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New methods to remove volatile organic compounds from post-consumer plastic waste

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ABSTRACT

While the annual European demand for polyolefins is 25 million tonnes, only 3 million tonnes of recycled polyolefins find their place in the market, despite collecting 15 million tonnes of post-consumer polyolefins every year. Brand owners of care products are showing their interest in using post-consumer recycled plastics for their packaging. However, there is a general concern in using these materials, as recycled polymers can contain unwanted substances that may expose the consumer to health risks or make the packaging unattractive. Accordingly, the presence of these contaminants narrows the market opportunity of recycled plastics to applications with low-quality requirements and in which the product is not in direct contact with the consumer.

Though mechanical recycling is the most widespread solution presents limitations in terms of decontamination, as only superficial substances are removed. Thereby, the volatile organic compounds (VOCs) migrated to the polymer matrix remain inside. Consequently, there is a need to find a solution to purify recycled plastics and increase their market share.

This study focuses on removing VOCs from post-consumer recycled HDPE through two innovative methods applied for the first time in this field, steam stripping and polyethylene glycol (PEG) extraction. The methodology implemented to analyze the volatile organic compounds in HDPE was HS-SPME-GC/MS. Both methods showed a decrease above 70\% in the VOCs content compared to extrusion-degassing. Moreover, these were compared to hot air stripping, a new technology developed at an industrial scale for the removal of VOCs. As a result, steam stripping improved efficiency in reducing the overall VOCs compared to hot air stripping. The PEG extraction method...
lowered the volatile polar compounds further than using hot air stripping. Additionally, none of these technologies modified the HDPE melting flow index.

**Keywords:** polyethylene, NIA, odor, contaminant, deodorization, smell

1. Introduction

Overall production of 8300 million tonnes of plastics is estimated from the origin of plastics in the 1950s. 70 % have been discarded as waste, and only 21 % of this waste has been treated through recycling or incineration processes. This fact leads to the accumulation of 6300 million tonnes of plastics in the environment so far (R. Geyer et al., 2017). Globally, only 14 % of collected post-consumer plastics are recycled as reported by the World Economic Forum (Neufeld et al., 2016), being PET the polymeric material with the highest recycling rate (Ellen MacArthur Foundation, 2017). Notably, in the EU countries, 30 % of post-consumer plastics are collected for recycling, but only 15 % of these are recycled within the EU framework, while the rest is exported to Asian countries with an unknown ending (Hestin et al., 2017). However, this situation is likely to change as the ban on plastic imports in China since 2017 forces the EU countries to find a solution to plastic waste accumulation. Consequently, the plastic recycling sector is getting attention inside the EU countries as the European Commission aims at recycling 55 % of all post-consumer plastic waste generated by 2025 (Hestin et al., 2017), as well as introducing 30 % recycled plastics in beverage plastic bottles (EU, 2018).

As reported by Plastics Europe (2018), the highest demand for plastic materials is concentrated in the packaging sector, where polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) resins contribute to 84 % of post-consumer plastic waste (Hestin et al., 2017). The most efficient collection performance is given in high-density polyethylene (HDPE) and PET bottles with 76 % and 79 % collection rates, respectively. Of which, only post-consumer PET bottles have been more explored in terms of decontamination and recyclability, even some of them could be reused after recycled for food-grade applications due to the positive scientific opinion of the European
Food Safety Authority (EFSA) on some recycling processes (Hestin et al., 2017). However, it is rare to use post-consumer HDPE recycled bottles for food contact applications. Only HDPE milk bottles have been examined in more detail to build a bottle-to-bottle recycling process (EFSA Panel on Food Contact Materials, Enzymes, Flavourings and Processing Aids (CEF), 2015).

On the other hand, recycled post-consumer HDPE is getting attention in the packaging used for home and personal care products. Some brands already showed their interest in producing bottles made of post-consumer recycled (PCR) HDPE. Unilever (2019b) got to manufacture 100 % PCR HDPE detergent bottles and aims to produce packaging with 100 % PCR for body care products (Unilever, 2019a) but, to achieve this goal, the company claimed for a higher quality of PCR resins. The company Procter and Gamble is also committed to using 100 % PCR in detergent packaging by 2020 (Packaging Europe, 2019). Another company, Alpha packaging (2019), is using PCR HDPE for personal care products packaging collected from community recycling programs.

Due to the growing interest in the use of PCR HDPE and because the topic of increasing the recycling rates of post-consumer plastic waste is an issue of concern in the EU countries, some studies recently arose uncovering, for instance, non-intentionally added substances (NIAS) in HDPE originating from the post-consumer collection. For instance, a previous study by Strangl et al. (2018) reported 33 NIAS identified as odor causative substances in post-consumer HDPE, e.g., linalool, α-damascone, α-isomethylionone, verdyl acetate, and β-ionone, among others. All these substances remained after the recycling process. In another study, Welle (2005) identified additive degradation products and flavor compounds, such as di-tert-butylphenol and limonene, as NIAS from HDPE bottles, which presented a higher concentration in post-consumer HDPE milk bottles than in virgin HDPE. Non-intentionally added substances in post-consumer HDPE were also identified in a recent study by Horodytska et al. (2020), corresponding to chemicals used in detergents and cosmetics ingredients, such as benzyl acetate, 2-phenoxyethanol or α-amylcinnamaldehyde; but also to polymer and additives degradation substances, such as 3-
dodecanone, 3,5-di-tert-butyl-4-hydroxyacetophenone or tert-butyl-(4-tert-butylphenyl)phosphinic acid.

With the increasing demand for high-quality recycled polymers, upgraded mechanical recycling processes are gaining a place in the research area, such as supercritical CO$_2$ extraction. Anouar et al. (2015) studied the efficiency of supercritical CO$_2$ extraction in removing the organic compounds emitted by new LLDPE pellet samples, operating at 300 bars and two different temperatures, 50 and 80 ºC, obtaining the best results when working at the highest temperature. As a result, a yield of 98% was achieved after 12 hours, twice more efficient than the experiment ran at 50 ºC. Another technology developed at a pilot scale for removing unwanted substances in post-consumer plastics applies to the Extruclean technology developed through the European project LIFE EXTRUCLEAN (García-Muñoz, 2017). The project outcome was a new technology that uses sCO$_2$ in the extrusion process to enhance the removal of contaminants by degasification. As a result, the effectiveness of decontamination was improved by 70% compared to conventional recycling. However, this additional step increases by 8% the recycling process environmental impact on a global score that includes human health, ecosystem quality, and resources. Nevertheless, the reduced environmental impact (56% - 86%) of the packaging manufactured with the recyclates obtained through this process compensates for the added environmental impact in the process.

