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CASE STUDY

REVISED Impact of recyclability on the tensile and Impact properties of coated plastic materials for the automotive and electronic sectors

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Abstract

This research focuses on the study of the tensile modulus and impact resistance of acrylonitrile-butadiene-styrene (ABS) and its blends with polycarbonate (ABS/PC) including recycled and painted material. A comprehensive assessment was done to determine the impact of reprocessing cycles, remaining coating and their combined effect in the final properties of the recycled polymer. Post-consumer materials are in an already-aged state, lowering their initial properties. Mechanical recycling methods showed that the reprocessing cycles have a higher impact on the mechanical performance than the amount of recycling material content. Also, the material is often coated when they are about to be recycled. The remaining coating impurities play a major role in the recycling process, losing up to 42% of the impact resistance for ABS and 28% for ABS/PC. It was demonstrated that below a 10% of remaining paint, both materials retained is performance as a neat product. Impurities was declared to be the most pernicious element on the recycling process and their elimination must be a priority regarding this objective. These results provide a better knowledge of the recycling effect and can be used to

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decide the potential recyclability of plastic. The ascribed project of this study (DECOAT) aims to develop efficient systems to remove coatings at the end-of-life of the part, to reduce the damage and promote the use of recycled material in high-tech applications.

Keywords
Recyclability, plastic, coating, automotive, electronic, tensile strength, impact strength, ABS, PC, reprocessing, mechanical performance, end-of-life

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REVISED **Amendments from Version 3**

The new changes in the document have been included. First, new references have contributed to enrich the introductory section with respect to the different recycling techniques of polymers, their blends and to introduce and scope of the current state of the recycling technologies for ABS and PC. Then, new corrections in the abstract and the introduction have been performed. Finally, the method section has been improved by explaining the TDS meaning and highlighting the tests and equipment used.

Any further responses from the reviewers can be found at the end of the article

Introduction

Plastics are one of the most relevant materials worldwide due to their unique combination of properties, including chemical resistance, ease of processing, low cost and lightweight potential. These properties allow them to be used in a variety of key components for different sectors, such as construction, architecture, cushioning, electronics or the aeronautical and automotive. On top of that, the increasing use of plastic materials increases the post-consumer plastic waste produced, giving concern about their management and recyclability techniques. According to a new report of the OECD organization, only about 9% of collected plastic waste is recycled while 22% is mismanaged globally. Although, recent improvements on the reusability and recyclability of plastics had been performed, the global production of plastics from recycled or secondary plastics has more than quadrupled in the last 20 years, but this is still only 6% of the size of total plastics production, being most of the plastics in use today virgin or primary plastics, made from crude oil or gas[1].

The automotive and electronic industries manufacture key products for the current market needs. They use high amounts of plastic materials, including polypropylene (PP), polyurethane (PU), polyvinyl chloride (PVC), acrylonitrile-butadiene-styrene (ABS), polycarbonate (PC) and many others. These sectors fulfil the demand of around a 15 % of the Europe demand for plastics materials[2]. Among them, ABS and PC are one of the most important ones. ABS is a polymeric material that stands out for being highly resistant to impact and chemical corrosion along with a low melting point that allows an easy processability. It is widely used automotive and electronics as an impact modifier or integral part of dashboards and steering wheel covers. However, ABS has lower mechanical properties than most of the engineering plastics on the market[3]. PC on the other hand, is a widely used amorphous plastic which has some outstanding characteristics like transparency or high impact strength but possesses poor solvent resistance and harder processability due to its high viscosity[4]. Combining those materials in a ABS/PC blend, increases the thermomechanical resistance of ABS[5,6] and reduces the cost and increases the processability of PC[3]. ABS/PC blends are commonly applied in automotive parts as well as housings of electronics and household appliances[7]. Automotive and electronics were one of the main demanding end-users for these kinds of plastics, accounting for about 9.9 and 6.2 % respectively of the total European plastic demand in 2018[8]. One of the main issues are the wastes generated from engineering plastics used in automotive and in electronic equipment, where ABS and PC take an important part. The waste generation of Waste Electrical and Electronic Equipment (WEEE) has increased from 8.3 Mt in 2010 to 10.4 Mt in 2021, whereas its collection has increased from 3.8 to 5.6 Mt[9]. On top of that, the demand of recycled engineering plastics reached 2.8 Mt in 2020. This means that although recycling is experiencing and increasing demand, the increasing production and low collection rates show us that there is still plenty of work to do.

The most common solutions for recycling plastics include thermal, chemical or mechanical recycling. Thermal recycling recovers energy from burning plastics but this method has bad prospects in environmental aspects[10,11]. Chemical recycling breaks down polymers into their original building blocks by a strong degradation provoked using chemical agents. However, it has some drawbacks that come from the high environmental impact by to the use of harmful chemicals and their consideration as an expensive method[12,13]. On the other hand, as most of the plastics used in automotive and electronics are thermoplastics, the most recommended recycling technique is mechanical recycling. Heren, plastics are transformed into pellets and then added to the virgin plastic (or another product), which then can be used for the same or an alternative use[14]. However, this technique cannot be used to recover thermosetting polymers (like epoxy or unsaturated polyester resins), because of their crosslinked nature[15].

The first step for most commercial plastics wastes is the sorting of materials into different components[16]. After sorting, sometimes the waste quality is not enough to justify a reprocessing step and so, reusing them into solid particles for bitumen, concrete or asphalt would be a cheap and effective solution[14]. Other reported uses included their use as reducing agents or binders[17,18] as well as designed blends where the quality is good enough but enhancing circularity[19]. In the case of blends, their processability is enhanced and properties are more versatile, problems of chemical incompatibility and of physical in- homogeneity of different plastics may arise. Brittleness, discoloration or yellowness, loss of optical clarity or degradation of mechanical properties are common issues[15].

Although ABS itself can be recycled through thermal or mechanical methods[20], for WEEE materials, solvents are commonly needed for a chemical recycling[21]. In the automotive and electronic sectors, Plastic components are employed in visible applications, where design plays an important factor in the consumer's decision and for that, they are commonly coated with paints or varnishes that improve their appearance and their resistance to external agents. Coatings are an additional stone on the recyclability path, as they are designed to be strongly attached to the substrate surface and resist aggressive conditions[22,23]. To allow its reuse, the coating must be separated from the component, adding an additional cost than just a mere mechanical recycling. However, it is very hard to eliminate all the coating impurities before the recycling process.

Several studies showed that impurities decrease the mechanical properties of the recycled materials, preventing its use on demanding applications[24–27]. This could have implications for the industry, due to the lack of repeatability from lot to lot with recycled polymers, which would result in injury or warranty issues for the company, leading to money loss. For that reason, the highly technological sectors, such as the automotive industry, have been reluctant to use large amounts of recycled plastic, fearing a significant reduction of the material performance and thus, making, painted parts virtually not recyclable. Indeed, recycling can affect the visual appearance of the resultant material, giving additional problems[28]. It was reported that even 1 wt.% of a polymeric impurity in composites, causes unacceptable reductions in impact resistance and ductility[29]. Such a challenge is of industrial importance and could lead to massive improvement in the use of recyclable materials in the automotive and electronic sectors. Besides impurities, several factors can still affect the final properties of the recycled materials. The ageing of the material at the end-of-life, the number of reprocessing cycles or the amount of recycled material can all negatively impact the performances of the material[23,25,30–33].

In the present study, a comprehensive assessment was done to evaluate the effect of each of those factors (ageing, reprocessing cycles and coating impurities) and a cross-combination of those which showed higher impact, to provide an insight about the factors influencing the performance of a recyclable material. The results provide a better knowledge of the recycling effect and can be used to decide the potential applications of recycled plastic. The ascribed project (DECOAT) aims to develop efficient systems to remove coatings at the end-of-life of the part, to reduce the damage and promote the use of recycled material in high-tech applications. Being part of a European project with industrial application, gives clear proof about the importance of close working environments between research entities and companies, giving results that impact on the society.

Methods

The assessment was done for 2 industrial use-cases:

- Automotive use-case: A rear door garnish made of ABS coated with a solvent-based primer, a black paint and a clear coat provided by Maier S. Coop (Gernika, Spain).
- Electronic use-case: A socket part made of ABS/PC coated with a water-based anthracite paint provided by Panasonic (Istanbul, Turkey).

