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Investigating sustainable approaches to reduce VOCs and odor from mechanically recycled polypropylene

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Post-consumer recycled polypropylene (PCR-PP) often contains volatile organic compounds (VOCs) and odorous compounds, limiting its use in high-value applications. This study investigates three treatment methods – polyethylene glycol (PEG) extraction, heated air purging, and additivation with zeolites to reduce VOCs in PCR-PP. Gas chromatography-mass spectrometry (GC-MS) was used to quantify VOC reduction, with additivation with zeolites achieving the highest reduction (89%), followed by heated air purging (78%) and PEG extraction (73%). Heated air purging was particularly effective for low-boiling-point VOCs, while additivation with zeolites demonstrated broad efficacy across VOC types. PEG extraction, although slightly less effective, provides an alternative method with potential for specific applications. Importantly, none of the methods significantly altered the melt flow index (MFI), maintaining suitability for extrusion processes. Energy consumption analysis highlighted additivation with zeolites as the most energy efficient approach (25 kJ kg^{-1}), followed by heated air purging (72 kJ kg^{-1}) and PEG extraction (159 kJ kg^{-1}). By effectively reducing contaminants without compromising material properties, these approaches enable PCR-PP to meet the quality standards required for non-food packaging applications, such as cosmetics and household products. This research highlights the critical role of advanced decontamination processes in improving the sustainability and market viability of recycled plastics, addressing challenges in the transition to a circular economy and reducing environmental and health risks associated with VOCs in recycled PP.

Sustainability spotlight

This research demonstrates sustainable approaches to reduce VOCs and odors in post-consumer recycled polypropylene (PCR-PP), enhancing its environmental viability. By improving the quality of recycled plastics without compromising material properties, the study supports the circular economy by enabling broader use of PCR-PP in non-food packaging, thus reducing reliance on virgin plastics. Additionally, the methods investigated—especially zeolite additivation—offer energy-efficient solutions, minimizing environmental impact. These advancements contribute to reducing hazardous VOC emissions, mitigating environmental pollution, and promoting the adoption of safer, more sustainable recycling technologies, benefiting both human health and the planet.

1 Introduction

Since the 1950s, approximately 8300 million tonnes of plastic have been produced, generating an estimated 6300 million tonnes of waste by 2015. Of this, only 9% has been recycled, 12% incinerated, and the remainder sent to landfill or released into the environment.[1,2] In Europe, while 30% of plastic waste is collected for recycling, only half is effectively recycled.[3] A significant portion of the remaining plastic waste has historically been exported, often to Asia, with little clarity on its ultimate destination.[4] China's 2017 ban on foreign solid waste, including plastics,[5] disrupted global waste flows and spurred developed nations to expand domestic recycling capacities. In response, initiatives such as the European Commission's target of a 55% recycling rate for plastic waste by 2025 aim to address these challenges.[6]

Polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) collectively account for approximately 80% of plastic waste.[7] High-density polyethylene (HDPE), PP and PET packaging have the highest collection rates of 76%, 68% and 79% respectively.[8] Globally, PET bottles are recycled in large volumes and are frequently used as recycled PET (rPET) in food

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packaging, enabled by decontamination processes verified by the European Food Safety Authority (EFSA). Similarly, food-grade mechanical recycling processes for HDPE have been approved in the UK.[9] Unlike PET, which can be effectively decontaminated by high-temperature, caustic washing and solid-state polycondensation, PP lacks established large-scale purification routes due to its lower thermal stability and higher affinity for hydrocarbon VOCs.[10] In comparison, HDPE generally retains fewer VOCs because of its higher crystallinity and lower polarity, which reduces odor intensity relative to PP. However, PP recycling remains underdeveloped, as it is still largely treated as a single-use plastic outside of limited non-food applications, underscoring the urgent need for new decontamination and recycling strategies.

The growing demand for post-consumer recyclates (PCR), driven by corporate commitments through initiatives like the Ellen MacArthur Foundations Global Commitment programme, has further heightened interest in recycled PP for non-food packaging applications, including cosmetics, home care, and household products (Global Commitment Progress Report 2022). Industries have already integrated PCR into various products including containers, wires, medical supplies, and even furniture.[11–14] Companies such as Hindustan Unilever and Alpha Packaging are exploring the use of PCR PP in daily-use products. However, significant challenges persist, including inconsistency in material properties,[15] and contamination.[16–18] Recycled HDPE and PP often contain non-intentionally added substances (NIAS), such as aldehydes and aromatic acids.[19,20]

One of the most critical issues is the presence of VOCs and odorous compounds in recycled PP, which compromise both safety and consumer acceptance.[21–24] One group of VOCs originates from PP manufacturing and processing, including degradation products, stabilizers, and additives such as hydrocarbons, chlorinated alkanes, and ketones. A second group consists of odorous compounds, particularly aldehydes, terpenes, and diketones, that are typically introduced during consumer use and strongly influence the sensory perception of recycled PP. A third group of contaminants is associated with exposure to healthcare and cleaning agents, including esters, alcohols, and essential oil derivatives, which migrate into the polymer during its service life. Finally, surfactant breakdown during use and recycling generates alkyl benzenes, which are persistent residues in post-consumer plastics and can be challenging to remove. Together, these categories represent the major sources and chemistries of VOCs in recycled PP, highlighting the complexity of developing effective decontamination and deodorization strategies.