On an industrial scale, existing technologies implemented in the mechanical recycling of plastics, such as extrusion, were upgraded to improve the removal of volatile organic compounds (VOCs) with degassing systems. Also, post-extrusion technologies were developed to remove the odors remaining in the polymer after recycling. Starlinger implemented a post-extrusion unit called Smell Extraction Unit (SEU), in which the odors are removed by feeding the pelletized recycled polymer to a vertical tower in which heat, time, and pressure are applied (Waste Management World, 2017). Another company specializing in extrusion machinery, Erema, launched a new technology to remove odors. It consists of a vertical column where air at high temperature is flushed through the
plastic pellets bed to remove the VOCs heavy fraction. This process requires residence times between 7 and 32 hours that imply a piece of equipment with a volume between 8.8 and 272 m³, and which energy consumption ranges from 0.09 to 0.13 kWh/kg (C. Kitzberger, 2017; Erema, 2017). The efficiency of this process was studied by Strangl et al. (2019), concluding that odor causative compounds of PCR HDPE, such as β-ionone or verdyl acetate, decreased more than 90% after treating the plastic for 7 hours with hot air.

Due to the lack of research on removing VOCs in the washing line, in which hazardous compounds could be removed before extrusion and therefore could prevent health risks for workers (K. Yamashita et al., 2007), this study proposes two new technologies: steam stripping and extraction with polyethylene glycol (PEG) to remove the VOCs and increase the quality of PCR HDPE.

Steam stripping has not been studied previously to remove VOCs from plastics, but it has been applied to decontaminate water and industrial wastes or extract essential oils. Hassan et al. (1992) studied the removal and recovery of 2-nitropropane from aqueous and non-aqueous industrial waste streams, reaching a recovery above 99%. Behnami et al. (2019) studied various approaches for removing benzene, toluene, and styrene from petrochemical wastewater, among which steam stripping and air stripping were considered. As a result of this study, steam stripping was selected as the most effective and cost-efficient option. Steam distillation is also used for stripping fatty acids from edible oils (Marcelo Usseglio et al., 2019; Daniela S. Laoretani and Oscar A. Iribarren, 2017), as well as for the extraction of essential oils such as α-pinene, myrcene, limonene, 1,8-cineole, and linalool, among others, from Lavandula angustifolia (P. Rubiolo et al., 2010). All these studies motivated the application of steam stripping for the removal of VOCs from PCR HDPE, as most of the mentioned VOCs in the previous publications have been identified in PCR HDPE as well.

Steam stripping is an efficient treatment for the extraction of VOCs that are immiscible with water - as most of the organics identified in PCR HDPE – due to immiscible VOCs boil at temperatures below 100°C in the azeotrope point. The formation of a minimum boiling point azeotrope enhances
the removal of substances with a boiling point above 100 °C, compared to air stripping, as shifts their boiling temperature under 100 °C (O. Tutkun, 1993).

The use of PEG as a green solvent is getting attention due to its low volatility and toxicity, compared to conventional solvents, and its higher miscibility with organic compounds compared to water. Some studies already showed a higher potential in extracting organic molecules using PEG compared to water extraction. Zhou et al. (2011) studied the extraction of organic compounds flavone and coumarin from medicinal plants using a PEG 200-water solution in microwave-assisted extraction, resulting in increased extraction of these compounds compared to pure water. Another study by Alanazi et al. (2020) showed that an organic molecule used as an anticancer drug, Gefitinib, presents a very low solubility in water, but it is soluble in PEG400. According to Manic et al. (2011), PEG is an effective extractant for linoleic acid from soybean oil. Kianpour and Azizian (E. Kianpour and S. Azizian, 2014) studied the extraction of several compounds, dibenzothiophene, benzothiophene, and 4,6-dimethyldibenzothiophene, from liquid fuels with PEG. Reductions of 98 % were achieved in this study. All these results were the motivation to apply PEG for the extraction of organic substances in PCR HDPE. Besides, the fact that PEG is water-soluble would facilitate removing residual PEG on the plastic surface by rinsing with water.

The VOCs resulting after treating the PCR HDPE with PEG extraction and steam stripping are compared to the ones obtained with recycled pellets from extrusion-degassing, as well as with the results obtained after treating the PCR HDPE with hot air, which simulates the post-treatment process already developed at industrial scale.

2. Materials and methods

2.1. Samples

The sample used in this study is pellets from post-consumer recycled HDPE (PCR HDPE) with 5mm diameter and 2 mm thickness. These pellets were produced from the post-consumer packaging
discarded in the yellow sack collection in Germany. The PCR HDPE is the resulting material after shredding post-consumer HDPE bottles to flakes of 3-6 cm length, washing the PC-HDPE flakes with hot water, drying them with a centrifuge, and finally extruding the flakes to produce the final PCR HDPE pellets. The extruder includes a melt filter for removing physical impurities, such as rubber, metals, paper, among others, and a degassing system to vacuum the VOCs released through the extrusion line.

2.2. Study cases for the removal of contaminants

Three different methods were applied to PCR HDPE pellets: PEG extraction, air stripping, and steam stripping. The efficiency of each method was based on the VOCs reduction obtained after each treatment. The efficiency of each of these treatments was then compared to that resulting from the extrusion-degassing technology, which is the most implemented technology to remove VOCs via mechanical recycling.