To perform the present study, the mentioned polymers were ABS Elix H605 Black (Elix polymers, Tarragona Spain) and ABS/PC Lupoy HT5007A White (LG Chem, South Korea). Polymer pellets where dried before injecting it with a WITTMANN DRYMAX E30 (Viena, Austria) and their moisture was measured with a Brabender Moisture meter AQUATRAC® - 3E (Germany). The granulator machine used was a WITTMANN G-MAX 23. The mixture of virgin and recycled pellets (after granulation) or painted pellets was done with a Vrieco-Nauta® laboratory mixer (HOSOKAWA MICRON B.V., Doetinchem, Netherlands)

Processing temperatures were determined according to the technical data sheet (TDS) of the selected polymers (220–240°C for ABS and 240–270°C for ABS/PC) with a mold temperature of 70°C for both cases. The studied cases were molded using an injection molding machine Engel Victory 350Tn (ENGEL, Austria), to obtain 3 kinds of samples according to the testing needs: Tensile strength (ISO-527-2 type A), impact strength (ISO-179-2) and plates of 110×160×3 mm. Average value and standard deviation of 5 samples were reported. When required, the samples were coated with their corresponding paint, according to the supplier. The injection parameters were as follows:

- For ABS, a temperature of 220–240°C for the plastificator part and 70°C for the mold. Pressure was 65-70/25-30/7 Kg/cm^2 (injection/post-pressure/counterpressure). The total time for injection (including all steps) was around 60 s.
- For ABS/PC, a temperature of 240–270°C for the plastificator part and 70°C for the mold. The injection machine conditions were 60-65/20-25/7 Kg/cm^2 (injection/post-pressure/counterpressure). The total time for injection (including all steps) was around 50 s.

Due to the requirements of this project, a single-screw injection machine was used. However, it must be punctuated that a single-screw extruder should not be used to melt-blend components, as it lacks sufficient shear forces for proper mixing. On the other hand, it is known that twin-screw cause more thermomechanical degradation.

The study was divided into two different methods, focusing on the impact of the ageing, reprocessing cycles, recycle content and amount of coating impurities on the properties of the case materials.

1.1. Method to assess the properties of the material at the end-of-life: effect of the ageing

In a real-life scenario, the parts presumed to be recycled are already damaged due to the exposure to different environmental conditions (temperature, moisture, sun irradiation, etc.) during several years along its lifetime. For that reason, the material is already in an aged state before the start of the recycling process. Commonly, an aged material has presumably lower mechanical properties than the pristine one[30,31]. To evaluate this loss of properties, ABS and ABS/PC samples were exposed to accelerated ageing tests (Figure 1), following the standard of the automotive and the electronic sector, respectively. After the ageing, the samples were tested to determine the tensile modulus and the impact resistance of the material, respectively. The use cases are depicted below:

- For the automotive use-case, DIN 75220 standard for exterior parts was followed, outlining the process of

simulating prolonged solar radiation exposure. The tests consist of alternating 10 dry cycles (including irradiation) with 5 humid cycles, for a total of 15 days of accelerated ageing. The exposure was done in a climatic chamber FITOTERM 14.000 (Figure 1A).

- For the electronic use-case, samples were exposed to 70 °C during 168 h in an oven (Figure 1B), following an internal standard from Panasonic.

1.2. Method to determine the effect of the recycling process on plastic material

During the recycling process of coated parts proposed in this study, we identified different factors that can affect the properties of the material. Table 1 summarize the parameters tested for each factor. For each factor, tensile and impact strength were reported. A factorial design resume is shown in the supporting information (**Table S1 and S2**)

▪ **The mechanical recycling process itself:**

The recycling process consists of several steps of reprocessing. First, the material parts are transformed into shredded material. Then, they are mixed with virgin one at different proportions according to the desired recycled content (15, 30, 50 and 100%). Last, the material is injected to prepare the test samples according to the standards. Following this procedure, the pressure, shear, and temperature during the reprocessing can shorten the polymeric chain, affecting the mechanical properties[22,29]. Since a circular approach is aimed, we evaluated the properties after five reprocessing cycles and different recycled contents (Figure 2).

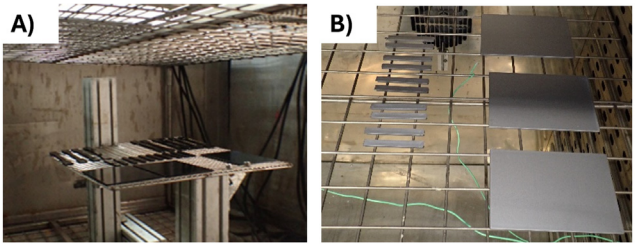

Figure 1. A) ABS samples into the climate chamber **B**) ABS/PC samples into the oven.

▪ **The remaining coating impurities:**

Most of the recycling procedures are not perfectly efficient, therefore some coating impurities can remain in the plastic substrate, affecting its properties[23,25]. In this case, mostly acrylic impurities from paint residues could be expected. To reproduce this situation, plastic pellets were coated and then mixed with virgin pellets, controlling the weight of coating that was introduced in the mixture (Figure 3). It was calculated that the automotive part (ABS) has 1,92 wt.% of coating and the electronic part (ABS/PC) has 0,40 wt.% respectively. Therefore, those proportions were considered as 100% coating impurities, corresponding to an untreated part.

▪ **Combined effect of reprocessing and coating impurities:**

Through the previous factors presented above, it was noted that the reprocessing of the material and the presence of coating impurities could have a big impact on the mechanical performance of the plastic product. For that reason, to study those combined effects, ABS and ABS/PC pellets were coated as in the process showed in Figure 3 (5, 10 and 20% of remaining coating impurities) and then subjected to a five-cycle reprocessing process. The aim of this analysis is to determine the possible synergistic effect between these recycling factors.

Results

Effect of the ageing on the mechanical properties of the material

Specimen samples were manufactured following the procedure explained in section 3 and then tested for tensile and impact strength. Five test samples were tested per material and their average was reported. As shown in Table 2, Aged ABS showed a significative loss of properties on both tensile modulus and impact resistance (**Figure S1, see *Extended data***), decreasing 12.3% and 18.8% respectively in comparison to virgin ABS. On the other hand, aged ABS/PC was also damaged by such process, with a loss of properties of 4.9% and 17.0% for tensile modulus and impact resistance, respectively (**Figure S2, see *Extended***

Table 1. Design of experiment to evaluate the effect of the recycling process proposed in this study.

	FACTOR 1. Mechanical recycling	FACTOR 2. Coating impurities	FACTOR 3. Combination of factors
Purpose	To determine the recycled content and n° of cycles with the best compromise between environmental impact and material performance	To determine the maximum remaining coating content to guarantee the circularity and effectiveness	To determine the impact of both effects (impurities and reprocessing) on the recyclability of the material
Variables	- Recycled content (15%, 30%, 50%, 100%) - N° of reprocessing cycles: 1 to 5	0.5%, 1%, 3%, 10%, 25%, 50% and 100% of remaining coating respect to a fully painted part.	- 5%, 10% and 20% of coating impurities - 1–5 reprocessing cycles

data) in comparison to pristine ABS/PC. The change in tensile modulus for ABS/PC is not significant as showed by the statistical data showed in the supporting information document and in Table 3. ABS suffered a higher degradation on its properties than the ABS/PC blends. This is explained by the lower UV radiation resistance of ABS due to the double bonds of the butadiene unit, whereas PC is relatively stable to the light[34]. Also, the higher tensile performance and Tg of PC, results on a higher resistance to thermal degradation than ABS, thus improving the overall properties in the blend. On top of that, it can be observed a higher damage on the impact resistance performance than in the tensile modulus in both ABS and ABS/PC. This is due to surface degradation upon ageing, mostly on the polybutadiene phase of the polymer. Ageing leads to chain scission and cross-linking, that restricts the polymer chain mobility and decreases the free volume, resulting in an increase of the Tg upon ageing, whereas the effect on the styrene-acrylonitrile phase is less significant[31,35]. It can be observed that automotive and electronic parts following an ageing process, suffer enough loss of mechanical properties. These results showed the importance of the ageing studies on automotive and electronic parts in the mechanical and life cycle analysis of these products.

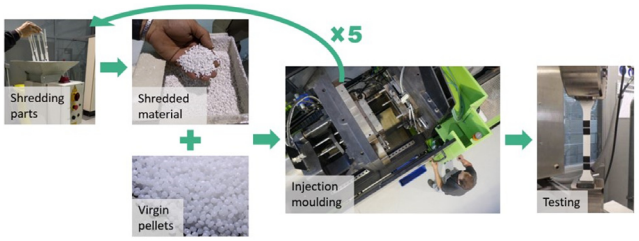

Figure 2. Experimental procedure to evaluate the mechanical recycling effect on the properties of plastic.

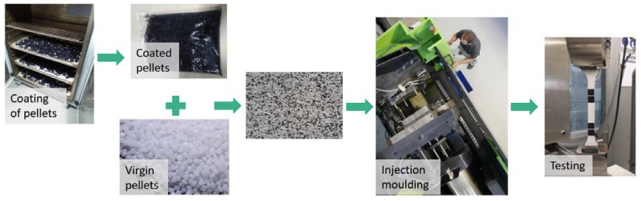

Figure 3. Experimental procedure to evaluate the effect of coating impurities.

1.3. Effect of the recycling and purification process on the mechanical properties

■ Assessment of the mechanical recycling effect

Samples were manufactured following the procedure explained in section 3.2 and then tested for tensile and impact strength. Five test samples were tested per material and their average was reported. Average values of tensile modulus are plotted in Figure 4 and Figure 5 for ABS and ABS/PC respectively. For recycled ABS, the tensile modulus remains very stable and close to the reference showed in Table 2 (1st cycle of 100 % recycled material), regardless of the recycled content nor the number of reprocessing cycles (Figure 4). These results showed the excellent behavior of ABS as a recyclable material for the automotive sector. It is not statistically significant the difference in

Table 2. Tensile modulus and impact resistance results of test specimens after ageing tests.

