of ethylene, an input for the previous process, whose contributions to GWP_{upk} and PED were, respectively, 4.4% and 4.8%, and the generation of electricity, whose environmental impacts are directly influenced by fossil coal, one of the sources of electricity generation that is part of the electric grid in the south of Brazil [37]. This sequence of causalities justifies the contributions of S1 for PMF (11%) and TAc (12%). Concerning the WS category, the largest sources of impact corresponded, once again, to the generation of electricity—in this case, however, due to the hydroelectric source (63%)—the production of coarse propylene (17%), and the processing of propylene per se (11%).

Looking at environmental performance from another perspective, the most significant precursors of GWP_{upk} impacts were fossil CO_2 (80%) and CH_4 (20%), while for PED, they were crude oil, natural gas, and coal. In addition, emissions of sulfur oxides (SO_x) and nitrogen oxides (NO_x), as well as ammonia (NH_3), were common causes of adverse effects

in the forms of PMF and TAc. In contrast, in addition to these, PMF was also affected by releases of particulate materials with diameters of less than 2.5 μm.

Partly replacing virgin resin with recycled material (S2 and S4) reduced adverse environmental effects in all categories analyzed. For GWP_{upk}, this decrease was 50% when the caps used were pellet-shaped (S2), while when presented as a flake (S4), the reduction was 41%. Along these lines, the best results were achieved with the production of tags exclusively from fragments derived from recycled PP (S5), when a 95% reduction in GWP_{upk} contributions was observed regarding the impacts generated by S1. In addition, coal-fired power generation, mine operation, and coal preparation contributed significantly to the results obtained by S5 for PMF (45%), TAc (48%), and PED (26%).

Adopting mass allocation to address the multifunctionality situation improved the performance for all impact categories selected to characterize this facet of the environmental dimension (Table 3 vs. Table 2). However, the repercussion of the mass allocation on the performance of each scenario is conditioned by the quantity produced of each material at the injection stage. For example, the field surveys showed that the conversion efficiencies from resin to tags reached maximum values in S5, around 75%, going to 50% in S2, 43% in S1, 41% in S4, and 40% in S3.

Because of this, the polymeric by-product that leaves the system takes a portion of the impacts generated in each category, which is complementary to those values. Thus, although all scenarios enjoyed the advantages of mass allocation, S3 was the most favored arrangement, while S5 was the least. In any case, S1 remained the scenario with the most significant associated impacts, even though these effects were reduced due to the application of this approach compared to those observed adopting the surplus method.

The performance of S1 in terms of GWP_{upk} pointed out in Table 3, was also due to the releases of CO_2 (81%) and CH_4 (19%) of fossil origin. However, in this specific case, when the environmental loads between tags and polymeric waste were treated by mass allocation, an input due to dinitrogen oxide emissions (N_2O: 1.1%) was still perceived, but also an impact deduction (–1.4%) due to CO_2 storage in the soil and in the biomass that integrated the local electric grid. This offset increased when virgin PP was partially substituted by PP manufactured with recycled caps (S2: −2.52%, and S4: −2.36%) and reached the most expressive values (S3 and S5: −13%) when the substitution was total. Finally, even though the production of pellets entailed additional transportation and higher electricity consumption than the processing of flakes, no significant differences in associated impacts were noted between these two forms of presentation of recycled PP.

Even though S5 prevailed over the others in terms of environmental performance as measured by the LCA technique, it was convenient and timely to know the result of the association of the impacts of all these categories evaluated at this stage of the study. The fact that each of these effects refers to a facet of the interaction between the biosphere and the anthroposphere led to applying a normalization procedure. Defined as an optional element of the impact assessment stage of LCA [32], normalization describes the results of the environmental diagnosis generated by the technique in terms of a single indication.

This strategy has been used recently with success on other occasions, as in the studies performed by Morita et al. [57] for trouser jeans, Moore and Kulay [31] for the evaluation of electric power generation in Brazil, Sakamoto et al. [58] in environmental analysis of water reuse in an oil refinery, and Paes et al. [59] in the planning of urban solid waste management actions. In all these situations, the individual values of each impact were divided by their corresponding values obtained by a reference scenario, selected among the options analyzed from objective criteria.