2.2.1. Polyethylene glycol extraction

Polyethylene glycol 400 (PEG400) was used for the extraction of VOCs from PCR HDPE pellets. A total of 15 g were stirred in a 250 mL beaker filled with 150 mL of PEG400. The extraction was carried for 2 hours at 100 ºC. The heating system consisted of a magnetic stirrer hot plate with an external temperature probe. Continuously, the HDPE sample was separated from the PEG400 using a sieve. The PEG400 remaining on the plastic surface was rinsed with fresh cold water for 30 minutes by stirring the pellets in a 250 mL beaker with a magnetic stirrer. Afterward, the water was drained, and finally, the pellets were placed on a clean surface to be dried for 24 h at room temperature.

2.2.2. Air stripping

The PCR HDPE pellets sample was treated with hot air for 2 hours at 100 ºC in order to remove the VOCs in the polymer matrix. 15 g of pellets were placed in a glass column where the sample stands on a porous surface. Compressed air was flushed firstly flowing through the electric heater, which
increased the compressed air temperature to 100 ºC, and secondly, the heated air was fed to the bottom of the glass column flowing through the plastic bed (Figure 1).

![Diagram](image)

Figure 1. Air stripping system for devolatilization of VOCs from PCR HDPE

2.2.3. Steam stripping

A sample of 15 g of PCR HDPE pellets was treated in a distillation unit (Selecta Pronitro I) for 2 hours. This distillation unit produces steam at ambient pressure and feeds the steam to the bottom of a glass tube where the plastic sample is placed. The vapor flows through the plastic bed and leaves on the top, passing to a condenser. Finally, an additional glass tube collects the condensate.

2.3. Analysis of volatile organic compounds with headspace solid-phase microextraction and gas chromatography and mass spectrometry

2.3.1. Extraction of volatile organic compounds using headspace solid-phase microextraction

The headspace solid-phase microextraction (HS-SPME) technique was applied to analyze the VOCs from the polymer matrix. A total of 10 ± 0.01 g of each sample were introduced in a glass vial of 100 mL volume sealed with a 20 mm diameter Teflon/Silicone septum. Next, an SPME syringe with a 75 μm Carboxen/Polydimethylsiloxane fiber was injected through the septum and held in the
vial headspace while adsorbing the volatile organic compounds (VOCs) emitted by the plastic sample. The VOCs extraction was facilitated by heating the sample in a water bath at 60 ºC for 1 hour while the SPME fiber was placed inside.

2.3.2. Analysis of volatile organic compounds by gas chromatography and mass spectrometry

The VOCs adsorbed on the fiber were desorbed in the injection port of the gas chromatograph Agilent 7890A (GC), where the compounds were separated using a non-polar HP5 capillary column (30 m length, 0.25 mm diameter, supplied by Agilent Technologies), after which the mass spectrum of each molecule was obtained with the Mass Spectrometer Agilent 5975C (MS). The method set in the GC/MS for the VOCs analysis is described in Table 1.

Table 1: Operating conditions in the gas chromatography-mass spectrometry device for VOCs identification.

<table>
<thead>
<tr>
<th>GC Conditions</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Split mode</td>
<td>5:1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injector temperature</td>
<td>280 ºC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Desorption time</td>
<td>10 min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow rate</td>
<td>1 mL/min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature program</td>
<td>T(ºC)</td>
<td>Rate (ºC/min)</td>
<td>Hold (min)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>130</td>
<td>3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>6</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>20</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

MS Conditions


Solvent delay 0.5 min
Scan mode 35 m/z – 400 m/z
Method of ionization Electron impact

2.4. Identification of the volatile organic compounds

Analytical standards were used for the identification of hexyl salicylate (supplied by Sigma-Aldrich), α-isomethylionone (supplied by Sigma-Aldrich), and β-ionone (supplied by Supelco). The rest of the specific compounds studied in this research were identified by comparing their mass spectrum with the NIST database, for which NIST MS search 2.0 software was used.

2.5. Melting flow index analysis

The melting flow index (MFI) equipment was provided by Instron, model MF20, certified by the standard ISO 1133-1. The tests were conducted according to ISO 1872. For each sample, 2.16 g were analyzed in 10 different points at a temperature of 190 ºC.

3. Results

3.1. Overall VOCs and subgroups

The four recycled post-consumer HDPE pellet samples were analyzed by HS-SPME-GC/MS. The first sample corresponds to the PCR HDPE after extrusion-degassing, the second to the pellets treated with extrusion-degassing followed by air stripping, the third to the pellets treated with extrusion-degassing followed by PEG extraction, and the fourth the pellets treated with extrusion-degassing followed by steam stripping. Accordingly, the quantity of VOCs was reduced 74 % after PEG extraction, 77 % after air stripping, and 84 % after steam stripping in comparison with extrusion-degassing (see Figure 2).
In Figure 3, the chromatogram area is divided into three regions for more in-depth insight. The first region corresponds to the VOCs detected at residence times below 20 min, the second to the VOCs detected between 20 and 40 min, and the third shows the VOCs detected after 40 min. In the input sample, named extrusion-degassing, most of the VOCs appear in the second region, from 20 to 40, and the lowest content appears after 40 minutes, most probably because of the type of analysis, as the substances detected after 40 min are heavier compounds with lower vapor pressure than the rest. However, after the treatments, the middle region substances are significantly decreased while the VOCs appearing earlier than 20 min remain at higher levels than expected. In principle, the VOCs in the first region should be easily removed due to their higher volatility. However, it seems that limonene, which is the most predominant substance at this range (17 min in Figure 2), has a strong affinity with polyethylene, as already concluded in previous studies by Kwapong et al. (1987) and Salder et al. (1991), and thereby still appears at a high level after treating PCR HDPE, thus, contributing to the increase of VOCs detected in the first region.
Figure 3. Peak area of volatile organic compounds, broken down in 3 regions based on chromatogram residence time, resulting from extrusion-degassing, air stripping, PEG extraction, and steam stripping applied to PC-HDPE recycled pellets.