While extrusion-based processes, supercritical CO_2 extraction, and commercial systems such as Erema are effective in VOC reduction, they are often energy intensive, time-consuming, and may cause polymer degradation, limiting their widespread application.[10] By contrast, solvent-assisted extraction such as polyethylene glycol (PEG), heated air purging, and zeolite additivation represent three promising routes that are comparatively simpler, less resource-demanding, and potentially more scalable:[25] PEG offers selective solubilization of polar contaminants while remaining non-toxic and environmentally benign. PEG is an attractive solvent due to its high miscibility with water and low toxicity, with potential applications for organic contaminant extraction from recycled plastic.[26,27] Heated air purging provides a cost-effective means of accelerating desorption of volatile molecules without chemical additives. Previously air stripping has been applied to post-consumer HDPE waste providing an approximately 74% reduction after applying extrusion degassing.[28] We have previously demonstrated that heated air purging can remove the VOCs and odorous compounds from multilayer packaging recyclates received from Uflex company situated in India.[29] Zeolites act as molecular sieves capable of trapping a wide range of VOCs while maintaining mechanical stability.[30] A comparative evaluation of these three approaches has not yet been systematically reported for post-consumer PP, despite their individual demonstration in earlier studies.[31,32]

The novelty of this study lies in the direct comparison of PEG-assisted solvent extraction, heated air purging, and zeolite additivation under optimized conditions for PCR PP, enabling a clearer understanding of their efficiency, energy demands, and scalability. Unlike prior reports that focused on HDPE or multilayer packaging, we specifically target PP, which remains underrepresented in decontamination research despite its large market share. Other approaches have focused on the addition of plasticizers, stabilizers, catalysts or solvent blending, but these often interfere with the mechanical and thermal properties of material. Finally, although CO_2-based extraction is energy intensive, it has been explored for high-value applications, achieving 98% VOC reduction after 12 h at 80 °C.[33] Despite the range of available technologies, a systematic comparison of efficiency, energy consumption, and scalability is still needed to identify the most effective methods for VOC reduction in recycled plastic.

In this research, three methods for VOC reduction are investigated; PEG extraction, heated air purging, and additivation with zeolites compared with the raw material. We based our approach to investigating the different treatment techniques on the workflow previously demonstrated by Cabanes and Fullana,[28] but we uniquely focus on PCR PP. The parameters within each process are optimized to achieve effective outcomes. These methods proceeded with a focus of scalability and potential for industrial application which will contribute to advancing sustainable practices in plastic recycling and promoting circular economy. By systematically contrasting these three strategies, this work not only identifies the relative advantages and limitations of each method but also provides insight into their industrial relevance, thereby filling a critical gap in the current recycling literature.

2 Material and methods

2.1 Samples

The samples used in this research were post-consumer recycled polypropylene (PCR-PP) pellets with dimensions of 5 mm in diameter and 2.5 mm in thickness. These sample were made from discarded packaging materials such as sheets, nets, boxes collected in India. The sheets were cut into pieces and shredded into lengths of 6–10 cm using a shredder was from Avanti Technologies with model number Model (BS 100 P). The recycled PP used in this study was unpigmented and unfilled, with no intentional addition of pigments, or other non-volatile additives; however, trace inorganic residues inherent to post-consumer recycling streams may still be present.

After shredding, plastic waste was washed for 30 minutes in 10 L of water with 5 kg material. The washing process involved a continuous flow of hot water at 50 °C in a stirred container, without the addition of surfactants. The washed pieces were then air-dried for 36 h at room temperature before being processed using a co-rotating twin screw extruder SPECIFIQ (specific engineering and automats), ZV20 series to produce pellets. The specifications of twin-screw extruder were as follows: screw diameter = 21.5 mm, channel depth = 4 mm, screw volume (OD/ID Ratio) = 1.55 (OD is called outer diameter and ID is called inner diameter), screw length = 820 mm, screw L/OD (length of injection molding screw/outer diameter) = 40, screw lobe = Bi lobe. The extruder was equipped with a volumetric feeder, an ultimate vacuum 760 mm of Hg, hydraulic screen changer, a water ring dies face cutter, and dry strand pelletizer. The feed throat was maintained at 90–110 °C to avoid pellet bridging and ensure smooth feeding. The barrel heating zones (Z1–Z5) were set at 190, 195, 200, 205, and 210 °C, which are appropriate for polypropylene processing and ensured complete melting and homogeneous dispersion of zeolite within the polymer matrix.

2.2 Methods to remove organic contaminants from recycled pellets

Three methods were implemented to remove volatile organic compounds and odorous compounds from recycled PP pellets: polyethylene glycol extraction, heated air purging, additivation with zeolites. The efficiency of VOCs reduction for each method was compared using gas chromatography-mass spectrometry (GC-MS) analysis.

2.2.1 Heated air purging. Recycled PP pellets were placed in an oven (made by popular traders with model HAC-405) without fan at 100 °C for 12 hours to remove the organic contaminants. Since the melting temperature of PCR polypropylene is 170 °C, this treatment did not affect the polymer's mechanical or thermal properties. 15 g of pellets were spread on a glass plate in the oven. After 12 hours, the pellets were removed, cooled at room temperature for 10 minutes and then sealed in plastic zipper bags.

2.2.2 Additivation with zeolites. A 15 g of sample of recycled PP pellets was mixed with 1.5 g of zeolites and extruded twice (details mentioned in 2.1) to ensure better mixing. The extruder speed was set to 350 rpm, with the polymer feeder running at 20 rpm.[34] The extruder operated at 6.52 amp and 87 bar pressure. It featured five temperature zones (Z1 to Z5), with temperature ranging from 160 °C to 195 °C. The polymer thread was cut using a die and then passed through a cooling water bath for a few minutes. The resulting pellets were left at room temperature for 24 hours to remove moisture before being packed in plastic zipper bags.

2.2.3 Polyethylene glycol extraction. PEG 400 was used to reduce VOCs from recycled PP packaging waste. In a 250 ml beaker, 15 g of PP pellets were mixed with 150 ml PEG 400. The mixture was heated at 100 °C, as measured by a temperature probe, and stirred using a magnetic stirrer for 2 hours. Afterwards, the pellets were separated from the solvent using sieve. The pellets were then washed with cold water and stirred in water for 30 minutes using a magnetic stirrer. Finally, the pellets were dried at room temperature for 24 hours before analysis.