The results of these operations were dimensionless and could therefore be added up to generate a single indicator for each arrangement. In this case, it was decided to elect S1 as the reference scenario because it depicts a trivial way of making signaling tags. Figures 3 and 4 show the normalized partial indexes and the single indicator of each design, respectively, for treating multifunctionality in injection via surplus and mass allocation methods. Overall, it can be stated that local power generation was primarily responsible

for the impacts associated with tag production in scenarios S2–S5. An action capable of dampening these effects would be to substitute, even partially, some of the sources of the electric grid with renewable alternatives, such as biomass, wind, or photovoltaic, which would be installed near the recycling and tag manufacturing plants.

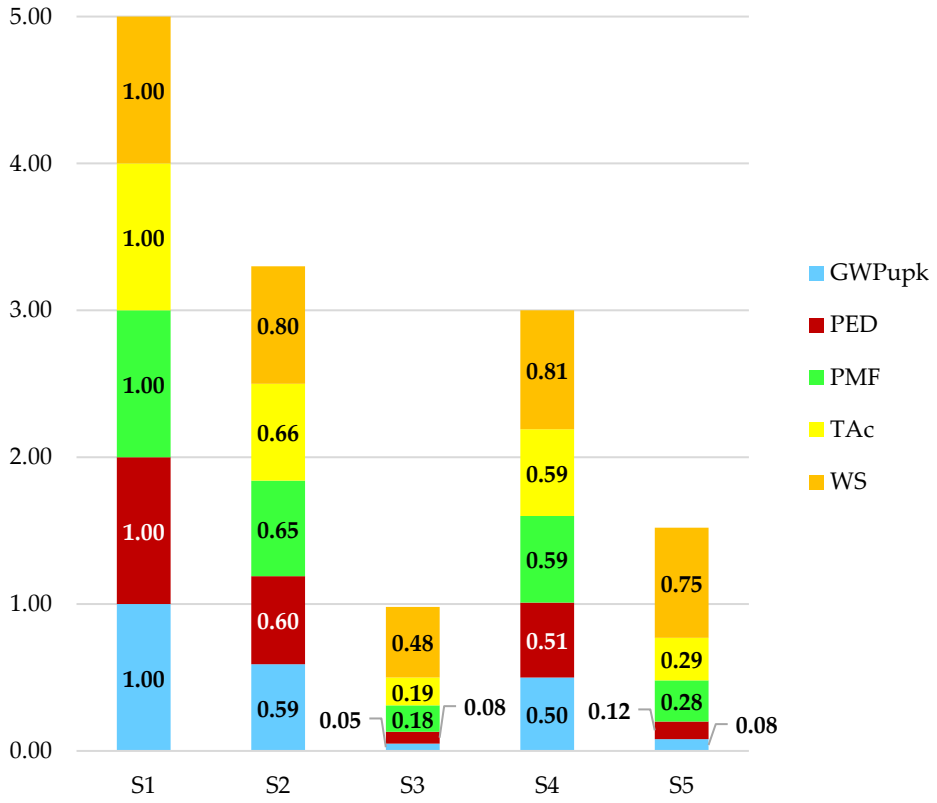


Figure 3. Normalized values and Single Environmental Performance Indicator for treatment of the multifunctionality situation in the injection stage by the surplus method.

As expected, the scenarios in which there was a complete substitution of virgin PP by recycled PP from plastic caps (S5 and S3) accumulated the best results of the whole series regardless of the load participation criteria used in the injection process. The gains reached 81% (surplus method) and 68% (allocation-mass) when the material had a flakes presentation, compared to the performance of S1.

3.2. Circularity Performance

Table 4 presents MCI values obtained for the scenarios under analysis in each signaling tag destination perspective (MCI-A and MCI-B). As discussed in Section 2.2.2, an MCI→0.0 indicates that the arrangement under analysis behaves similarly to the Linear Economic Model. At the same time, values of MCI→1.0 corroborate a performance compatible with that of the Circular Economic Model.