3.2. Specific VOCs

To further study the treatment efficiencies, 19 substances were selected as representative NIAS and IAS from PC-HDPE recycled pellets. These substances are divided into four groups according to their origin. The first group comprises four substances previously identified by Horodytska et al. (2020) originating by the formulation of the material itself: butylatedhydroxytoluene (BHT) is used as an antioxidant in polyethylene (IA), 2,2,4,4,6,8,8-heptamethylnonane is a NIA originating from polyethylene, 3,5-di-tert-butyl-4-hydroxybenzaldehyde is a degradation compound caused by an antioxidant additive (NIA), and diethylphthalate is a plasticizer (IA) (Figure 4 (a)). The second subgroup is formed by two substances previously identified as odor active compounds from PC-HDPE by Strangl et al. (2018): α-isomethylionone and β-Ionone (Figure 4 (b)). The third group comprises 7 NIAS that belong to ingredients from health care and cleaning agents that have migrated to the HDPE package during its use phase, namely, hexyl acetate, dihydromircenol, benzyl acetate, 2-phenoxyethanol, 3-(4-isopropylphenyl)-2-methylpropionaldehyde, amyl salicylate, and hexyl salicylate (O. Horodytska et al., 2020) (Figure 4 (c)). In fourth place, an array of 6
alkylbenzenes corresponding to NIAS from surfactants breakdown products are studied too (O. Horodytska et al., 2020) (Figure 4 (d)).

### 3.2.1. Removal of (N)IAS originating from HDPE

Focusing on the compounds mentioned above, a reduction of more than 50 % is achieved for all the compounds in the PCR HDPE pellets after treated with the three methods, air stripping, steam stripping, and PEG extraction (Figure 4). In the first group, Figure 4 (a), all the VOCs related to the polymer show a reduction above 70 %. BHT is reduced an additional 11 % by applying steam stripping and PEG extraction than with air stripping. While 3,5-di-tert-butyl-4-hydroxybenzaldehyde is not detected after the treatment with steam stripping and PEG extraction, a minor fraction of 7 % remains in the sample after treating the PCR HDPE with air stripping. In the case of 2,2,4,4,6,8,8-heptamethylnone and diethylphthalate, the extraction with PEG provided a lower removal, and the residual content in PCR HDPE of the latter one is similar after applying both steam and air stripping. The compound 2,2,4,4,6,8,8-heptamethylnone is further reduced (3 %) with steam stripping than by treating with air stripping.

### 3.2.2. Removal of NIAS related to odor-active substances

In the second group (Figure 4 (b)), the residual content is lower than 10 % for both odor-active compounds, α-isomethylionone, and β-methylionone. Steam stripping shows an increased reduction of these substances, followed by PEG extraction and air stripping. Both compounds are halved after treating PCR HDPE with steam stripping compared to air stripping.

### 3.2.3. Removal of NIAS from body care products and cleaning agents

The trend observed in the VOCs presented in Figure 4 (c) is the same as for odor-active substances, except for hexyl salicylate that is equally reduced after steam stripping and PEG extraction. The residual content of these substances in PCR HDPE is lower than 45 % in all the cases. The highest difference is observed for the first two compounds, hexyl acetate and dihydromyrcenol, the residual
content of which, after air stripping, is 44 and 39 %, respectively, while steam stripping lowered the residual content of them up to 11 and 12 %, respectively.

3.2.4. Removal of NIAS from surfactants breakdown products

Overall, the array of alkylbenzenes is reduced by more than 85 % in all cases. PEG extraction shows a lower reduction of these compounds compared to air stripping and steam stripping. The mean residual content of this array of alkylbenzenes after steam stripping and air stripping is 8 % in both cases. This average is the result of the distribution observed in the six compounds, as three of them showed a higher reduction with air stripping ((5-Decyl)benzene, (1-Pentylhexyl)benzene and (1-Butylheptyl)benzene), one of them with steam stripping ((1-Propyloctyl)benzene) and the other two show very similar results in both treatments ((4-Decyl)benzene, (3-Decyl)benzene), but in all the cases with a variance below 2 %.
3.3. Study of melting flow index

The MFI was determined for each sample following the method explained in section 2.4. Figure 5 shows the mean value of the 10 points analyzed in each sample and their standard deviation. The resulting MFIs of the four samples are in the range of 0.33 to 0.35. Although the difference is lower than 0.1 between all the samples, the MFI values of the samples treated with air stripping and steam
stripping are closer to the MFI of the sample extruded with degassing, while the sample treated with PEG has a slightly lower MFI.

Figure 5. Melt flow index of PCR HDPE after the extrusion-degassing, steam stripping, extraction with PEG, and air stripping.

4. Discussion

4.1. Polyethylene glycol-derived compounds

The previous results showed that the extraction with PEG400 could reduce VOCs in PCR HPDE above 70%. Nevertheless, few new substances appear as a result of using PEG for the extraction. These substances, identified by HS-SPME-GC/MS, are methoxyethanol, ethoxyethanol, 2-methoxyethyl ethenyl ether, and diethylene glycol monomethyl ether (see Table 2). All of them are minor compounds with boiling points below 200 °C. The most remarkable compound is diethylene glycol monomethyl ether, as it presents the highest concentration and boiling point compared to the rest. From their molecular structure, it is deduced that these compounds belong to PEG breakdown products, as all of them present on their structure the PEG monomer chain.

Table 2. New substances in PCR HDPE after using PEG for the extraction of NIAS. The % match quality is the probability of a compound corresponding to the peak detected based on the NIST library
<table>
<thead>
<tr>
<th>Compounds</th>
<th>CAS</th>
<th>RT (min)</th>
<th>% Match quality</th>
<th>% Total area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methoxyethanol</td>
<td>109-86-4</td>
<td>2.52</td>
<td>79.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Ethoxyethanol</td>
<td>110-80-5</td>
<td>3.63</td>
<td>78.5</td>
<td>0.2</td>
</tr>
<tr>
<td>2-Methoxyethyl ethenyl ether</td>
<td>1663-35-0</td>
<td>4.02</td>
<td>77.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Diethylene glycol monomethyl ether</td>
<td>111-77-3</td>
<td>12.52</td>
<td>95.8</td>
<td>3.5</td>
</tr>
</tbody>
</table>

### 4.1.1. Environmental impact of PEG breakdown products

Biodegradability is considered as the indicator to assess the environmental impact of each substance. The biodegradability is measured based on the 10-day window test used for testing the degradation of organic chemicals (OECD, 2003). This test defines an organic substance as readily biodegradable when it has achieved 10% biodegradation within 10 days from the start.