2.3 Extraction of volatile organic compounds by headspace solid phase micro extraction (HS-SPME)

The HS-SPME technique was applied to extract the VOCs for GC-MS analysis. For each sample, 10 ± 0.1 g of material was placed in a 100 ml glass vial. This vial was sealed with a septum made of silicon/Teflon. After sealing, an SPME syringe equipped with a 75 μm polydimethylsiloxane (PDMS) fiber was inserted through the septum and left in place for 1 hour at 60 °C. The PDMS fiber efficiently adsorbed VOCs and odorous compounds emitted by recycled pellets.

2.4 Analysis of volatile organic compounds by gas chromatography mass spectroscopy

After adsorbing the VOCs onto the fiber surface, the fiber was inserted into the injection port of the GC-MS, manufactured by Thermo Fischer, equipped with a non-polar HP5 column DB 624 (260 °C), 30 m × 250 μm × 0.25 μm. Following separation, VOCs were directed to mass spectrometer *via* the capillary column. Various parameters used for the analysis in GC-MS analysis are detailed in Table S1.

2.5 Identification of volatile organic compounds and odorous compounds by NIST database

To identify the VOCs in PP waste, we used the National institute of standards and technology (NIST) library for the match with GC-MS database.

2.6 Melt flow index

The melt flow index (MFI) of PCR-PP and zeolite-filled composites was measured using a Dynisco LMI 4000 plastometer, calibrated according to ISO 1133-1. The test was carried out at 230 °C with a load of 2.16 kg, which corresponds to standard conditions for polypropylene. Approximately 2.16 g of sample was tested at ten different measurement points, and the mean value was reported.

2.7 Energy consumption

The potential energy required for the methods applied during the process was estimated with different enthalpies using data of certain heating system (see Table 1). The ambient temperature for all the processes were in between 25 °C to 100 °C. Addition of latent heat of vaporization has done in case of steam.

Table 1 Formulas to calculate the enthalpy difference for three different methods

Method	Equation	Energy consumption (kJ Kg^{-1} fluid)
PEG extraction	$\Delta H_{\text{air}} = \int_{25}^{100} C_{\text{p,air}}\,\mathrm{d}T + X_{\text{water}} \int_{25}^{100} C_{\text{p,water}}\,\mathrm{d}T$ (I)	159
Heated air purging	$\Delta H = \int_{25}^{100} C_{\text{p,PEG}}\,\mathrm{d}T$ (II)	72
Additivation with zeolites	$\Delta H_{\text{steam}} = \int_{25}^{100} C_{\text{p,water}}\,\mathrm{d}T + \Delta \mathrm{H}_{\text{evaporation}}$ (III)	25

3 Results

3.1 Overall volatile organic compounds and subgroups

Three methods were applied to reduce VOCs and odorous compounds from recycled PP pellets: PEG extraction, heated air purging, and additivation with zeolites. Fig. 1a shows the control sample, the PP without any treatment method. Fig. 1b shows the pellets of sample that have been treated with PEG extraction method. Fig. 1c showed the PP that has been treated with heated air purging. Finally, Fig. 1d shows the GC-MS data for the PP that has been treated with additivation with zeolites. For the GC-MS data for all the different treatment methods it was clear that there were qualitative differences in terms of the types of VOCs removed by the different treatments and also the amount of VOCs present. By determining the total area under the peaks for each treatment method and comparing it to the control sample, the total quantity of VOCs was reduced by 73% after PEG extraction, 78% after heated air purging, 89% after additivation with zeolites. During this process, part of the VOC reduction may arise from volatilization at extrusion temperature, in addition to adsorption within the microporous zeolite framework. The zeolite particles remain embedded in the PP matrix after compounding, together with the VOCs adsorbed on their surfaces, and were not removed prior to analysis. Therefore, the measured VOC reduction reflects the combined effect of volatilization during extrusion and adsorption by zeolite, rather than adsorption alone. A no-zeolite blank extrusion was not performed in this study and is identified as a limitation for