Table 4. S1–S5 in circularity were obtained with the MCI for two perspectives of the destination of tags: MCI-A and MCI-B.

Scenario	MCI-A	MCI-B
S1	0.10	0.52
S2	0.33	0.74
S3	0.55	0.96
S4	0.33	0.74
S5	0.55	0.96



Figure 4. Normalized values and Single Environmental Performance Indicator for treatment of the multifunctionality situation in the injection stage by allocation with the mass criterion.

An analysis of scenarios S1–S5 for the perspective that post-consumer tags are sent to the landfill (MCI-A) reveals circularity gains of around 3.3 times due to the 50% substitution of recycled for virgin PP (S1 vs. S2 and S4). However, this benefit can be up to 5.5 times if recycled plastic cap flakes replace virgin PP. Furthermore, the indicator cannot distinguish the appearance (pellet or flakes) of the recycled material because it considers, in its estimates, only the quantity that will be consumed to make the tags. Finally, it is worth mentioning that despite the advantages of using plastic caps to replace virgin PP in the process, the fact that the tags are discarded in landfills severely penalized the performance of all scenarios for the MCI-A condition. This is so true that the best results of the whole series for this circumstance, achieved by S3 and S5, project arrangements that are still far from the circular model.

When that limitation is removed, and the tags start being recycled to be used as raw material for manufacturing another product (MCI-B), all scenarios present significant improvements in circularity. However, S3 and S5, which accumulate in their arrangements the complete substitution of virgin PP by the recycled form to produce tags, and the recycling of these in post-consumption, only do not reach full circularity since the recycling processes and product manufacturing generate waste that cannot be used. Furthermore, when virgin and recycled PP were mixed in equal proportions, as occurred with S2 and S4, the distribution directly influenced the MCI values, showing linear behavior for this case.

The results obtained from the MCI bring interesting considerations, especially regarding the design of products generated from reused materials and whose destination is also reused in another cycle. In this sense, the use of recycled PP from plastic caps to replace fossil-based polymer resins to produce products is perfectly aligned with the purposes of the circular economy, of perpetuation and use of existing resources, as opposed to the linear model of continuous extraction of resources to meet expectations and fulfil functions.

3.3. Technical Performance

The results of the technical performances of the signage tags, measured based on the behavior of their mechanical properties during the strain and impact tests, are presented in Table 5. Table 6 describes the same properties, but after the products have undergone the accelerated weathering test performed in the UV chamber for 1000 h.

Table 5. Mechanical properties test results for scenarios S1–S5.

Scenario	Tensile Strength at Yield (MPa)	Elongation at Yield (%)	Modulus of Elasticity (MPa)	Notched Izod Impact Strength (J/m)
S1	26 ± 1.0	6.75 ± 0.11	1262 ± 222	86.2 ± 6.20
S2	24 ± 1.0	10.1 ± 0.12	1013 ± 201	91.4 ± 15.9
S3	23 ± 1.4	11.6 ± 0.20	917 ± 109	72.9 ± 7.40
S4	25 ± 1.0	9.73 ± 0.15	1030 ± 156	76.6 ± 8.00
S5	21 ± 1.0	11.4 ± 0.26	770 ± 113	68.2 ± 7.80

Table 6. Results of the mechanical properties testing for scenarios S1–S5 after exposure in the UV chamber. The numbers in parentheses represent the variation between the properties before and after the accelerated weathering test.

Scenario	Tensile Strength at Yield (MPa)	Elongation at Yield (%)	Modulus of Elasticity (MPa)	Notched Izod Impact Strength (J/m)
S1	23 ± 0.5 (−11.5%)	5.95 ± 0.2 (−11.9%)	836 ± 75.0 (−33.8%)	74.7 ± 6.70 (−13.3%)
S2	21 ± 1.0 (−12.5%)	9.21 ± 0.3 (−8.4%)	565 ± 44.0 (−44.2%)	**91.6 ± 14.8 (+0.16)**
S3	20 ± 0.8 (−13.0%)	11.9 ± 0.3 (−2.7%)	650 ± 75.0 (−29.1%)	57.9 ± 11.4 (−20.5%)
S4	22 ± 0.9 (−12.0%)	8.96 ± 0.4 (−7.9%)	685 ± 155 (−33.5%)	**80.5 ± 10.6 (+5.0%)**
S5	19 ± 1.0 (−9.52%)	**11.82 ± 0.4 (+4.0%)**	572 ± 41.0 (−25.7%)	49.2 ± 7.20 (−27.9%)