According to the European Chemicals Agency (ECHA) (2020b), methoxyethanol is readily biodegradable in freshwater while it does not fulfill the 10-day window in saltwater. Several studies were performed to evaluate the biodegradability of methoxyethanol in the water showing that adapted bacterial populations significantly increase the biodegradation rate. In the case of freshwater, the 10-day window is reached in both adapted and unadapted bacterial populations. In contrast, the biodegradability of methoxyethanol in saltwater reaches the 10-day window only when adapted bacterial populations are present.

Likewise, ethoxyethanol is classified as readily biodegradable due to its high biodegradability in wastewater (Federal Institute for Occupational Safety and Health Notification Unit, 2007). A biodegradability of 70% was reached within 10 days. Additionally, other tests conducted with ethoxyethanol led to 100% degradation after 14 days based on the dissolved organic carbon
The biochemical oxygen demand analysis showed a 63 - 83 % degradation within 14 days. The same applies to diethylene glycol monomethyl ether, determined as a readily biodegradable organic compound (ECHA, 2020a). This compound achieved complete biodegradation after 28 days.

There is no information regarding the biodegradability of 2-methoxyethyl ethenyl ether to the best of our knowledge.

4.1.2. Health impact of PEG breakdown products

To evaluate the toxicity of these four compounds, firstly we looked into the Commission Regulation (EU) No 10/2011 that lists the authorized substances that can be present in plastic materials and articles intended to come into contact with food. As a result, none of these compounds was found in the list, meaning that plastics containing any of them can not be used for food contact applications, such as food packaging or disposable plastic cups and plates.

Secondly, we reviewed the list of substances authorized as cosmetics ingredients, the European CosIng database. In this list, methoxyethanol and ethoxyethanol are identified as substances prohibited from being used as cosmetics ingredients because they are readily absorbed through the skin, and some studies demonstrated that these substances have reproduction toxic effects. Diethylene glycol monomethyl ether is also classified as a prohibited substance in cosmetics according to Regulation (EU) 1223/2009, but there is no report regarding its toxicity. The compound 2-methoxyethyl ethenyl ether is not listed in the European cosmetics ingredients database, but its dermal LD 50 is above 7000 ppm, which means it is a practically non-toxic substance.

Furthermore, methoxyethanol and ethoxyethanol are classified in the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation as substances of very high concern (SVHC) due to its harmful effects on fertility in both cases, and, particularly methoxyethanol can
cause damage to organs. Diethylene glycol monomethyl ether is suspected of damaging fertility, but it is not classified as an SVHC.

In short, the breakdown products originating from the use of PEG as an extractant agent may expose human health risks if the recycled plastics are used for products to come in direct contact with the consumer, such as food or personal care products packaging. However, the recycled plastics resulting after the PEG extraction, which contain less VOCs, and lower odor intensity, could be employed in less demanding applications, as for home care packaging.

4.2. Comparison of overall and specific VOCs results

Figure 3 showed the total quantity of VOCs emitted after the treatments, in which steam stripping presents the highest effectiveness, followed by air stripping and PEG extraction. However, these results do not match the trend depicted by target compounds in Figure 4. In this figure, PEG extraction shows an improved performance compared to air stripping, except for the non-polar compounds, which are 2,2,4,4,6,8,8-heptamethylnonane, and the array of alkylbenzenes. This discrepancy can be explained by the decreased miscibility of the non-polar compounds with PEG. Due to PEG is a polar solvent, it is expected that polar molecules present higher solubility with PEG, as is the case of ketones, alcohols, and aldehydes, while hydrocarbons, which have a lower polarity, present a reduced solubility with PEG and a higher affinity with HDPE, hindering their extraction.

The predominant VOCs in the PCR HDPE chromatogram are mainly linear hydrocarbons that appear as polyethylene breakdown products. These compounds have a low solubility in PEG, and therefore are removed with lower efficiency, affecting the overall efficiency of VOCs removal presented in Figure 3. However, the contaminants of cosmetics, most of which contain oxygenated groups in their chemical structure, are polar substances highly soluble in PEG, which results in increased efficiencies, explaining the other trend observed in Figure 4. If the overall VOCs,
classified by their GC residence time, are presented without considering the linear hydrocarbons produced by the HPDE material itself, the trend observed in the range from 20 to 40 min is similar to the one observed for the specific VOCs with polar character (Figure 6 (b)). Additionally, if PEG derivative substances mentioned in Table 2 are excluded too, then a reduction of VOCs is observed in the range of less than 20 min (Figure 6 (b)). Therefore, it can be concluded that the overall concentration of volatile NIAS in PCR HDPE is further reduced with PEG extraction than using air stripping as long as the NIAS produced by HDPE and the PEG related substances are not considered.

Figure 6. Comparison of chromatogram area divided by residence time ranges: (a) considering all the VOCs detected, (b) overall VOCs excluding NIAS from HDPE itself and PEG derivate substances

4.3. Comparison of the different treatments based on specific VOCs

4.3.1. Comparison of air stripping and steam stripping

The specific VOCs studied in section 3.2.4 are used to compare the studied treatments. A paired comparison of both treatments efficiency, steam and hot air stripping, is performed by projecting
the residual VOCs percentage after both treatments (Figure 7). The points appearing under the diagonal belong to the substances that were further reduced using steam stripping, and both processes similarly reduced the substances corresponding to the points on the diagonal or close to it. As shown in the graph, the heaviest compounds (orange, B.P> 290 °C) are equally removed with steam stripping and air stripping, while steam stripping shows a better performance than air stripping in the removal of lighter VOCs, presented in blue color.