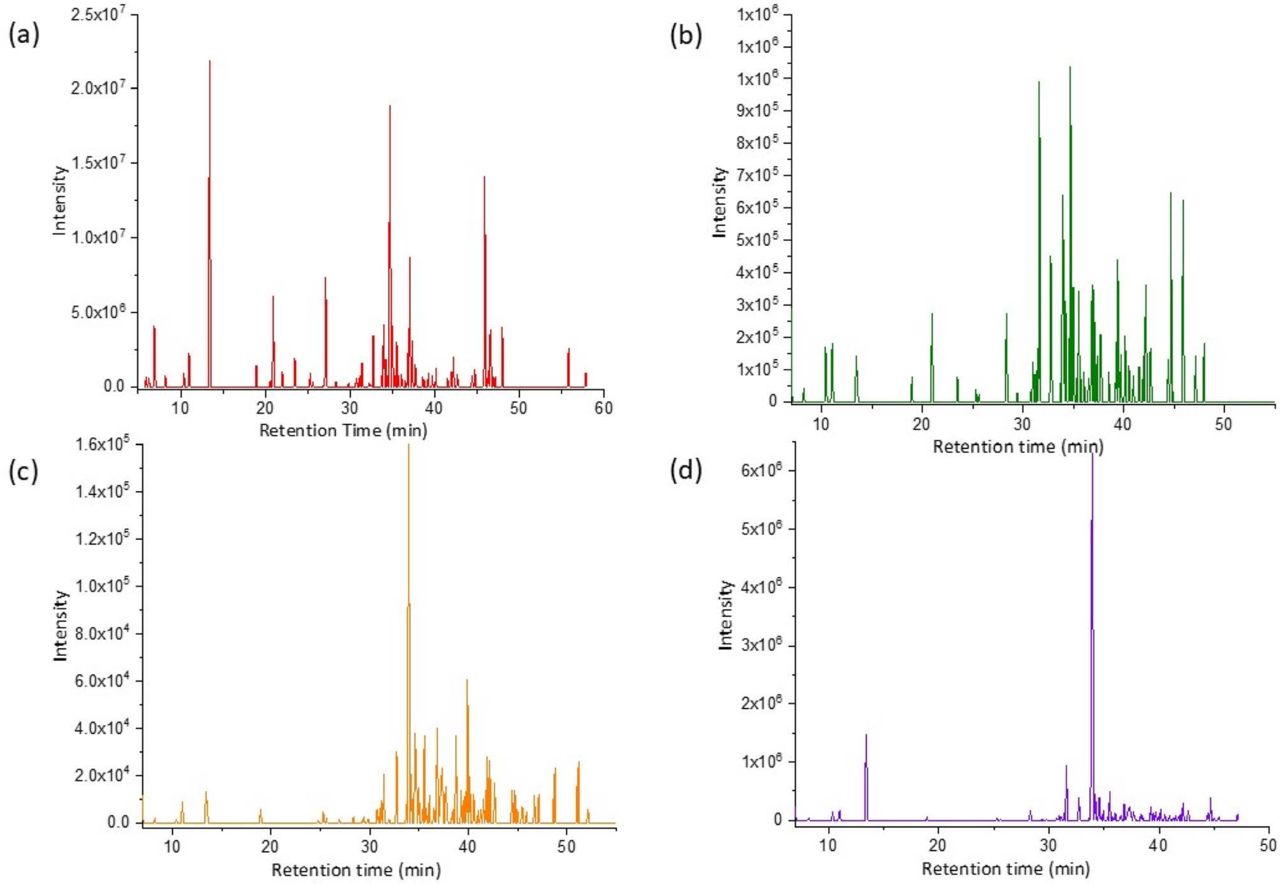

Fig. 1 Effect of treatment type on the reduction of VOCs from recycled PP as determined by HS-SPME-GC-MS: (a) post-consumer recycled PP pellets (b) PEG extraction materials, (c) heated air purging materials, (d) additivation with zeolites.

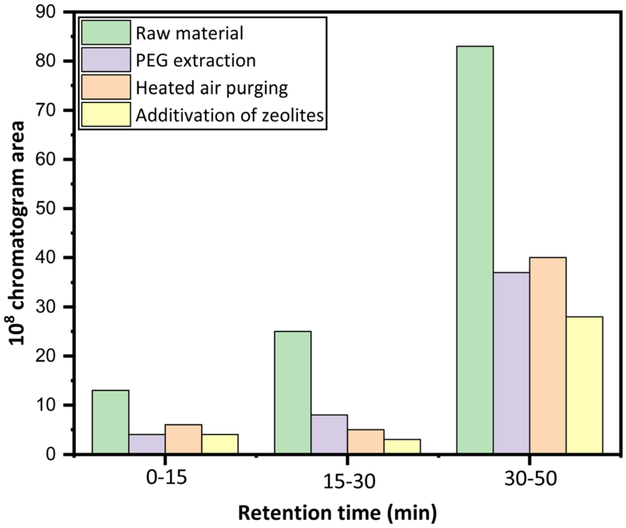

Fig. 2 Peak area of volatile organic compounds and odorous compounds, broken down in three regions based on retention time, for post-consumer recycled PP when treated by: PEG extraction, heated air purging or additivation with zeolites.

future work. The types of VOCs removed by the different treatment methods will be explored in more detail in the subsequent sections of the paper.

To categorize the differences between the VOCs, we found the different treatment methods. The chromatogram area was divided into three regions based on retention time (Fig. 2). The first region (0–15 minutes) includes VOCs with high volatility and vapor pressure with a smaller number of VOCs presence, the second region (15–30 minutes) comprise VOCs with intermediate volatility, while the third region (above 30 minutes) contains volatile organic compounds which had the strongest affinity with recycled PP pellets. The untreated sample exhibited the highest concentration of VOCs in the third region, with lower level in the first region, aligning with the detection of lighter compounds with higher vapor pressure below 15 minutes. Notably, heptane (retention time 33.93), the most prominent VOC, exhibited a stronger affinity with polypropylene than limonene (retention time 13.42) and remained at elevated levels even after treatment.

3.2 Specific volatile organic compounds

Among the organic contaminants present in recycled PP, 18 representative VOCs were selected to evaluate treatment efficiencies. These VOCs and odorous compounds were grouped into four categories, and their relative levels were determined post-treatment by comparing with the control PP sample. The first group comprises compounds originating from PP manufacturing or processing, including nonadecane; 1-chloro hexadecane; acetophenone, which function as antioxidants, degradation products and additives.[20,35] As shown in Fig. 3a, the PEG extraction showed the greatest reduction for acetophenone and 1-chlorohexadecane. Heated air treatment decreased nonadecane by 40% and completely removed 1-chloro hexadecane and acetophenone. Zeolite additivation entirely removed nonadecane and significantly reduced acetophenone but was less effective for 1-chlorohexadecane. Among the methods, heated air purging showed the greatest overall effective reduction of these VOCs.

The second group contains odorous VOCs commonly found in post-consumer recycled PP, including 2-butyl octanal; 5-hydroxycyclooctane-1,2-dione; limonene; tridecanal.[36,37] Fig. 3b shows that heated air purging achieved over 50% reduction of these odorous compounds, with limonene proving the most persistent and difficult to eliminate across treatments. However, heated air purging provided the highest reduction for limonene. Tridecanal, though less effectively removed by PEG extraction, showed >99% reduction after zeolites additivation.

The third group includes six VOCs associated with ingredients in healthcare or cleaning products, such as hexyl acetate; ethyl acetate; methyl salicylate; 4-methyl,2-propyl-pentanol; eucalyptol that contaminant post-consumer recycled plastics.[38] Fig. 3c indicates that 2-propyl-4-methyl pentanol was entirely removed by both PEG extraction and additivation with zeolites. Eucalyptol was fully eliminated by heated air purging, while ethyl acetate and methyl salicylate showed similar reductions across all three methods. Hexyl acetate showed the greatest reduction, down to 20%, following zeolite additivation.