The data shown in Table 5 reveal that the tags manufactured from post-consumer plastic caps showed a slight reduction in technical performance compared to virgin PP. The exception was the elongation at yield. Consistently, the materials evaluated in scenarios S3 (100% recycled material in pellet form) and S5 (100% recycled material in flake form) registered the highest rates of reduction in mechanical properties compared to the result obtained by the tag made of virgin PP (S1). Moreover, the properties were partially recovered by adding virgin PP to the tags obtained in S2 and S4. Such behaviors can be explained by the fact that during mechanical recycling, post-consumer plastic caps are subjected to shear stresses under temperature action, which result in a reduction of molar mass and, consequently, in changes in their morphology and mechanical properties. The hypothesis that these materials have suffered degradation during their life cycles—motivated by exposure to chemical, physical or mechanical agents—leading to loss of mechanical and chemical properties also cannot be ruled out.

Another finding about the data in Table 5 is that the most affected properties were the modulus of elasticity and the notched Izod impact strength, especially for S3 and S5, where the labels were produced entirely from recycled material. Conversely, an increase in elongation at the yield point was observed for the same scenarios when these performances were compared with those for blends of post-consumer and virgin material (S2 and S4) or virgin PP (S1). A combined evaluation of the values depicted in Tables 5 and 6 showed a reduction in mechanical properties for almost all the scenarios after the samples were subjected to the accelerated weathering test. The deviations were regarding the elongation point for S3, and notched Izod impact strength for S2 and S4, although the increases were still within their standard deviations.

During the weathering test, the tags were exposed to ultraviolet radiation to simulate sunlight and water vapor to represent rain and humidity. UV radiation is one of the most

efficient methods to (photo)degrade polymeric materials, causing irreversible chemical changes and affecting their properties. In the photodegradation of polymers such as PP, chain scission reactions predominate, reducing their crystallinity [60]. When comparing the properties under analysis before and after the accelerated weathering test, it was noticed that the most affected property was Young's modulus. This behavior could, therefore, be related to the reduction of crystallinity index, besides justifying the increases in the values of elongation at yield observed, respectively, in S1, S2, S4, and S5 [21,55]. Stress–strain tests showed similar behavior profiles for scenarios S1, S3, and S5. In all these cases, maximum stress values were recorded for strains around 10%. However, it was also noted that values equal (or superior) to 50% for this parameter were reached by the same tension. In addition, weathering significantly weakened the material. This was so true that after being subjected to these conditions, the tags exhibited levels of deformation equivalent to those obtained without exposure to weather conditions with stresses up to 25% lower.

The tags obtained by the arrangements specified in S2 and S4 presented similar profiles to the counterparts produced according to S3 and S5. This suggests that the mixture of virgin and recycled materials in mass proportions [50:50] had little influence on the behavior of this parameter when compared to tags manufactured only with recycled resins. S1 achieved the highest tensile strength in yield value among all investigated alternatives; moreover, no significant differences were noticed in this parameter for the other scenarios. Conversely, all products' toughness reductions were notorious after being submitted to the weathering test. Figure A1 in Appendix A shows the stress–strain curves of the tags obtained for S1, S3, and S5 before and after the accelerated aging test.

Both virgin and recycled PP had their mechanical properties reduced because of thermomechanical degradation and photodegradation; however, there was a slight disparity between the values obtained and those reported in the literature [21,55] due to the dosage of substances that lend themselves exactly to dampen these adverse effects in the mixture subjected to injection. Finally, it is important to point out the impossibility of determining the elongation in range for any of the scenarios analyzed since the samples did not break even when the full scale of the equipment in which the tests took place was reached. The same behavior was maintained for the labels submitted to the accelerated weathering test.