Test samples	ABS-ref	ABS-After automotive ageing	ABS/PC-ref	ABS/PC-After electronic ageing
Tensile modulus (Mpa)	2407.4 ± 84.8	2110.6 ± 131.4	2276.5 ± 159.7	2165.7 ± 118.0
Impact resistance (KJ/m^2)	18.43 ± 0.25	14.97 ± 0.32	50.53 ± 2.00	41.93 ± 1.77

Table 3. ANOVA statistical studies for tensile studies.

Test performed	ANOVA test (one factor)	F value	Critical F value	P-value (<0.05)
Tensile ageing test	ABS	20.74	4.67	0.00054073
	ABS/PC	2.34	4.67	0.15004974
Tensile mechanical recycling test	ABS	2.91	3.24	0.06685515
	ABS/PC	57.85	3.24	0.00000001
Tensile modulus-Coated and reprocessed	ABS	1.73	3.89	0.21847025
	ABS/PC	0.04	3.89	0.96443924

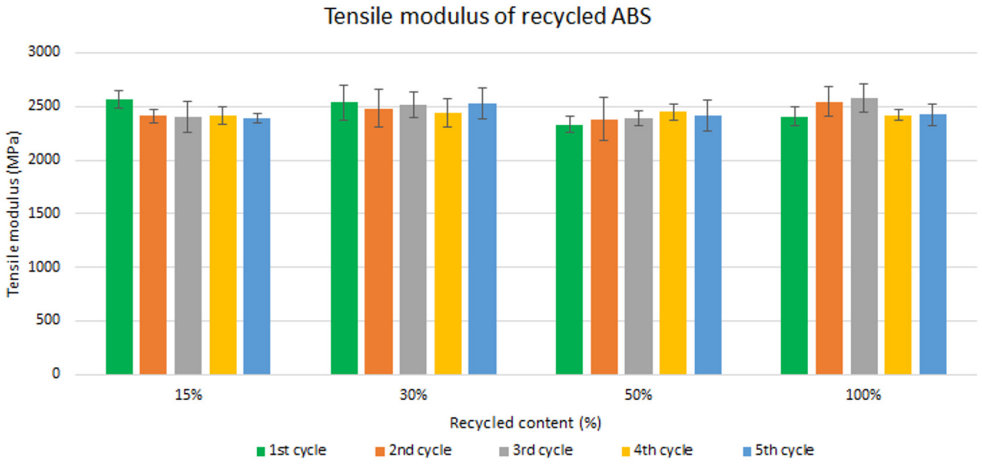

Figure 4. Effect of recycled content and reprocessing cycles on the tensile modulus of ABS.

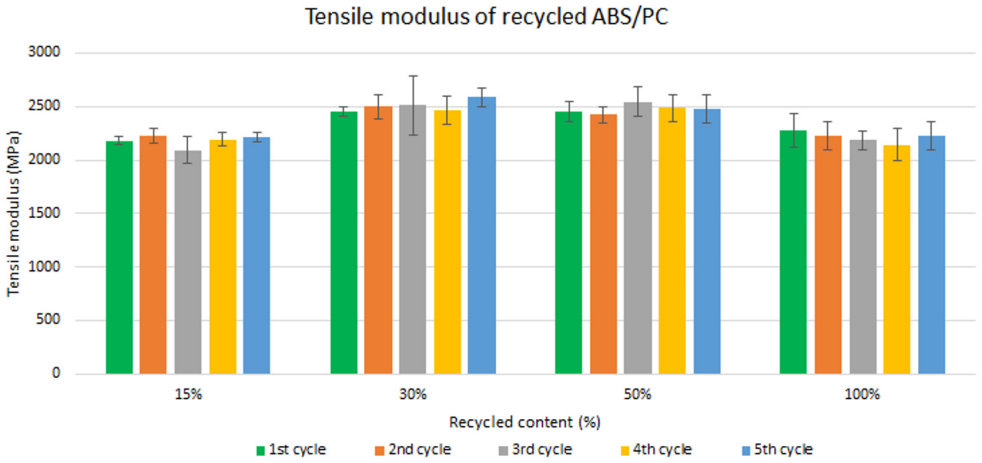

Figure 5. Effect of recycled content and reprocessing cycles on the tensile modulus of ABS/PC.

ABS tensile modulus results, as showed in the Table 3. Regarding ABS/PC for electronics, the effect of the recycling content and different injection cycles on the tensile strength showed a positive impact (Figure 5). Like ABS alone, the values of ABS/PC remain close to the reference one (Table 2). Notably, an initial increase (about 10%) of the tensile modulus with the introduction of increasing content of recycled material was observed. It was reported that changes in the orientation of the polymeric chains at the macromolecular scale could lead to bear increasing loadings during the test[36]. The reprocessing effect showed as well increasing values with a slightly higher impact than ABS alone. Degradation caused by several injections could produce a reduction in the mean distances and the length of the PC macromolecular chains, thus increasing the Van der Waals interactions and leading to an increasing tensile strength[37]. Despite this, it is expected a reduction on the mechanical performance after more than 5 cycles due to the continuous degradative process[38].

Unlike the tensile strength, impact resistance performance changes especially with each reprocessing cycle. Five test samples were tested per material and their average was reported. Average values of charpy impact resistance are plotted in Figure 6 and Figure 7 for ABS and ABS/PC respectively. In both materials, the impact of increasing recyclable content is almost negligible, although the presence of recyclable content decreases the performance in comparison to the reference Table 2. The impact resistance dropped on average by 5.9% for ABS and 14.5% for ABS/PC when recycling content is introduced. On the other hand, the impact of the reprocessing cycles is of significance. The first cycle of each recycled content for ABS keeps similar strength as the reference (Table 2). However, after

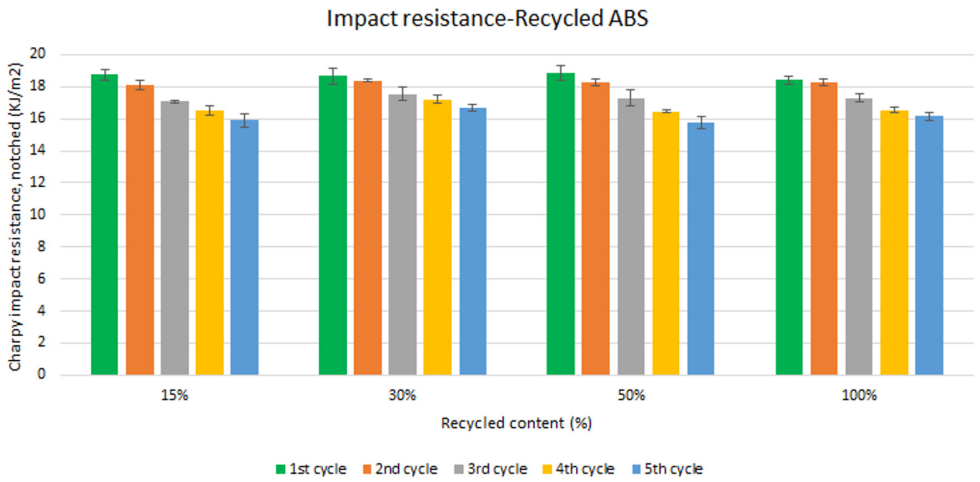

Figure 6. Effect of recycled content and reprocessing cycles on the impact resistance of ABS.

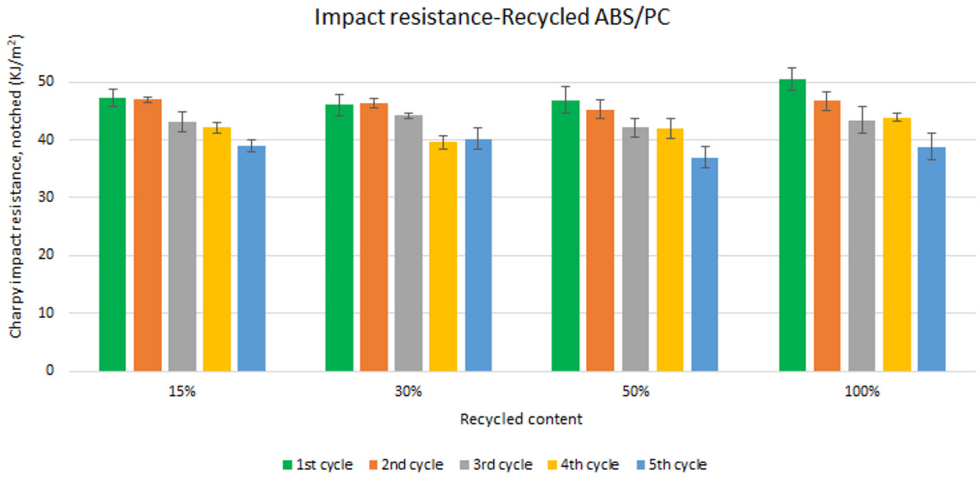

Figure 7. Effect of recycled content and reprocessing cycles on the impact resistance of ABS/PC.

each additional cycle, the performance drops dramatically, decreasing up to 12.5% on average for the 5th cycle (Figure 6). In the case of ABS/PC, the loss of performance due to the reprocessing cycles is even more dramatic than in the ABS case. ABS/PC losses impact resistance from the first reprocessing cycle and drops 23 % on average after 5 cycles (Figure 7). On the other hand, ABS/PC seems to show higher stability on the first two reprocessing cycles regardless of the recycling content but drops abruptly after the 3rd cycle. The loss of mechanical properties in ABS is often attributed to thermo-oxidative degradation in the polybutadiene phase only, whereas additional physical ageing can also occur in the styrene-acrylonitrile phase[39]. The polymeric degradation of ABS is thermodynamically favorable after periods of exposure to heat and oxygen (such as after reprocessing), leading to a deterioration of the mechanical properties[40]. Commonly, the introduction of PC leads to a higher stability upon reprocessing[41,42]. However, it was reported that the decrement of strength with reprocessing might be attributed to the decrease of the molecular weight and chain scission. Broader chain length distribution and shorter chain induced poor chain entanglements, and consequently, the impact strength dropped with increasing reprocessing[3]. Further studies including thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) techniques could give more information about the degradation of the material with the increasing reprocessing cycles.