This effect can be explained by the fact that the pure VOCs boiling point affects their azeotropic composition. To analyze this trend, 34 VOCs, similar to those identified in PCR HDPE, with boiling points between 140 and 310 °C, were gathered from literature (American Chemical Society, 1973). These compounds include 2-vinlyoxyethanol, 1,4-oxathiane, 2-propoxeythanol, isobutyric acid, 2-ethoxyethyl acetate, 3-methoxy-1-butanol, 3-hepten-2-one, 2-ethylthioethyl vinyl ether, 2,4-hexadienal, 3-dimethylamino propionitrile, bis(2-chloroethyl)ether, 2,3-dichloro-1-propanol, valeric acid, ethylene glycol diacetate, 2-ethylbutyric acid, (epoxyethyl)benzene, 2-methylpentanoic acid, acetoophenone, guaiacol, hexanoic acid, 2-chloroallylidene diacetate, bis(2-chloroethoxy)methane, 2-ethylhexanoic acid, 2-ethyl-3-hexenoicacid, 1,2-bis(2-chloro-ethoxy)ethane, 1,2-epoxy-3-phenoxyp propane, 2-phenoxetyl acetate, 2-ethylbutyl 2-ethyl-hexanoate, butyl salicylate, dimethyl phthalate, dibutyl fumarate, bis(α -methylbenzyl)ether, 2-(ethylhexyl)phenol and 3,9-diethyl-6-tridecanol. The correlation between pure substances boiling point and their composition in the azeotrope is presented in Figure 8, where it is observed that the organics with a boiling point above 290 °C present a negligible concentration in the azeotrope (< 1 %). Therefore, the effect of evaporating the VOCs from PCR HDPE with steam stripping, taking advantage of the azeotrope, disappears for compounds with a boiling point higher than 290 °C. Thereby, the heaviest VOCs are equally removed by air stripping and steam stripping, as the mechanism is governed by the stripping of the substances located on the surface of the plastic with hot gas, below their boiling point.
4.3.2. Comparison of PEG extraction and air stripping

A paired comparison of the percentage of residual VOCs after PEG extraction and air stripping is presented in Figure 9. The VOCs selected for this study are the specific VOCs from section 3.2.4,
as in the previous case. PEG extraction presents a higher reduction for the VOCs with lower partitioning coefficient octanol/water (orange color), which are the compounds with higher polarity. In contrast, all the organic compounds with partitioning coefficients above 7 (blue color), which are less polar, appear above the diagonal line in the graph, meaning that they are present with a higher concentration in PCR HDPE after PEG extraction.

Figure 9. Pairwise distance of percentage of residual specific VOCs in PCR HDPE after PEG extraction vs. air stripping

4.3.3. Comparison of PEG extraction and steam stripping

As in the previous two cases, the same procedure is followed to compare the PEG extraction and steam stripping efficiencies. Figure 10 shows the paired comparison, representing the percentage of residual specific VOCs after treating PCR HDPE with PEG extraction vs. steam stripping. Steam stripping presents a higher reduction in all the specific VOCs, but two points stand out over the rest, presenting a longer distance to the diagonal and, therefore, a higher content in PCR HDPE after PEG extraction than after steam stripping. These are hexyl acetate and 2,2,4,4,6,8,8-heptamethylnonane. The first one is the compound with the lowest boiling point among all the specific VOCs selected, which favors its devolatilization by steam stripping due to its higher vapor
pressure. The second compound is a non-polar organic compound, the one with the highest partitioning coefficient value, which means it has the lowest miscibility with PEG compared to the rest, and thus, the extraction of this compound is less effective.

Figure 10. Pairwise distance of percentage of residual specific VOCs in PCR HDPE after PEG extraction vs. steam stripping

4.4. Melting flow index

The MFI is an extendedly used parameter for the quality control of thermoplastics. The MFI is an indicator of a polymer viscosity, a crucial parameter for the manufacturing of polyolefins that permits the adjustment of extrusion operating conditions as a function of it. As the MFI range required for the extrusion of sheets, bottles, thin tubes, and cables is between 0.1 and 0.5 g/10 min (Van Krevelen and Te Nijenhuis, 2009), the PCR HDPE resulting after the three treatments is suitable for the extrusion of these.

4.5. Comparative study of energy consumption
In this section, the potential energy consumption is estimated for each of the three treatments studied in this research: hot air stripping, PEG extraction, and steam stripping. It is considered the energy consumed for heating the media to 100 °C (air, water, and PEG) and the heat transfer efficiency.

### 4.5.1. Energy consumption for heating

The energy required for heating air, steam, and PEG is estimated with the differential enthalpies, using the data of the specific heats for each fluid and assuming that each fluid enters the heating system at an ambient temperature of 25 °C and is heated up to 100 °C, and, in the case of steam, adding the latent heat of vaporization (see Table 3). As a result, 76 kJ/kg are consumed for heating air, 159 kJ/kg for PEG, and 2571 kJ/kg for heating and evaporating water (Table 4). Accordingly, hot air stripping seems the most economical solution.

However, the possibilities for energy integration should also be considered, as it could be highly beneficial for the steam stripping process. After stripping the VOCs from recycling post-consumer HPDE pellets, the steam leaves the system at 100 °C, presenting a potential thermal energy source. The latent heat of evaporation of the steam can be transferred to the water make-up steam or other recycling process units, decreasing the overall recycling process energy costs by implementing recuperators, economizers, or waste heat boilers in the system (H. Jouhara et al., 2018). Considering the most favorable scenario in which the latent heat of water evaporation is wholly recovered, 2256 kJ/kg can be saved with energy integration, which means that the steam stripping process consumption could be reduced to 315 kJ/kg.

However, the energy consumed in the process depends on the energy needed to heat 1kg of fluid and the efficiency of each process to remove the VOCs, which requires further research to optimize each method. Based on this first estimation, PEG extraction would be a more cost-efficient process than hot air stripping if the air mass flow rate required to treat 1 kg of plastic doubled the PEG flow
rate. Likewise, the steam stripping process could be less costly than hot air stripping if the air mass flow rate required to treat 1 kg of plastic was 33 times higher than the steam flowrate, with no energy integration. However, if the latent heat is recovered, an air flow rate 4 times higher than the steam flow rate would make the steam stripping process more economical than hot air stripping.

Furthermore, as explained in the next section, the heating rate also plays an essential role in energy consumption due to the fluid needs to heat the polymeric material that enters the system at 25 ºC.