As occurred before with the environmental performances estimated by LCA for the scenarios under study, their technical dimensions were also described from single indicators. For this purpose, the tensile strength, elongation, modulus of elasticity, and notched Izod impact strength results obtained after the accelerated weathering tests of the tags produced in S1–S5 were related to a normalization procedure like the one described in Section 3.1. Once again, S1 acted as the baseline for applying the method. These results are shown in Figure 5.

In general terms, it was observed that using recycled material, both partially and completely, regardless of its presentation as flakes or pellets, provided superior technical performance to that obtained with virgin PP. The most significant gains, of about 10%, occurred when the virgin resin was replaced in whole with flakes from recycled caps (S1→S5), while using pellets of recycled material in the same function (S1→S3) yielded 4.0% benefits. From this analysis, it is possible to conclude that the recycled PP can replace the virgin congener without harming the technical performance of the signaling tags, even when exposed to adverse weather conditions for long periods. On the other hand, for such advantages to be improved, it is recommended to use flake-shaped material during the manufacture of the signaling tags.

3.4. Integration between Environmental (Based on Environmental Performance and Circularity) and Technical Dimensions

After knowing the individualized performances of scenarios S1–S5 in terms of generating environmental impacts, circularity, and technical implementation, it became immediate and compulsory to see the behavior of these arrangements considering all the dimensions simultaneously. The values of their normalized performance indicators were related for this

to occur, as presented by Equation (1). It is important to note that while the best technical and circularity performances were registered by increasing indicators, the environmental performance in terms of impact behaved oppositely, with adequate results expressed by decreasing hands. Because of this, the Global Performance Indicator (GPI) was constituted as a quotient. In addition, EPI, MCI-A, and TPI received equal weights.

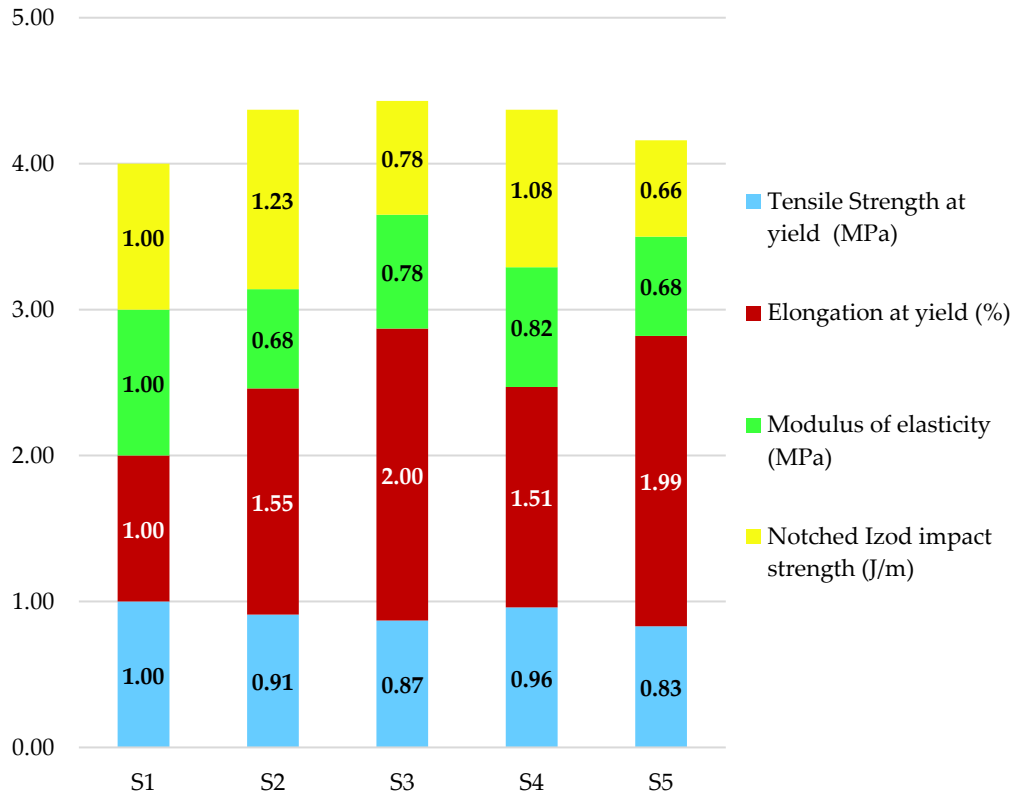


Figure 5. Normalized technical performance values for the scenarios evaluated after exposure in a UV chamber.