■ Assessment of the coating impurities effect

Samples were manufactured following the procedure explained in section 3.2 (Figure 3) and then tested for tensile and impact

strength. Results are showed in Table 4, and **Figures S3** and **S4** (**see *Extended data***). Five test samples were tested per material and their average was reported. Regarding ABS, the tensile modulus decreases when coating impurities are present. For coating contents from 0.5 to 50%, the tensile modulus decreases 12% on average. With 100% of remaining coating, it decreases 16%. For ABS/PC, the effect of coating impurities on the tensile modulus is not clear, since there is a huge variability of data which is more evident with the higher impurity content. However, a slight decrease in the performance can be presumed. For the impact resistance, again, a clear relationship was found between the amount of coating impurities and the performance of both ABS and ABS/PC. Both ABS and ABS/PC can retain its properties when the coating impurities fall below 3% compared to the neat material. However, with full coating (100% impurities) decreases the impact resistance of ABS and ABS/PC by 42% and 28%, respectively. It can be thus noted the better performance of ABS/PC with respect to ABS. According to the trend curves, it is enough with 14.2% and 21.2% of the remaining coating impurities to lost about the 10% of the performance of the reference ABS and ABS/PC, respectively. The presence of coating impurities had a very large impact on the mechanical properties. It was reported that these impurities usually have different dimensions and produce an inhomogeneous structure with weak mechanical points, which resulted in local cavitation and higher stress for the ABS matrix that allows an easy breakage[7,26,43]. Further studies including scanning electron microscopy (SEM) analysis for the microstructure of the polymers would be recommendable. This result shows the importance of a good cleaning process before the start of a recycling procedure.

▪ Assessment of the combined effect of coating impurities and reprocessing cycles

Specimen samples were manufactured following the procedure explained in section 3.2 and then tested for tensile and impact strength. Five test samples were tested per material and their average was reported. Results for ABS analysis are shown in Figure 8 and Figure 10 whereas for ABS/PC are shown in Figure 9 and Figure 11. The data for the tensile modulus

Table 4. Tensile modulus and impact resistance of ABS with varied coating impurities (%).

Material	Mechanical performance	Coating impurities (%)							
		Ref	0.50%	1.00%	3.00%	10.00%	25.00%	50.00%	100.00%
ABS	Tensile modulus (Mpa)-Avg	2407.4 ± 84.8	2129.2 ± 124.8	2120 ± 159.0	2119.8 ± 263.4	2155.6 ± 21.9	2090.1 ± 98.1	2147.1 ± 73.5	2025.8 ± 231.9
	Impact resistance (KJ/m²)-Avg	18.43 ± 0.25	17.98 ± 0.18	18.53 ± 0.45	18.38 ± 1.89	17.6 ± 0.27	14.73 ± 0.4	13.13 ± 0.4	10.7 ± 0.28
ABS/PC	Tensile modulus (Mpa)-Avg	2276.5 ± 156.7	2333.5 ± 219.6	2119.5 ± 84.8	2176.4 ± 330.5	2171.9 ± 91.8	2203.3 ± 128.0	2191 ± 118.3	2431.5 ± 173.6
	Impact resistance (KJ/m²)-Avg	50.53 ± 2.00	49.22 ± 2.07	49.08 ± 1.65	51.11 ± 1.73	46.09 ± 1.81	44.87 ± 1.37	41.26 ± 1.02	36.49 ± 1.11

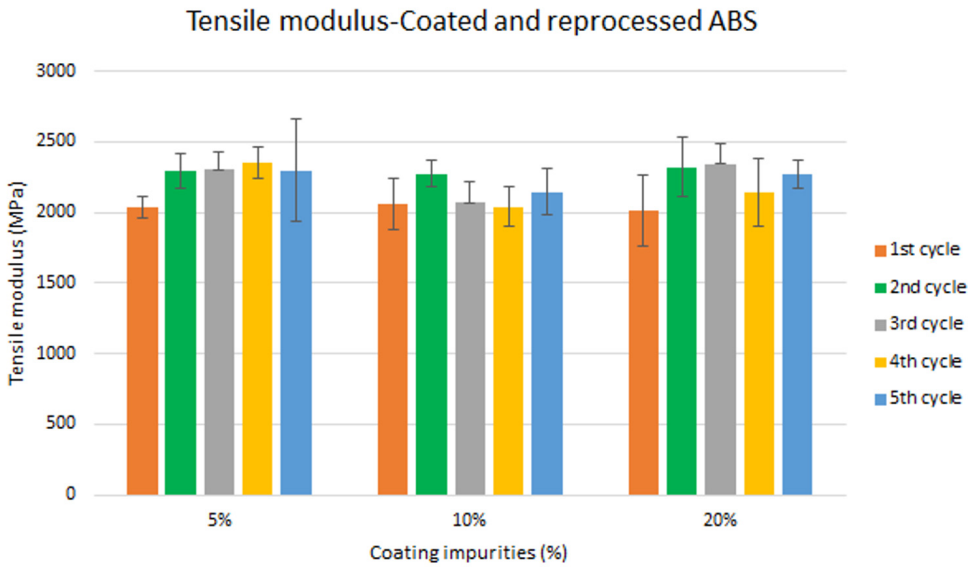

Figure 8. Combined effect of reprocessing cycles and coating impurities on the tensile modulus of ABS.

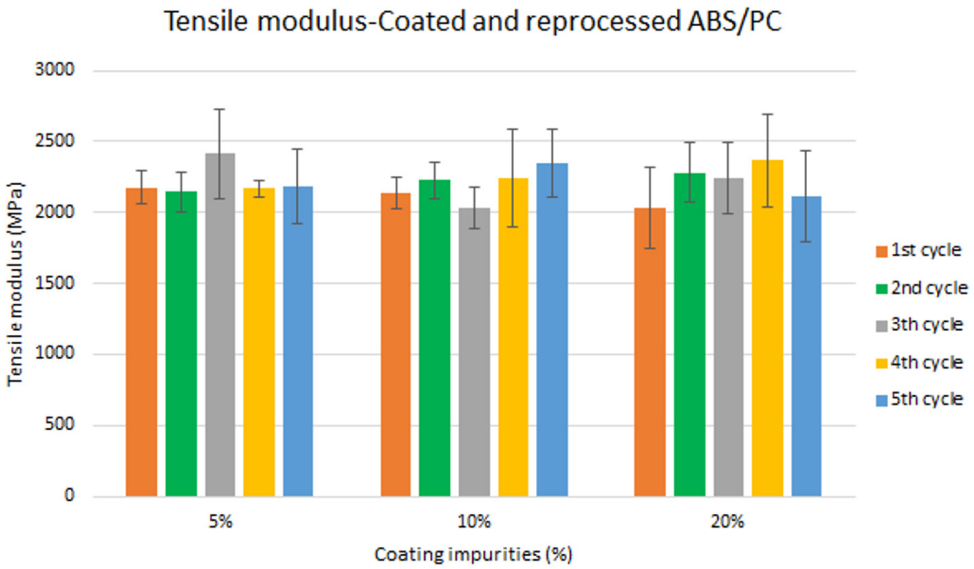

Figure 9. **Combined effect of reprocessing cycles and coating impurities on the tensile strength of ABS/PC.**