Table 3. Parameters used for the calculation of the enthalpy

<table>
<thead>
<tr>
<th>Method</th>
<th>Parameter name</th>
<th>Parameter abbreviation</th>
<th>Parameter value</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot air stripping</td>
<td>Specific heat of the air</td>
<td>$C_{p,\text{air}}$</td>
<td>1.006 kJ/kg ºC</td>
<td>(Yaws, 2015b)</td>
</tr>
<tr>
<td></td>
<td>Specific heat of water</td>
<td>$C_{p,\text{water}}$</td>
<td>1.86 kJ/kg ºC</td>
<td>(Yaws, 2015a)</td>
</tr>
<tr>
<td></td>
<td>Saturated water fraction in air at 25 ºC</td>
<td>$x_{\text{water}}$</td>
<td>0.02</td>
<td>(Haynes, 2014)</td>
</tr>
<tr>
<td>PEG extraction</td>
<td>Specific heat of PEG</td>
<td>$C_{p,\text{PEG}}$</td>
<td>2.115 kJ/kg K</td>
<td>(Yan Kou et al., 2019)</td>
</tr>
<tr>
<td>Steam stripping</td>
<td>Enthalpy of vaporization water</td>
<td>$\Delta H_{\text{vaporation}}$</td>
<td>2501 kJ/kg</td>
<td>(Yaws, 2015a)</td>
</tr>
<tr>
<td></td>
<td>Enthalpy coefficients</td>
<td>A</td>
<td>-203.6060</td>
<td>(JD Cox et al., 1984; Malcolm W. Chase Jr., 1998)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>1523.290</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>-3196.413</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
<td>2474.455</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>E</td>
<td>3.855326</td>
<td></td>
</tr>
</tbody>
</table>
PEG 1000 was taken as a reference because no data regarding PEG 400 was found in the literature.

Table 4. Calculation of the enthalpy difference for the three methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Equation</th>
<th>Energy consumption (kJ/kg fluid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot air stripping</td>
<td>$\Delta H_{air} = \int_{T=25}^{T=100} C_p,<em>{air}dT + x</em>{water,<em>{j</em>{1=25}}} \int_{T=25}^{T=30} C_p,_{water}dT$ (I)</td>
<td>78</td>
</tr>
<tr>
<td>PEG extraction</td>
<td>$\Delta H_{PEG} = \int_{T=25}^{T=100} C_p,_{PEG}dT$ (II)</td>
<td>159</td>
</tr>
<tr>
<td>Steam stripping</td>
<td>$\Delta H_{steam} = \int_{T=25}^{T=100} C_p,<em>{water}dT + \Delta H</em>{vaporation}$ (III)</td>
<td>2571</td>
</tr>
<tr>
<td></td>
<td>$\int_{T=25}^{T=100} C_p,_{water}dT = At + Bt^2 + Ct^3 + Dt^4 - \frac{E}{t} + F - H$ (IV)</td>
<td></td>
</tr>
</tbody>
</table>

4.5.2. Heat transfer

The heat transfer from the fluid to the polymer occurs as an exchange of thermal energy between the two substances by assisted convection. The fluid at 100 °C transfers the energy to the polymer, which at first is at ambient temperature, 25 °C. The heat transfer rate depends on the heat transfer coefficient and the temperature difference between the polymer surface and the fluid (in this case, $dT = 75 °C$). Using Newton's Law of Cooling (equation V) with the values of heat transfer coefficients obtained from the literature (Table 5), each fluid results in a heat transfer rate of 38 kW/m² for the air, 1125 kW/m² for PEG, and 7500 kW/m² for the steam. Accordingly, steam is the
fastest media for heating the HDPE pellets. Fluids with a high heat transfer rate may result in lower energy costs as demand lower flowrates, but again this has to be demonstrated by optimizing each method.

Table 5. Typical heat transfer coefficients (Kosky et al., 2013)

<table>
<thead>
<tr>
<th>Method</th>
<th>Type of fluid</th>
<th>$h_c$ (W/m² K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot air stripping</td>
<td>Air</td>
<td>500</td>
</tr>
<tr>
<td>PEG extraction</td>
<td>Liquid</td>
<td>15000</td>
</tr>
<tr>
<td>Steam stripping</td>
<td>Condensing water vapor</td>
<td>100000</td>
</tr>
</tbody>
</table>

$$q = h_c A dT$$

In this equation:

- $q$ is the heat transferred per unit time (W)
- $A$ is the heat transfer area of the polymer surface (m²)
- $h_c$ is the convective heat transfer coefficient of the process (W/(m²·°C))
- $dT$ is the temperature difference between the surface of the polymer and the bulk fluid (°C)

4.6. Environmental impact

4.6.1. The potential circularity of HDPE in the packaging sector

The contribution of removing VOCs from recycled polymers in the circular economy of plastics can be measured with the substitution rate of virgin resins by recycled resins. Lower VOCs in recycled polymers are reflected in an improved quality that could increase their demand (SusChem, 2018). Nowadays, plastic converters are reluctant to use post-consumer recycled resins in packaging applications due to the high levels of contamination in recyclates originating from post-consumer sources (Hestin et al., 2017). This contamination, generated by substances in contact with the packaging during its use phase or due to cross-contamination through the collection system, may generate off-odors in the recyclates that difficult their market entry. Besides, these unknown
substances may lead to health concerns for the packaging producers.

According to the regulation EU 10/2011, the use of recycled polymers in food contact applications is prohibited. Furthermore, previous research studies by Strangl et al. (2018) and Horodytska et al. (2020) support this restriction as identified the presence of substances in recycled post-consumer HDPE that are not allowed to come into contact with food and, therefore, support the idea that the use of recycled polymers with unknown traceability, as is the case of post-consumer plastics, may expose a health concern for consumers. The only exception of using post-consumer polymers for food contact packaging applies to the case of PET bottles. The EFSA (2019; 2018) already authorized few processes capable of decontaminating post-consumer PET. In this case, PET water bottles are separately collected through deposit systems and subjected to an in-depth decontamination process, which allows a bottle to bottle recycling in a closed loop. However, this is not the case of polyolefins, or more precisely, of HDPE. Milk bottles, shampoo bottles, and cleaning products bottles made of HDPE are collected together in the packaging fraction without separating food and non-food packaging. Besides, in-depth decontamination processes assuring complete removal of unwanted substances in polyolefins are not available in the market yet. Consequently, recycled HDPE from post-consumer sources can only cover the market share of non-food contact packaging.