The circularity index was described only for the situation in which the end-of-life of the tags would be landfill (MCI-A), the most likely case for disposal of this material, regardless of whether it registered worse MCI results than the counterpart alternative. For this composition, the better the collective performance of a scenario, the lower its GPI. Table 7 lists all scenarios' EPI, MCI-A, and TPI values and presents the corresponding GPIs.

$$GPI = [\frac{EPI}{(MCI - A) \times (TPI)}] \quad (1)$$

where:

GPI: Global Performance Indicator
EPI: Environmenal Performance Indicator
$MCI - A$: Material Circularity Indicator for situation "A": final disposal of tags in sanitary landfill
TPI: Technical Performance Indicator

Even though its TPI value mitigated the environmental burdens imposed, S1 remained the worst of the options evaluated. The partial substitution of recycled virgin PP led to global performance reductions ranging from 5.5 times (S2) to 6.1 times (S4) compared to S1. On the other hand, the most promising overall performance was achieved by S3, mainly due to its behavior regarding environmental impacts. Even though S3 showed slightly lower technical indices than S5, its EPI value corresponded to about 64% of that obtained by its counterpart, thus deciding the dispute in its favor. However, despite this, S5 also

has sufficient conditions to be met on an industrial scale under the management of the Tampinha Legal program.

Table 7. The Global Performance Indicator (GPI) for scenarios S1–S5.

Scenario	EPI	MCI–A	TPI	Global Performance Indicator
S1	5.00	0.10	4.00	12.5
S2	3.30	0.33	4.36	2.29
S3	0.97	0.55	4.42	0.40
S4	3.01	0.33	4.36	2.09
S5	1.52	0.55	4.16	0.67

4. Conclusions

This study investigated the effect of replacing virgin PP from petroleum with a substitute derived from recycled plastic caps to produce signaling tags used by the telephone industry. Recycled PP in flakes or pellets was used to make these consumer goods. The analysis was performed for the environmental dimensions, characterized by applying the LCA technique for different environmental impacts and by estimating the Material Circularity Indicator (MCI) and the technical dimension, defined by tensile strength and impact strength tests. The strategy adopted was to compare performances, and for this reason, five analysis scenarios were elaborated. The research observed the performance of each scenario both in isolation and from the integration of the same results.

The assessment undertaken by LCA estimated the gains in terms of global warming potential with CO_2 uptake (GWP_{upk}) to be 92% and 95%, respectively, from the total replacement of virgin PP with recycled PP in the form of pellets and flakes. The other impact categories assessed by the metrics—Primary Energy Demand, Water Scarcity, Formation of Particulate Matter, and Terrestrial Acidification—followed the same trend.

The circular performance was evaluated through the MCI for two circumstances: (i) destination of post-consumption platelets to landfill (MCI-A); and (ii) reuse of this waste for another use via recycling (MCI-B). The results for the MCI-A showed gains of 3.3 times in circularity for the scenarios that considered partial substitution of virgin material for recycled material and 5.5 times when the substitution was total. On the other hand, the case approached by MCI-B revealed even greater superiority of the tags originating from recycled PP over its fossil counterpart because of considering the possibility of post-consumer tags recycling.

The tensile strength and impact strength tests that defined the technical dimension were performed before and after an accelerated weathering test. In this case, the tags obtained from virgin PP showed superior properties to those manufactured in post-consumer PP before and after the weathering test. The exception occurred for elongation at yield.

Finally, the integrated analysis of the three dimensions ratified the individual results of each extent analyzed by pointing out that the scenarios of total replacement of virgin PP by recycled material from plastic caps were the environmental and technically most favorable choices. Although there are limitations in the scope of this study (i.e., the use of average data to describe the logistics of collection and distribution of plastic closures throughout the state of Rio Grande do Sul or obtaining data on the production of pellets, flakes, and the tags themselves from a few industrial runs), the results obtained by this investigation are conclusive as to the value of recycling polymeric materials for open loop recycling contexts. These findings also confirm the Tampinha Legal program's expectations of alignment with sustainability and circular economy principles.