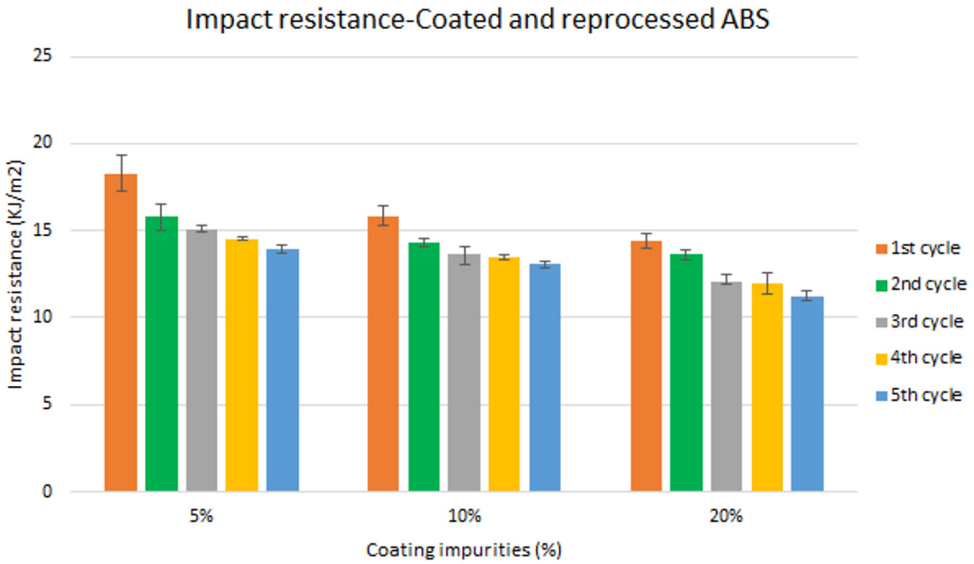

Figure 10. **Combined effect of reprocessing cycles and coating impurities on the impact resistance of ABS.**

and impact resistance of ABS showed a general drop on the properties of the material with increasing reprocessing cycles and coating impurities. ABS decreased on average 9% and 24% for the tensile and impact strength respectively. This result implies a higher effect on the impact resistance than in the tensile modulus. Nonetheless, the combined factors showed no synergistic effect, being the effect of the coating individually, the one with probably higher contribution. In the case of ABS/PC, the performance decreased on average by 3.0% and 15% for the tensile and impact strength respectively. ABS/PC retained notably its properties in comparison to ABS. In the same way as ABS, no synergistic effect was found. One possibility to explain this lack of synergistic degradative effects could be on the impurities size and distribution. As the materials are reprocessed, the impurities could be distributed homogeneously due to the temperature and shear stress of the process, thus reducing its size. As the impurities size diminishes, the local stress increases due to the interaction between the polymer molecules, leading to a reduced effect of coating impurities on the impact strength decrease[43].

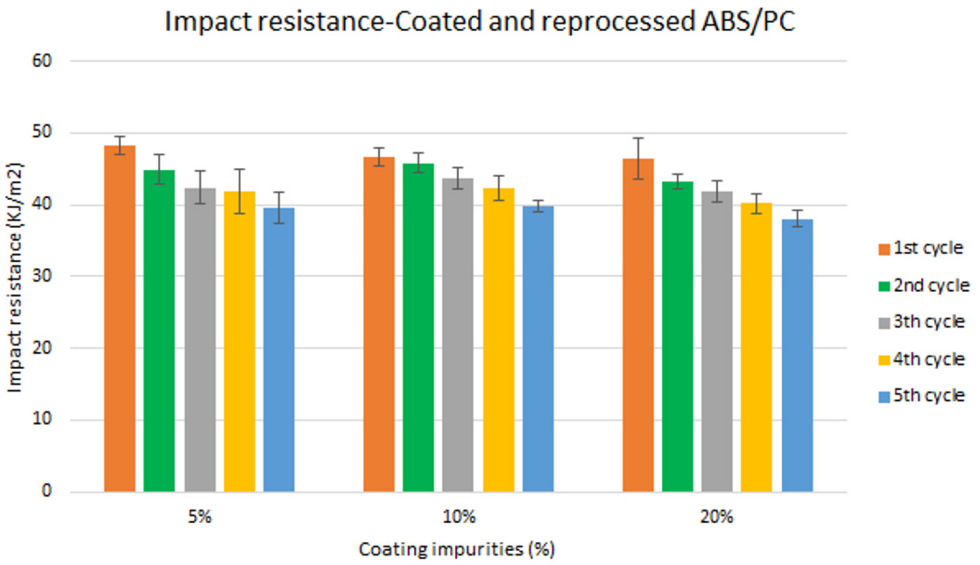

Figure 11. Combined effect of reprocessing cycles and coating impurities on the impact resistance of ABS/PC.

• Statistical studies for tensile strength of testing materials:
An ANOVA test (one factor) was performed to check if the average values reported are statistically different from each other. Herein the statistical data for the tensile strength of ABS and ABS/PC testing probes will be shown. It can be seen that the F value is higher than their corresponding critical value in the cases of ABS for the ageing test (Figure S1) and in the ABS/PC for the mechanical recycling effect (Figure 5). Indeed, the P-values are <0.05 in the same cases. This indicates that the averages are significantly different in these cases. In the cases where the averages are not significantly different, this could be a result of using a single screw injection machine and not using a twin screw, resulting in little chain scission.

Conclusion

A comprehensive assessment of the mechanical properties of recycled materials was done during this, isolating different factors that can potentially damage the polymers and therefore, limit their application in high-tech sectors such as automotive and electronic industries. Through ageing tests, it was demonstrated that a part to be recycled is already damaged by years of environmental exposure. Therefore, the recycling process should have almost no impact to avoid even more degradation.

- Mechanical recycling showed that ABS and ABS/PC are stable after the first reprocessing cycle, regardless of the recycled content, but a loss of properties is reported after 2 cycles or more, affecting mostly the impact resistance.
- In coated parts, the coating impurities were proved to be very pernicious in terms of mechanical properties, especially for the impact resistance. These impurities must be eliminated allowing only almost <10 % impurities to retain the mechanical performance.
- The analysis for the combination of both previous factors showed no synergistic effect between the degradative processes. Impact resistance was the one with a high depletion on its performance.

From this study, it is encouraged by the importance of a high-performance cleaning process that avoids the presence of coating impurities in the recyclable material in order to ensure the use of recyclable products into high-end industries like automotive and electronics.

Data availability

Underlying data

The raw data cannot be made public since it is within the non-disclosure agreement (NDA) signed by the Consortium. The reader should apply for individual access to the data directly with vanesa.ventosinos@ctag.com.

Data are available for readers under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Extended data

[Repository]: Supporting information, images and documents: 10.5281/zenodo.15544574

This project contains the following extended data:

- Supporting information - Figure S1, Figure S2, Figure S3, Figure S4 and Table S1 and S2.

Data are available under the terms of the Creative Commons Zero "No rights reserved" data waiver (CC0 1.0 Public domain dedication).

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Open Peer Review

Current Peer Review Status: ? ✓ ✓ ✓

Version 4

Reviewer Report 24 March 2026

https://doi.org/10.21956/openreseurope.22264.r59790

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✓ **Jude Shalitha Perera**
The University of Melbourne, Melbourne, Australia

No further comments

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Consumer and kerbside plastic recycling and material recovery process.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 3

Reviewer Report 21 May 2025

https://doi.org/10.21956/openreseurope.21721.r50964

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? **Jude Shalitha Perera**
The University of Melbourne, Melbourne, Australia

The article presents a well-designed experimental program and results to study the effect of *paint* coating on recycling cycles. The writing is clear and scientifically sound. However, the reviewer believes that the literature on the effects of recycling cycles is not sufficiently covered in the introduction. There is a lack of recent, relevant studies on recycling of other types of plastics,

which would help provide the reader with a clearer understanding of the current state of research in this area. Also note the following corrections.
Abstract : correct "resistance)" to "resistance"
Introduction : 9.9 and 6.2 %, respectively
Methods: 1. explain the acronym TDS
2. Details regarding the tensile and impact tests are insufficient. The manuscript should specify the testing standards followed (e.g., ASTM or ISO), the sample dimensions and preparation methods, the type and model of equipment used, and the testing conditions. Providing this information is essential for the reproducibility and validation of the experimental results.

Is the background of the case's history and progression described in sufficient detail?
Yes

Is the work clearly and accurately presented and does it cite the current literature?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Is the case presented with sufficient detail to be useful for teaching or other practitioners?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Consumer and kerbside plastic recycling and material recovery process.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 30 May 2025

Denise GARCÍA MURIAS

- **Suggestion 1: literature expansion in introduction:**

Thanks for the suggestion. The introductory section has now included more recent literature from reviews and individual studies where it is discussed the current state of recycling techniques and their uses after recycling as well as the effects of several reprocessing (brittleness, color changes, etc.).

- **Suggestion 2: Abstract and introduction correction:**

Thanks for the corrections. Now they have been changed in the new document version.

- **Suggestion 3: methods. TDS explanation:**

Thanks for the suggestion. Now it has been explained in the new document version (technical data sheet).