The fourth group consists of six alkyl benzenes, surfactant breakdown products, including 1,2,4-trimethyl benzene; 1-methyl-3-propyl-benzene; 1-methyl-4-propyl-benzene; 1,2-dimethyl-4-ethyl benzene; 1,2,4,5-tetramethyl benzene; 2,3-dimethyl-1-ethyl benzene (see Tables S4–S7). As seen in Fig. 3d, alkyl benzene was reduced by more than 80%, with 1-methyl-4-propyl-benzene completely removed by PEG extraction and heated air purging. Heated air purging and additivation with zeolites also significantly reduced 1,2,4,5-tetramethyl, and 2,3-dimethyl-1-ethylbenzene was undetected following heated air purging.

Overall, each method's effectiveness varied by compound type and molecular properties and no single treatment methods showed superior behaviour across the VOCs of interest. The results demonstrate substantial VOC reduction across all treatments; however, we do not claim complete elimination. Since only single-pass treatments were tested, further retreatments may yield additional but smaller reductions. This limitation will be addressed in future work.

3.3 Study of melt flow index

Melt flow index (MFI) is useful to assess the flow behavior and processability of recycled PP. The MFI of PCR-PP and its treated variants was determined according to ISO 1133-1 at 230 °C under a 2.16 kg load. As shown in Fig. 4, the untreated control exhibited an MFI of 0.35 ± 0.01 g/10 min. The sample treated with PEG extraction showed a reduced value of 0.24 ± 0.01 g/10 min, representing the only treatment with a measurable deviation from the control. In contrast, the samples treated with heated-air purging (0.33 ± 0.01 g/10 min) and with zeolite additivation (0.34 ± 0.01 g/10 min) remained statistically comparable to the untreated control within the margin of error. These results confirm that, except for PEG extraction, the applied treatments do not significantly affect the flowability of

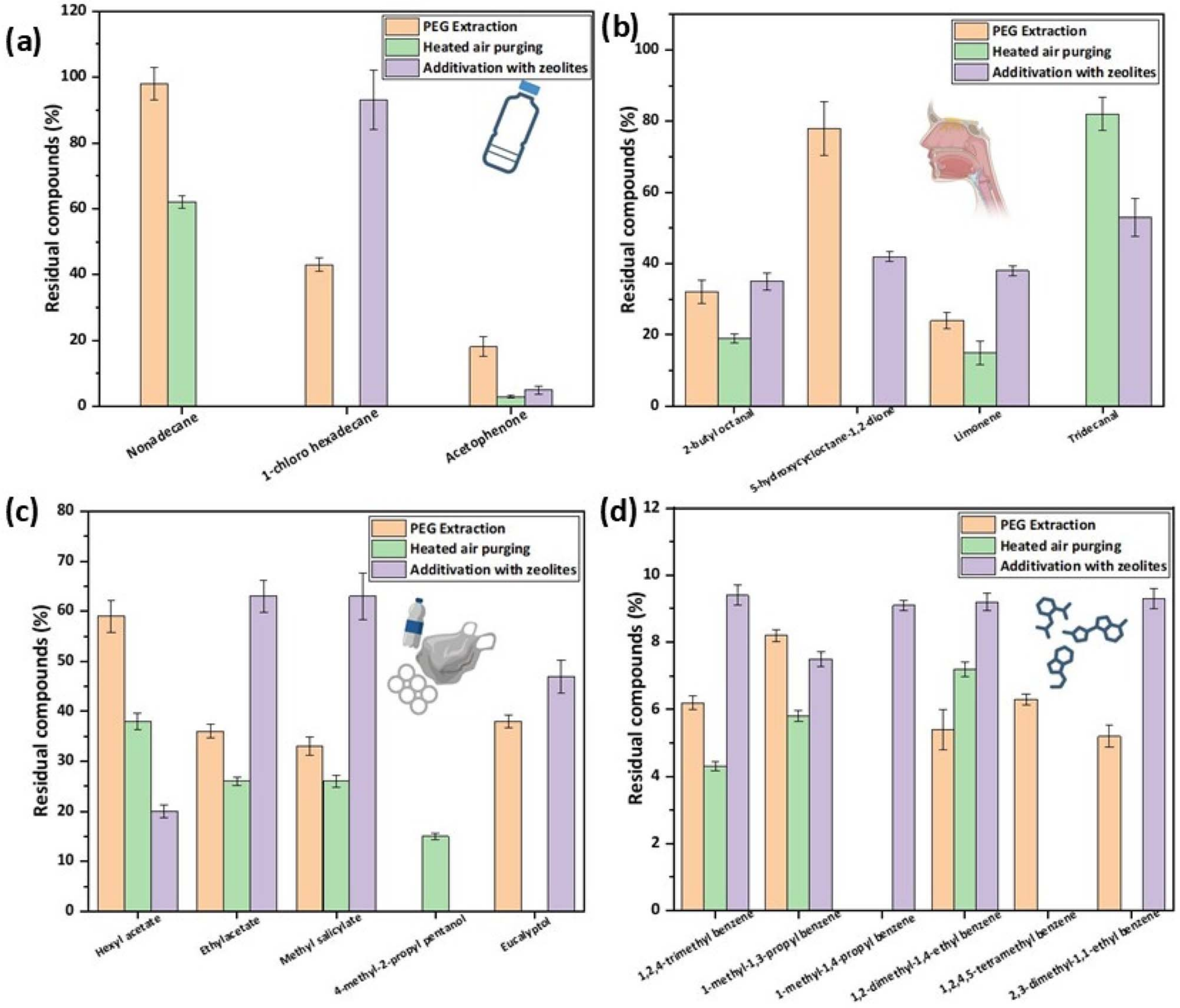

Fig. 3 Relative concentrations of VOCs after PEG extraction, heated air purging, and additivation with zeolites, expressed as percentages relative to untreated recycled PP (set as 100%). (a) VOCs associated with virgin PP, (b) odorous compounds, (c) migrating substances originating from healthcare and cleaning agents, and (d) breakdown products such as alkyl benzenes. The *y*-axis scales differ among the graphs to enable clear representation of the data.

recycled PP, thereby preserving its suitability for standard melt-processing operations.