Author Contributions: Conceptualization, B.A.d.S.T., I.L.C.C. and L.K.; methodology, B.A.d.S.T., I.L.C.C. and L.K.; software, B.A.d.S.T. and I.L.C.C.; validation, H.W., T.S.V. and L.K.; formal analysis, B.A.d.S.T., I.L.C.C., H.W., T.S.V. and L.K.; investigation, B.A.d.S.T. and I.L.C.C.; resources, A.F.d.O.S. and I.L.C.C.; data curation, B.A.d.S.T., I.L.C.C., V.O. and S.S.d.S.; writing—original draft preparation, B.A.d.S.T. and I.L.C.C.; writing—review and editing, H.W., T.S.V., M.L.d.S.N., A.F.d.O.S., S.S.d.S. and L.K.; supervision, H.W., T.S.V. and L.K.; project administration, M.L.d.S.N. and T.S.V.; funding acquisition, S.S.d.S. and A.F.d.O.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

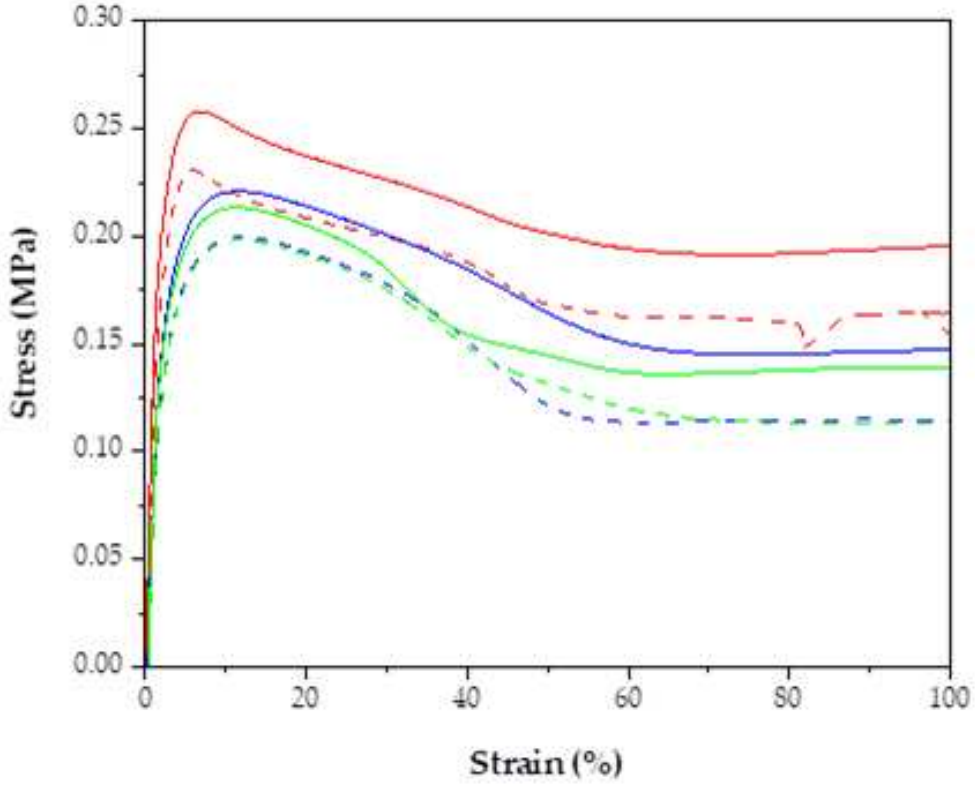


Figure A1. Stress–strain curves of virgin PP and recycled PP from the conditions described. Legend: scenarios (-) S1, (-) S3, and (-) S5, before the accelerated weathering test; and scenarios S1 (--), S3 (--), and S5 (--) after the accelerated weathering test.

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