- **Suggestion 4: Methods: Test detailed:**

Thanks for the comment. In the methods section, there were already explained the standard tests for tensile strength (ISO-527-2 type A), impact strength (ISO-179-2) and dimensions of the plates of 110×160×3 mm. Indeed, their pretreatment to avoid moisture influence was shown as well as the equipments used: "*Polymer pellets where dried before injecting it with a WITTMANN DRYMAX E30 (Viena, Austria) and their moisture was measured with a Brabender Moisture meter AQUATRAC® - 3E (Germany)*." Also, it was said that they were molded using an injection molding machine Engel Victory 350Tn (ENGEL, Austria) and their injection parameters. Please check the text as shown in the document: *Processing temperatures were determined according to the technical data sheet (TDS) of the selected polymers (220–240°C for ABS and 240–270°C for ABS/PC) with a mold temperature of 70ºC for both cases. The studied cases were molded using an injection molding machine Engel Victory 350Tn (ENGEL, Austria), to obtain 3 kinds of samples according to the testing needs: Tensile strength (ISO-527-2 type A), impact strength (ISO-179-2) and plates of 110×160×3 mm. Average value and standard deviation of 5 samples were reported. When required, the samples were coated with their corresponding paint, according to the supplier. The injection parameters were as follows:*

- *For ABS, a temperature of 220-240°C for the plastificator part and 70°C for the mold. Pressure was 65-70/25-30/7 Kg/cm ^{2} (injection/post-pressure/counterpressure). The total time for injection (including all steps) was around 60 s.*
- *For ABS/PC, a temperature of 240-270°C for the plastificator part and 70°C for the mold. The injection machine conditions were 60-65/20-25/7 Kg/cm ^{2} (injection/post-pressure/counterpressure). The total time for injection (including all steps) was around 50 s.*

Due to the requirements of this project, a single-screw injection machine was used. However, it must be punctuated that a single-screw extruder should not be used to melt-blend components, as it lacks sufficient shear forces for proper mixing. On the other hand, it is known that twin-screw cause more thermomechanical degradation. The study was divided into two different methods, focusing on the impact of the ageing, reprocessing cycles, recycle content and amount of coating impurities on the properties of the case materials.

Competing Interests: No competing interests were disclosed.

Reviewer Report 11 April 2025

https://doi.org/10.21956/openreseurope.21721.r52571

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Dylan Jubinville
University of Waterloo, Waterloo, ON, Canada

I would like to thank the authors for their patience with the process and for accommodating my request/attempts to enhance this manuscript.

All the best with future work!

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Polymer chemistry, polymer recycling, bioplastics, sustainable composites, advanced characterization, 3D printing, melt blowing, polymer and rubber foaming.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 07 April 2025

https://doi.org/10.21956/openreseurope.21721.r52572

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Peng Gao
Western Washington University, University of Massachusetts Lowell, Bellingham, USA

I have checked the revision and the authors address all my comments. I think the quality of the manuscript meets the indexing standard of the journal

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Biopolymers, Injection molding, plastic sustainability, mechanical recycling, crystallization and morphology

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 2

Reviewer Report 04 March 2025

https://doi.org/10.21956/openreseurope.20572.r51272

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?

Peng Gao
Western Washington University, University of Massachusetts Lowell, Bellingham, USA

Please find some minor suggestions below:

Typo: Methods: ABS/PC (LG Chem, South **Korea**)

Methods: Did the authors dry the materials before molding? For both ABS and PC-ABS, removing moisture is critical for obtaining high mechanical performances.

Image quality of Figure 2 and 3 are low on my end, please double check and verify.

Methods: I suggest the author to include a DOE table at the end of the section. The combination of factors are unclear to me. Under FACTOR 1 described in Table 1, there are 2 individual factors have 4 and 5 different levels. Did the author perform a full-factorial design of all individual factors?

Results: Table 2, tensile modulus is missing its unit.

Results: Section 1.3, I suggest the authors to present p-values or factorial plots in the main text to show factors being significant or not.

Is the background of the case's history and progression described in sufficient detail?
Yes

Is the work clearly and accurately presented and does it cite the current literature?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Is the case presented with sufficient detail to be useful for teaching or other practitioners?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Biopolymers, Injection molding, plastic sustainability, mechanical recycling,

crystallization and morphology

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 26 Mar 2025

Denise GARCÍA MURIAS

- **Suggestion 1: Typo (South Korea):**

Thanks for the correction. Now it has been changed in the new document version v3.

- **Suggestion 2: Methods (Material drying):**

Thanks for the comment. It is mentioned in the document how the pellets were dried: "*Polymer pellets where dried before injecting it with a WITTMANN DRYMAX E30 (Viena, Austria) and their moisture was measured with a Brabender Moisture meter AQUATRAC® - 3E (Germany)*."

- **Suggestion 3: Figure 2 and 3 quality change:**

Thanks for the comment. Figures 2 and 3 have been included from the TIFF document in the repository (10.5281/zenodo.14999538) with higher quality. We have also included the other images in a higher quality.

- **Suggestion 4: Methods: DOE table**

Thanks for the comment. According to your suggestion, we have decided to include a DOE table in the supporting information explaining how the factors and their levels affect the material's performance. We did not perform a full factorial design but a simple design in which we could study all the factors and their levels individually. Then, we obtained the result that coating and reprocessing could have an important effect combined. For that reason, our aim here was to evaluate a possible synergistic effect between those combined factors in one simple answer. *As it can seen in these tables, we could perform a simple evaluation of these factor to obtain an outcome that is consistent with our conclusion, which is that coating impurities have a very high impact on the final performance of recycling materials and so, it is very important to clean the materials prior to the start of the recycling process.*

- **Suggestion 5: Table 2 missing units**

Thanks for the correction. Now it has been changed to the new document version v3.

- **Suggestion 6: Section 1.3**

Thanks for the suggestion. It was made before an ANOVA test for all the tensile tests (see supporting information) to ensure the significance of the results. The restuls from these analysis was introduced in the novel version v3.

Competing Interests: No competing interests were disclosed.

Reviewer Report 21 February 2025

https://doi.org/10.21956/openreseurope.20572.r50877

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?

Dylan Jubinville
University of Waterloo, Waterloo, ON, Canada

I would like to thank the author(s) for completing my revisions. The revisions were well incorporated, and the comments were clear.

However, my main concern remains largely unchanged, leaving me uncertain about how to proceed. Single-screw extruders are rarely used by plastic recyclers for mixing multiple components, though they may be used for recycling a single polymer type (e.g., upcycling).

A single-screw extruder should not be used to melt-blend components, as it lacks sufficient shear forces for proper mixing. Without thermal r morphological analysis for correlation, I find it hard to see how the author(s) could confirm that the virgin and recycled components form a uniform when using a single screw. The authors correctly note that twin-screw extruders cause more thermomechanical degradation, but this reflects real-world conditions.

For acceptance, the authors should include a small statement regarding the limitations of using a single-screw extruder for mixing.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Polymer chemistry, polymer recycling, bioplastics, sustainable composites, advanced characterization, 3D printing, melt blowing, polymer and rubber foaming.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 26 Mar 2025

Denise GARCÍA MURIAS

Thanks for the valuable suggestion. A statement has been included in the methods section in page 5 in the novel version v3 to highlight the limitations of using single-screw extruders for this study.

Competing Interests: No competing interests were disclosed.

Version 1

Reviewer Report 14 August 2024

https://doi.org/10.21956/openreseurope.18250.r39863

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?

Dylan Jubinville
University of Waterloo, Waterloo, ON, Canada

The work for review presents a clear and interesting approach to the global issue of waste accumulation by focusing on ABS, PC, and blends in the forms of virgin and post-consumer materials. The authors discussed the degradation of the plastic component may experience during its service life which more often results in a deterioration of results.

There are some grammar issues found throughout the paper but nothing too impactful that the paper's message is lost. Please ensure to give another read-through.

Please note, that the bolded numbered parts must be addressed for the article to be scientifically sound (as required by the reviewer form).

--Introduction --
The introduction was written clearly and with good flow.

1. **I would suggest adding a line for the specific production/waste or collection rate for ABS and PC plastics to strengthen why these two materials should be of focus.**

2. Polymer names are common nouns, and as such should not need to be capitalized, please finish on page 3 second paragraph. The capitalization may be just for the acronym but it is still an incorrect writing technique.

3. The authors state even 1 wt.% of impurity in ABS can cause unacceptable reductions in results however, this is usually the case for most polymers. I would suggest listing specific impurities in ABS processing or leaving it more general to most plastics.

4. I would argue high technology sector's hesitation to implement recycled compounds is due to the lack of repeatability from lot to lot with recycled polymers which would result in injury or warranty issues for the company, leading to money loss. This is opposed to just the materials' performance itself just decreasing the mechanical properties.

5. **The authors write that polymers and their properties all decrease as a result of aging however this is not true. If material crosslinks and branches as a result of degradation then viscosity and tensile strength increases. If the material is annealed, then the modulus and overall hardness increases. Please correct that statement on page 3 end of paragraph 2.**

-- Materials and Methods --

1. **Did the authors dry the PC and ABS/PC blends?**

    1. **ABS may be hydrophobic but PC is reported to be broadline and other papers have reported drying PC before processing.**

2. **Do the authors have the exact formulations for the 2 industrial case studies?**
    1. **The post-consumer parts can/be filled with a ton of additives to prevent aging which will offset the trend there were seen. As well, the date or production and or length of service will also have a significant impact on the properties of the post-consumer parts.**

3. Are PC and ABS compatible with one another in blending operations?

-- Results --
The results for this work are what would have been expected from this type of work. However, 2 major issues are present in this work.