4.6.2. Contribution of VOCs removal technologies to the 2025 recycling targets

The total HDPE demand sums 6.2 million tonnes in the EU countries (Plastics Europe, 2018), mostly distributed in food contact packaging applications (1.7 million tonnes) and non-food contact packaging applications (1.4 million tonnes) (Marie Kampmann Eriksen et al., 2019). The rest of the end-use markets for HDPE are building and construction, automotive, pharmaceuticals, and electronics.

To achieve the EU target of recycling 55% of post-consumer plastics by 2025, 12 million tonnes
of recycled materials need to penetrate the plastics market. To this end, Hestin et al. (2017) propose a distribution of absorption rates of recycled plastics classified by applications and types of resins. Accordingly, 1.764 million tonnes of recycled HDPE have to be introduced as raw material for packaging applications. Since recycled HDPE cannot be used for food contact applications, only the non-food packaging market can be targeted now, which sums 1.4 million tonnes. Currently, only 143 kt of recycled HDPE a year are used in the non-food packaging sector, which leaves a margin of 1.3 million tonnes of recycled HDPE. Since the VOCs previously identified as odor-causative substances were reduced through the processes studied in this research, VOCs removal technologies implementation can positively impact HDPE recycling rates absorbed by the packaging sector. It is assumed that the removal of odorous substances increases the polymer quality and, thus, the polymers fulfill the quality requirements to be used as raw material for non-food packaging production.

Therefore, assuming that mechanical properties of recycled HDPE are adequate for the manufacturing of packaging, it is considered that the implementation of a VOCs removal process in the mechanical recycling of plastics can assist in replacing 1.3 million tonnes of virgin HDPE.

4.6.3. GHG savings

The replacement of virgin plastics by mechanically recycled plastics avoids Greenhouse Gases (GHG) to the environment. A previous study by Hestin et al. (2015) analyzed the GHG emissions produced by post-consumer plastic waste recovery. The scope of the plastics recovery includes every step of the recycling value chain: collection (17.36 kg CO₂e/t), sorting (26.5 kg CO₂e/t), transportation to recyclers (21.88 kg CO₂e/t) and mechanical recycling (348 kg CO₂e/t). Overall, 413.74 kg CO₂e are produced along the entire HDPE recycling chain. However, GHG emissions derived from the virgin HDPE production (1800 kgCO₂e/t) could be avoided if recycled resins replaced virgin resins. Accordingly, substituting 1 kg of virgin HDPE with 1 kg of recycled HDPE avoids 1386 kg CO₂e/t of GHG emissions to the environment. Replacing 1.3 million tons of virgin
HDPE by recycled HPDE with low VOCs and low odor intensity can save 1.8 Mt CO$_2$e a year. These GHG emissions are equivalent to those produced by 225 000 EU citizens a year, to give an order of magnitude. Nevertheless, these GHG emissions savings are estimated with the data from the conventional mechanical recycling process, which has to be updated with the additional decontamination unit carbon footprint to calculate the real impact.

5. Conclusion
The volatile organic compounds from PCR HDPE were reduced by applying two novel treatments, steam stripping and PEG extraction. As a result, a reduction above 70% was achieved in both cases respect the input pellets extruded with a degassing system. Focusing on the overall VOCs, steam stripping exhibited the highest reduction.

The results were compared to the VOCs emitted from PCR HDPE pellets after applying hot air stripping, which is the current solution developed for VOCs removal in the industry. Steam stripping showed improved efficiency in reducing VOCs content compared to this technology, while the extraction with PEG presented a lower efficiency in removing the overall VOCs than steam stripping and hot air stripping.

Specific compounds corresponding to NIAS and IAS originating from the polymer formulation, external contaminants related to NIAS from detergents and cosmetics, and odor-causative compounds have been evaluated. As a result, the treatment with steam stripping and the extraction with PEG showed an increased reduction of the VOCs associated with contaminants from external sources than hot air stripping. Nevertheless, new substances appear after treating the PCR HDPE pellets with PEG, which do not present a hazard to the environment due to their high degradability, but may expose human health risks, thereby hindering the use of this recyclate in high-value packaging applications.
The melting flow index of the treated samples does not significantly change after treating the PCR HDPE with the proposed treatments, and in the three cases, the MFI value is between the range that permits the manufacturing of sheets, bottles, tubes, and cables.

In short, steam stripping and polyethylene glycol extraction can be recommended to reduce VOCs in PCR HDPE. Both processes improved the plastic decontamination compared to conventional recycling processes that use extraction with a degassing system. Moreover, steam stripping showed an increase in the VOCs extraction yield compared to hot air stripping, which leads to shorter treatment times if the process is developed at an industrial scale.

Regarding energy consumption, with no optimization, hot air stripping seems to be a more cost-efficient solution than the rest, despite all of them should be optimized to get a real estimation of energy costs.

It is expected that the upgraded quality of recycled post-consumer HDPE due to VOCs removal expands the recycled polymers market, creating a positive impact on the environment. Only in the EU countries, replacing virgin HDPE used in manufacturing non-food packaging with recycled HPDE could save up to 1.8 Mt CO2e a year to the environment.

In the future, economic feasibility has to be demonstrated for these processes to bring them into the market. To that end, it is essential to determine the VOCs concentration limit required to use recycled polymers for packaging applications, the process profitability based on utility and equipment cost, and the recycled polymers market price.

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Declaration of competing interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:
CRediT author statement

Andrea Cabanes Gil: conceptualization, methodology, software, investigation, formal analysis, writing-original draft, writing-review and editing, visualization.

Andres Fullana Font: conceptualization, software, funding acquisition, writing-review and editing, supervision, project administration, validation.
Graphical abstract
Highlights

- Odor and contamination in post-consumer plastics limit their reuse for packaging
- Steam stripping and PEG extraction as sustainable solutions to purify plastics
- Steam stripping and PEG extraction applied to post-consumer rHDPE reduce the VOCs
- Increased VOCs reduction with steam stripping than with hot air stripping