3.4 Energy consumption

The energy consumption for each VOC reduction method was calculated. PEG extraction consumed the most 159 kJ kg^{-1}, followed by heated air purging is 72 kJ kg^{-1}, and additivation with zeolites is 25 kJ kg^{-1}, making zeolite additivation the most energy-efficient method. However, the energy consumption for heated air purging also warrants consideration, as the VOCs are expelled at 100 °C, providing a significant thermal source. This latent heat could potentially be recovered and utilized within the system in vaporizing, recuperating, or waste heat boiler applications. For additivation with zeolites, based on calculations by,[39,40] the energy is primarily consumed during extrusion, requiring 10–15 kW. This total energy includes purging, degassing, and warming the instrument of the equipment. Energy requirements during processing also depend on the amount of plastic treated. Larger batches of pellets consume proportionally less energy per kilogram due to economics of scale, for instance, processing 1 kg compared to 10 g yields a more efficient VOC reduction per unit. Increased pellet qualities further enhance latent heat recovery in which A, B, C, D, E, F, G, H are coefficients specific to the substance being analyzed. However, these methods still require quantitative optimization for ideal energy efficiency (see Table 2).

3.5 Comparison of different treatments based of specific VOCs

The VOCs originating from surfactant products, as outlined in Section 3.2.4, were analyzed to compare the efficiency of heated air purging and additivation with zeolites. The percentage of

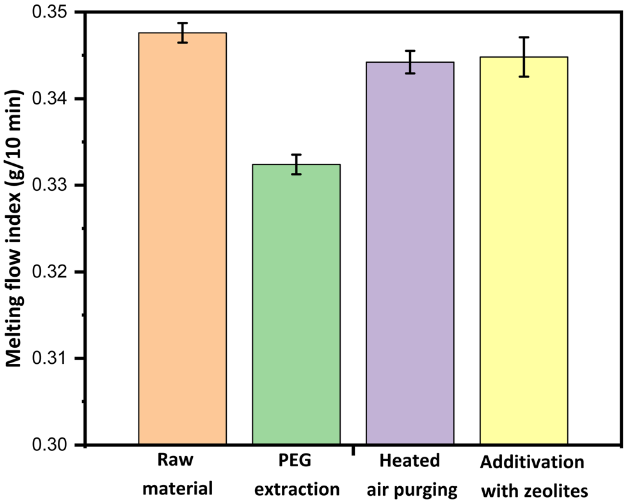

Fig. 4 Comparison in melting flow index of raw material and the materials after applying either PEG extraction, heated air purging or additivation with zeolites method.

Table 2 Parameters to calculate the enthalpy from 1 g of each material

Method	Parameters	Value	References
PEG extraction	Specific heat	2.12 kJ kg^{-1} °C	41
Heated air purging	Specific heat ($C_{\mathrm{p,air}}$)	1.02 kJ kg^{-1} °C	42
	Specific heat ($C_{\mathrm{p,water}}$)	1.8 kJ kg^{-1} °C	43
	Saturated water fraction in air at 25 °C	0.021 s.u.	44
Additivation with zeolites	Vaporization water enthalpy coefficients	A: −203.6 B: 1523.3 C: −3196.41 D: 2474.46 E: 3.86 F: −256.5 G: −488.71 H: −285.8	28

residual VOCs after each treatment is shown in Fig. 5a. Points below the diagonal indicate higher removal efficiency with heated air purging, while compounds above the diagonal correspond to higher efficiency of zeolite additivation. Compounds with higher molecular weight and boiling point were removed comparably well by both treatments, whereas heated air purging was more effective for low-boiling VOCs. This behavior can be explained by the principle (Meissner & Greenfeld, 1948) that boiling points influence azeotropic composition. To further investigate, 36 organic contaminants from recycled polypropylene with boiling points between 130–370 °C were matched with literature data (Corrections for Azeotropic Data—I, 1973). It was observed that high-boiling VOCs occurred only at low concentrations (<1%). Consequently, heated air purging is particularly effective due to the elevated temperature, which facilitates dissipation of low-boiling azeotropes, while heavier compounds showed similar reductions with both methods.

A comparison of the residual VOCs after PEG extraction and heated air purging is presented in Fig. 5b. In this case, points below the diagonal indicate higher efficiency for heated air purging, whereas points above correspond to greater efficiency for PEG extraction. As most compounds lie above the diagonal, PEG extraction was overall more effective in reducing VOCs compared to heated air purging. Finally, the efficiency of PEG extraction *versus* zeolite additivation was evaluated (Fig. 5c). Here, points above the diagonal correspond to higher efficiency of PEG extraction, while points below the diagonal indicate greater efficiency of zeolite additivation. As the majority of compounds are located below the diagonal, zeolite additivation was overall more effective than PEG extraction for VOC removal in recycled polypropylene.

4 Discussion

The different extraction methods led to considerable differences in efficiency and selectively of the removal of different VOCs. The efficiency of VOC removal methods was compared for surfactant-related compounds, showing that heated air purging is particularly effective for low-boiling-point VOCs, while both heated air purging and additivation with zeolites performed similarly for high-boiling-point compounds. PEG extraction generally exhibited lower VOC reduction efficiency compared to both heated air purging and additivation with zeolites, with the latter demonstrating the highest overall VOC removal. These findings highlight the varying effectiveness of the methods depending on compound properties, particularly boiling points and azeotropic behaviours.

The overall VOC reduction achieved by PEG extraction was approximately 74%. However, new compounds appeared in the chromatogram after PEG extraction, as analyzed by HS-GC-MS. These identified substances include hexane; 2,3,4-trimethyl hexane; propanamide; α-thujene; 4-methyl nonane (see Table S2). Cabanes *et al.* applied PEG Extraction method after extrusion degassing on HDPE, observed no generation of new compounds.[28] There must be a reason that extrusion degassing is the most important step to restrict new compounds. Each compound was detected at a much lower concentration compared to limonene and hexane, with boiling points below 215 °C. Among them, propanamide showed the highest boiling point (213 °C) but contributed the lowest area percentage in the chromatogram. Notably, three of the five compounds were alkanes, likely originating from the PEG monomer chain.