1. **The material was seemingly "recycled" in an injection molding machine which is not an adequate method for studying this. It is not adequate because this type of recycling process (post-consumer (e.g. down cycling)) typically includes a twin screw extruder which imparts greater thermo-mechanical forces such as shear and heat compared to a single screw injection molding machine. In addition, the residence time in an extruder would be different when compared to an Injection molding machine. Also, if blending the recycled offsets into a virgin matrix via injection molding cause the results, in general, to be questioned as the mixing of the different constituents would be poor and not efficient as single screw set-ups are used to convey material from one end (feeding zone) to the other end (die). They are NOT to mix/blend like a twin screw set-up would.**
   The authors need to justify this for this manuscript to be accepted.

2. **The tensile strength results are not statistically significant and with the lack of mention I would assume no ANOVA was performed on these results. However, looking at the means of the results, show that these results are highly likely to all be statistically insignificant (FIG 4, 5, 8, 9). This is not bad, necessarily, as it just means the material is more stable but the results discussion needs to reflect the no significance in tensile results.**
   Please provide an ANOVA to prove your tensile results are significant.
   The lack of tensile results may be a result of "recycling" within a single screw and not using a twin screw resulting in little chain scission.

3. **With the last point, the ABS/PC ref to after aging electronic, I would argue is not significant. Please check with ANOVA.**

4. **To prove chain scission, molecular weight analysis through whatever means (GPC, DLS, rheology) should be included.**

5. **The authors are constantly flipping between tensile strength and modulus. I assumed this is all tensile strength but please look through the entire work and fix it.**

6. **Please include the standard deviation in Table 3.**

7. **Include 100% cycle 1 in bar graphs. The reader should not have to work to compare**

your results.

8. Was the supporting information file uploaded as well?
I could not locate it so please ensure you have uploaded it.

-- Conclusion --
No comment

-- Abstract --
Well written and concise - no other comment.

Is the background of the case's history and progression described in sufficient detail?
Partly

Is the work clearly and accurately presented and does it cite the current literature?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Is the case presented with sufficient detail to be useful for teaching or other practitioners?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Polymeric recycling, processing/compounding of blends and composites as well as polymer characterization (advanced/standard).

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 22 Nov 2024

Denise GARCÍA MURIAS

--Introduction --

1. **I would suggest adding a line for the specific production/waste or collection rate for ABS and PC plastics to strengthen why these two materials should be of focus.**

ANSWER: A paragraph has been included in the next version of the article submitted, within the introduction section, highlighting the waste and collection rates of these polymers.

1. Polymer names are common nouns, and as such should not need to be capitalized, please finish on page 3 second paragraph. The capitalization may be just for the acronym but it is still an incorrect writing technique.

ANSWER: Thanks for the comments, polymers nouns have been fixed accordingly (mainly found in the introduction) in the next version submitted.

1. The authors state even 1 wt.% of impurity in ABS can cause unacceptable reductions in results however, this is usually the case for most polymers. I would suggest listing specific impurities in ABS processing or leaving it more general to most plastics.

ANSWER: Thanks for the valuable suggestion. The reference was adjusted to show a more general view of the phenomena.

1. I would argue high technology sector's hesitation to implement recycled compounds is due to the lack of repeatability from lot to lot with recycled polymers which would result in injury or warranty issues for the company, leading to money loss. This is opposed to just the materials' performance itself just decreasing the mechanical properties.

ANSWER: Thanks for the suggestion, we introduced a comment highlighting this possible fact in the introduction.

1. **The authors write that polymers and their properties all decrease as a result of aging however this is not true. If material crosslinks and branches as a result of degradation then viscosity and tensile strength increases. If the material is annealed, then the modulus and overall hardness increases. Please correct that statement on page 3 end of paragraph 2.**

ANSWER: Thanks for the comment. We stated there are several factors that can affect the performance of the material at the EOL, ageing, impurities presence, reprocessing cycles and amount of recycled material. It does not mean they decrease; it means they “impact negatively” on the performance of the material where the modified properties resultant after they EOL could be probably not desired. -- Materials and Methods --

1. **Did the authors dry the PC and ABS/PC blends?**
    1. **ABS may be hydrophobic but PC is reported to be broadline and other papers have reported drying PC before processing.**

ANSWER: Yes, the materials were dried before the injection procedure. Polymers where dried before injecting it with a WITTMANN DRYMAX E30and their moisture was measured with a Brabender Moisture meter AQUATRAC® - 3E. This comment was included in the methods section.

1. **Do the authors have the exact formulations for the 2 industrial case studies?**
    1. **The post-consumer parts can/be filled with a ton of additives to prevent aging which will offset the trend there were seen. As well, the date or production and or length of service will also have a significant impact on the properties of the post-consumer parts.**

ANSWER: Thanks for the suggestion. Unfortunately, the exact formulations cannot be disclosure as they are commercial products belonging to a private consortium in a European project.

1. Are PC and ABS compatible with one another in blending operations?

ANSWER: Thanks for the question. For this project, the PC/ABS was selected from the commercially ones available in the market. In this case, a (PC + ABS) Lupoy HR5007A White specially used for injection molding was chosen. -- Results --

The results for this work are what would have been expected from this type of work. However, 2 major issues are present in this work.

1. **The material was seemingly "recycled" in an injection molding machine which is not an adequate method for studying this. It is not adequate because this type of recycling process (post-consumer (e.g. down cycling)) typically includes a twin screw extruder which imparts greater thermo-mechanical forces such as shear and heat compared to a single screw injection molding machine. In addition, the residence time in an extruder would be different when compared to an Injection molding machine.**
   Also, if blending the recycled offsets into a virgin matrix via injection molding cause the results, in general, to be questioned as the mixing of the different constituents would be poor and not efficient as single screw set-ups are used to convey material from one end (feeding zone) to the other end (die). They are NOT to mix/blend like a twin-screw set-up would.
   The authors need to justify this for this manuscript to be accepted.

ANSWER: Thanks for the question and explanation. We think that the reviewer is mostly right about his/her assumption. Our machine is an injection molding machine Engel Victory 350Tn. It consists of a single-screw injection molding machine. The procedure for testing the mechanical recycling effect was as follows, first, the material (recycled) was shredded into new small pieces and then mixed with virgin ones in a mixing machine. Then, they are injected again to manufacture new tests samples. We used this procedure as it was the common one for the recycling industry, being our intention to be a real simulation of the loss of properties only during this step. Although by using and extruder machine the mixing would be better, we did not use an extruder machine as we believe that this could bring additional thermo-mechanical stress to the material, making the comparison to the virgin material even harder and not aligned within the aim of the project. We introduced comments in the method section including the mixing machine we were using to obtain the pellets for injection.

1. **The tensile strength results are not statistically significant and with the lack of mention I would assume no ANOVA was performed on these results. However, looking at the means of the results, show that these results are highly likely to all be statistically insignificant (FIG 4, 5, 8, 9). This is not bad, necessarily, as it just means the material is more stable but the results discussion needs to reflect the no significance in tensile results.**
   Please provide an ANOVA to prove your tensile results are significant.
   The lack of tensile results may be a result of "recycling" within a single screw and not using a twin screw resulting in little chain scission.

ANSWER: Thanks a lot for the suggestions. We performed ANOVA (one factor variance) in the results from figures 4,5,8 and 9. The data from Figure 4 showed that there is not a significant variance on the results: ANÁLISIS DE VARIANZA *Origen de las variaciones Suma de cuadrados Grados de libertad Promedio de los cuadrados F Probabilidad Valor crítico para F* Entre grupos 33449.55 3 11149.85 **2.906305 0.0668551 3.238872** Dentro de los grupos 61382.96 16 3836.435 Total 94832.51 19 The data from Figure 5 showed that there is a significant variance on the results: ANÁLISIS DE VARIANZA *Origen de las variaciones Suma de cuadrados Grados de libertad Promedio de los cuadrados* ***F Probabilidad Valor crítico para F*** Entre grupos 439245.7 3 146415.2 **57.84654 8.28E-09 3.238872** Dentro de los grupos 40497.56 16 2531.098 Total 479743.3 19 For

Figure 8, results showed that there is not a significant variance: ANÁLISIS DE VARIANZA *Origen de las variaciones Suma de cuadrados Grados de libertad Promedio de los cuadrados* ***F Probabilidad Valor crítico para F*** Entre grupos 50705.5281 2 25352.7641 **1.73130012 0.21847025 3.88529383** Dentro de los grupos 175725.263 12 14643.7719 Total 226430.791 14 For Figure 8, results showed that there is not a significant variance: ANÁLISIS DE VARIANZA *Origen de las variaciones Suma de cuadrados Grados de libertad Promedio de los cuadrados F Probabilidad Valor crítico para F* Entre grupos 1082.1056 2 541.0528 0.03631791 0.96443924 3.88529383 Dentro de los grupos 178772.201 12 14897.6834 Total 179854.307 14 Based on this, a comment was included in the discussion showing this results and a sum-up table was included in the supporting information along with a brief discussion.