The environmental impact of any substance can be partially assessed through its biodegradability. Hexane emissions often occur due to evaporation during the production or incomplete fuel combustion. Hexane has low solubility in water (0.0098 g L^{-1}) and a high vapor pressure (10 kPA). A read-across study on naphtha biodegradation (primarily C4–C11 alkanes) indicated that hexane degrades relatively easily.[45] The environmental impact of 2,3-dimethylhexane depends on factors such as its production, usage, disposal, and possible release into the environment. While details on the environmental toxicity of 2,3-dimethylhexane are limited, as a hydrocarbon, it may pose risks if released into the natural ecosystem, especially concerning air,

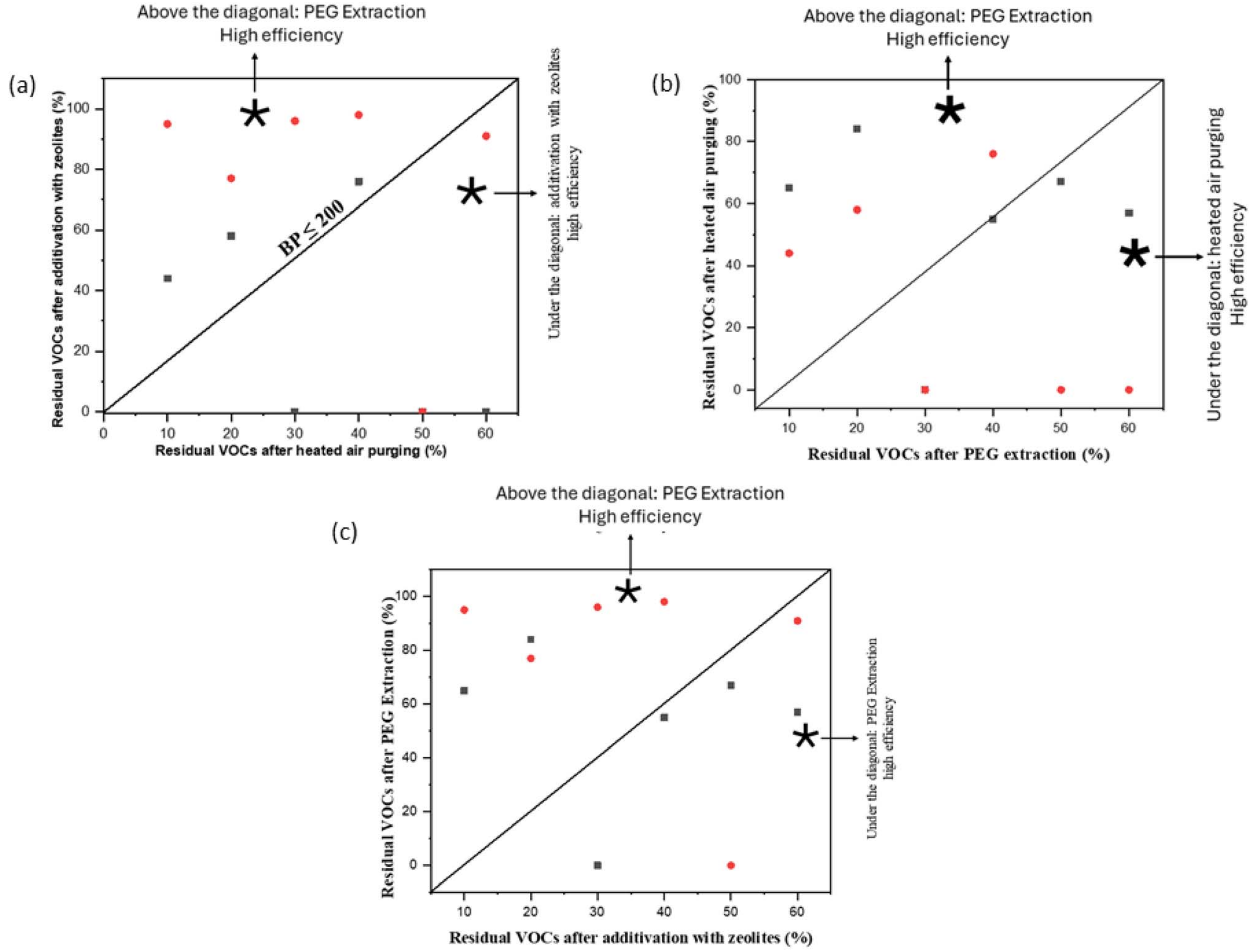

Fig. 5 Comparative efficiency plots of (a) PEG extraction *vs.* heated air purging, (b) PEG extraction *vs.* heated air purging (alternative analysis), and (c) PEG extraction *vs.* zeolite additivation. Points above the diagonal indicate higher efficiency of PEG extraction, while those below represents greater efficiency of the alternative treatment method.

water, and soil contamination, which could negatively affect both ecosystems and human health. Propanamide is commonly used in various industrial processes, including the production of polymers and pharmaceuticals. Although propanamide itself may not represent a significant environmental risk, its manufacture, use, and disposal could lead to environmental impacts that require proper handling and regulatory oversight. Thujene, a natural organic compound found in various plants, particularly in coniferous trees like cedar and pine, typically does not pose environmental concerns due to its natural abundance. Conversely, 4-methylnonane, though less studied could present risks to air quality, aquatic environments, and human health if not appropriately managed.[46–48] The environmental impact of the identified substances ranges from low risk for naturally occurring thujene to moderate risks for hexane, 2,3-dimethylhexane, propanamide, and 4-methylnonane, which require careful management due to their potential for environmental contamination and health hazard.

The health impact organic compounds identified in the PEG extraction product were assessed using European commission regulation (number 10/2011)[49] which lists compounds permitted for contact with food in plastic products. According to this EU regulation, compounds not included on this list are unsuitable for use in food contact items like boxes, cups, mugs, and plates. None of the five compounds from our analysis were listed.