1. **With the last point, the ABS/PC ref to after aging electronic, I would argue is not significant. Please check with ANOVA.**

ANSWER: Thanks for the suggestion. We checked by analysis of variance (ANOVA) at 95% confidence level the results and found that whereas ABS showed important differences, ABS/PC performed in a more resilient way. ANÁLISIS DE VARIANZA-ABS tensile test *Origen de las variaciones Suma de cuadrados Grados de libertad Promedio de los cuadrados F Probabilidad Valor crítico para F* Entre grupos 293697.4541 1 293697.454 20.7431082 0.00054073 4.66719273 Dentro de los grupos 184064.3587 13 14158.7968 Total 477761.8128 14 ANÁLISIS DE VARIANZA-ABS/PC tensile test *Origen de las variaciones Suma de cuadrados Grados de libertad Promedio de los cuadrados F Probabilidad Valor crítico para F* Entre grupos 40924.3494 1 40924.3494 2.3400345 0.15004974 4.66719273 Dentro de los grupos 227354.144 13 17488.7803 Total 268278.494 14 As you can check above, the results for ABS are far more divergent than for ABS/PC. A comment was included in the “Effect of the ageing on the mechanical properties of the material” results part.

1. **To prove chain scission, molecular weight analysis through whatever means (GPC, DLS, rheology) should be included.**

ANSWER: Thanks for the suggestion. We agree that these tests could help to obtain better insights into the results. Unfortunately, these tests were not included into project proposal, and we do not have such techniques in our facilities portfolio.

1. **The authors are constantly flipping between tensile strength and modulus. I assumed this is all tensile strength but please look through the entire work and fix it.**

ANSWER: Thanks for pointing out this fact. We found that it is better to harmonize everything on “tensile modulus” and “impact resistance”. Following this, a revision was made through all the document and all images have been modified accordingly. **Please include the standard deviation in Table 3.**

ANSWER: Thanks for the suggestion. Table 3 was modified to include the standard deviation.

1. **Include 100% cycle 1 in bar graphs. The reader should not have to work to compare your results.**

ANSWER: Thanks for the valuable suggestion, Figures from 4 to 7 has been modified according to your comments.

1. Was the supporting information file uploaded as well?
   I could not locate it so please ensure you have uploaded it.

ANSWER: Yes, supporting information document was also included in the next version

submitted. -- Conclusion --
No comment

Competing Interests: No competing interests were disclosed.

Reviewer Report 10 June 2024

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Macaulay Mfon Owen
Universiti Tenaga Nasional, Kajang, Selangor, Malaysia

Reviewer's comments/ Reports:

The article titled "Impact of recyclability on the mechanical properties of coated plastic materials for the automotive and electronic sectors" have been reviewed.
The research focuses on the study of the mechanical properties (tensile and impact strength) of Acrylonitrile-Butadiene-Styrene (ABS) and its blends with Polycarbonate (ABS/PC) including recycled and painted material, to determine the impact of ageing, reprocessing cycles, and coating impurities on the final properties of the recycled polymer.

The research is an interesting study, and well written within the scope. However, a significant revision is needed to further improve on the quality of the manuscript.

The research novelty must be clearly emphasized with strong justifications in the introduction and literature sections, as there are lot of work already done on ABS, blends of ABS/PC and their recyclability.

Research title:
I am of the opinion that the title should be reviewed as "***Impact of recyclability on the tensile and Impact properties of coated plastic materials for the automotive and electronic sectors***"
Because only tensile and impact tests were done.

Methods:
State the processing temperature, pressure and time used.
How did you determine the processing temperature used for the injection moulding of the recycled ABS, and ABS/PC?.
Mechanical recycling process:
Mention the equipment used for the shredding process.
Coating Impurities:
Explain the coating impurities and give some examples.

List out the parameters of the five-cycle reprocessing process used.
Characterizations and Testing
Mechanical tests; Why did you not conduct other mechanical tests such as compressive, flexural, hardness, etc.,

Thermal Analysis;
There are no any thermal analysis mentioned in your work. Why did you not conduct DSC and TGA?

Microstructural Analysis;
Why didn't you carry out Scanning Electron Microscope SEM?

Is the background of the case's history and progression described in sufficient detail?
Yes

Is the work clearly and accurately presented and does it cite the current literature?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
No

Are the conclusions drawn adequately supported by the results?
Partly

Is the case presented with sufficient detail to be useful for teaching or other practitioners?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Engineering thermoplastic polymer processing, Polymer composites, Fiber reinforced composites, Materials processing, characterization and testing, Textiles, Fibers, wovens and Nonwovens, Chemical treatments,

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 22 Nov 2024

Denise GARCÍA MURIAS

Reviewer's comments/ Reports + Replies from authors in blue below:

The article titled "Impact of recyclability on the mechanical properties of coated plastic

materials for the automotive and electronic sectors" have been reviewed.
The research focuses on the study of the mechanical properties (tensile and impact strength) of Acrylonitrile-Butadiene-Styrene (ABS) and its blends with Polycarbonate (ABS/PC) including recycled and painted material, to determine the impact of ageing, reprocessing cycles, and coating impurities on the final properties of the recycled polymer.

The research is an interesting study, and well written within the scope. However, a significant revision is needed to further improve on the quality of the manuscript.

The research novelty must be clearly emphasized with strong justifications in the introduction and literature sections, as there are lot of work already done on ABS, blends of ABS/PC and their recyclability. Within the next version of the article submitted today, a comment was included in the introduction highlighting the differentiation between this study as a proof of closed working and the common research studies.

- **Suggestion 1: Research title:**

I am of the opinion that the title should be reviewed as "Impact of recyclability on the tensile and Impact properties of coated plastic materials for the automotive and electronic sectors" Because only tensile and impact tests were done.
Answer 1:
Thanks for the suggestion, we changed the title accordingly in the next version submitted as we believe it matches better the content.

- **Suggestion 2: Methods:**

State the processing temperature, pressure and time used. How did you determine the processing temperature used for the injection moulding of the recycled ABS, and ABS/PC?. **Answer 2:**
Thanks for the valuable suggestion. The processing temperatures were determined according to the TDS of the selected polymers:

- For ABS, a temperature of 220-240 ºC for the plastificator part and 70 ºC for the mold. Pressure was 65-70/25-30/7 Kg/cm^2 (injection/post-pressure/counterpressure). The total time for injection (including all steps) was around 60 s.
- For ABS/PC, a temperature of 240-270 ºC for the plastificator part and 70 ºC for the mold. The injection machine conditions were 60-65/20-25/7 Kg/cm^2 (injection/post-pressure/counterpressure). The total time for injection (including all steps) was around 50 s.

A comment stating this parameters are now included in the methods section.

- **Suggestion 3: Mechanical recycling process:**

Mention the equipment used for the shredding process.
Answer 3: Thanks for the comment. The granulator machine used was a WITTMANN G-MAX 23. This was included in the draft in in the methods section.

- **Suggestion 4: Coating Impurities:**

Explain the coating impurities and give some examples.
List out the parameters of the five-cycle reprocessing process used.
Answer 4: Thanks for the suggestion and focus on injection parameters. We believe it could improve our article. The coating impurities were made mostly of paint residues. According to the TDS for the coatings, these are made of an acrylic-based coating. A comment highlighting this was included in page 7. The conditions for the five cycles were similar as the ones stated before in **Answer 2**. Temperatures were decreased a bit whereas slightly

pressures were augmented to increase fluidity and compactness of the resulting testing pieces.

Characterizations and Testing

- **Suggestion 5: Mechanical tests:**

Why did you not conduct other mechanical tests such as compressive, flexural, hardness, etc.,
Answer 5: Thanks for the tests suggestions. Other mechanical tests were not included as they were not part of the project nor included into the assigned budget. Tensile and impact were chosen as the ones with higher impact and representativity for the study. Although we believe that if the study was more general with regard to the mechanical properties, the mentioned tests could be a good addition.

- **Suggestion 6: Thermal Analysis:**

There are no any thermal analysis mentioned in your work. Why did you not conduct DSC and TGA?

Answer 6: Thanks for the suggestions. We believe that these techniques could bring higher insights about the degradation of the polymeric chains due to thermomechanical stress. However, in a similar way as the last suggestion, DSC and TGA were not included in the project, and it is very hard to perform them now as they are out of the assigned budget or tasks included into our work packages. Nonetheless, the objective of the article is to study the impact of recyclability on the mechanical properties, although we are aware of the relation with thermal processes. As it could be necessary to include newer tests on the study, some comments about the needs of future tests for SEM were included into the draft in page 12.

- **Suggestion 7: Microstructural Analysis:**

Why didn't you carry out Scanning Electron Microscope SEM?
Answer 7: Thanks for the valuable suggestions. SEM is a very interesting technique to include that could give us deep knowledge about the microstructure of the polymers. Unfortunately, we do not have such technique into our facilities and this test was not included as part of the budget for the related European project. As there was a focus on newer tests to include more information than the current one, some comments about the needs of future tests for SEM were included into the draft in page 13.

Competing Interests: No competing interests were disclosed.