Further investigation was conducted using the European CosIng database on the official website of the European Council to assess their relevance in cosmetic products. Hexane was the only compound flagged on this list, classified under the chemicals directive 67/548/EECC as a Carcinogenic, Mutagenic, or Toxic to reproduction (CMR) substances. Hexane appears in European regulation 1223/2009 under entry 999 as a restricted ingredient in cosmetics, where it is prohibited due to its potential to cause skin irritation and rashes. The remaining compounds (2,3-dimethyl hexane; propanamide; thujene; 4-methyl nonane) were not listed as hazardous in cosmetics. Additionally, according to Registration, Evaluation, Authorization and Restriction of chemicals (REACH) regulation and substance at very high concern (SVHC) list, none of the five compounds were present, confirming they are not considered of high concern under Article 59(10) of the REACH Regulation.

The breakdown products from PEG extraction process showed less than 1% area in the chromatogram which aligns with regulatory thresholds.[50] Since the contaminated compounds do not present significant health and environment risks, PEG extraction offers a promising method for creating high value products such as household and home care products. This process significantly reduces VOCs, highlighting its value in enhancing the safety and utility of recycled plastic products.

The three different treatment methods did not cause any important changes in the MFI values for the PCR PP. For PP, the MFI range should be in between 0.1 g min^{-1} to 0.5 g min^{-1} for extruding the sheets, nets, wires and lids, all treatments resulted in PP with MFI values within this range. Comparing these findings with[51] for the quality and processability of recycled PP reports that commercially available PP post-consumer recyclates usually exhibit melt mass-flow rates (MFR) typical for injection molding grades, with MFR values around 2–4 g/10 min. These higher MFR values are suitable for injection molding but may require adjustment for extrusion processes that demand lower MFI values.

Feasibility Study on the Production of Low Melt Flow Rate Recycled Polypropylene research investigates producing low MFR of PP recyclates from packaging waste, aiming for MFR values suitable for extrusion applications. The challenges in achieving low MFR values directly from recyclates and suggests blending with virgin materials to attain the desired flow properties.[52] This research aligns with the literature cited, demonstrating that appropriate treatment methods can adjust the MFI of recycled PP to meet specific application requirements. Achieving MFI values within the 0.1 to 0.5 g/10 min range indicates that treated PCR PP is well-suited for extrusion processes, comparable to or even better than some reported recyclates. This comparison underscores the effectiveness of treatment methods in tailoring the rheological properties of recycled PP for targeted applications.

Heat transfer process occurs by exchanging thermal energy from on medium to other. The fluid starts energy to polymer material from its ambient temperature (25 °C) to 100 °C. Heat transfer coefficient and temperature difference between two mediums are responsible for heat transfer ($\mathrm{d}T = 75$ °C in this case). To calculate the heat transfer, Newton's law of cooling is used ($Q = hA(T - T\infty)\Delta t$, where h is the heat transfer coefficient, A the surface area, T the object temperature, and $T\infty$ the surrounding temperature). Heat transfer coefficient values are mentioned in Table S3. While the area is considered as constant. The value of heat transfer rate is similar for PEG extraction and additivation with zeolites method. The minimum value is calculated for heated air purging *i.e.*, 37.5 kW m^{-2}. However, for HDPE each fluid results in a heat transfer rate of 38 kW m^{-2} for the air purging.[28] It has been calculated that VOC reduction by CO_2 extraction method is 765 kW m^{-2}, which is more than twenty times.[53]

The principles of sustainability and a circular economy are essential in advancing the polypropylene recycling market. Reduction of VOCs in recycled PP reflects the quality improvement that could significantly increase its demand within the packaging industry.[54] Nowadays, additives such as plasticizer, resins, zeolites help limit contamination in recycled plastics, more of which originates from material itself.[55] A major source of contamination occurs when packaging interacts with food products or is collected alongside other material, generating substantial VOCs emissions and off-odor that can restrict market entry.[56] Additionally, these contaminants can raise health concerns for both packaging producers and consumers. According to the European regulation 10/2011, recycled plastic packaging is not permitted in food industries. Significant research has been conducted on the life cycle assessment of recycled PP, assessing impact from the manufacturing phase to collection.[57–59] However, there is limited research focused on addressing recycling challenges with cost effectively.[20,60,61] The only exception within food packaging is recycled PET bottles, where the EFSA has approved bottle-to-bottle recycling due to effective decontamination and deodorization. Research is ongoing for HDPE and LDPE, but no equivalent advancements have been made for PP, which is widely used in nets, sheets, lid, bottle caps, and bottles for non-food packaging. Since effective, deep decontamination and deodorization methods for PP are still unavailable, its use largely remains limited to non-food packaging that does not require decontamination.

5 Conclusion

Recycled PP is extensively used in application like sheets, nets and bottles for outdoor use, where higher concentration of organic contaminants is often present. As these materials are frequently repurposed for body care and cosmetics products, post-consumer recycled PP contains VOCs originating from cosmetic ingredients and surfactant oligomers. This study demonstrates that VOC reduction is achieved by three different treatment methods, with each method effectively decreases VOC concentrations while maintaining the MFI value similar to that of the starting PCR PP, which supports extrusion requirements for high value applications. These results underscore the critical role of advanced decontamination methods and improved sorting processes in enhancing the quality of recycled PP, reducing cross-contamination, and addressing market barriers. By aligning with European regulations on additives and packaging standards, these methods contribute to advancing the sustainability and market viability of recycled PP. This study provides a practical pathway for integrating sustainable decontamination processes into PP recycling, promoting broader adoption in non-food and potentially high-value applications, and supporting the transition to a circular economy. While MFI was used as a standard indicator of processing quality, it does not fully represent the complete mechanical performance of the composites. Moreover, the present study demonstrates the relative effectiveness of the treatments in reducing VOCs, but absolute quantification of residual VOC levels is still needed for end-use safety. A follow-up study employing complementary techniques such as thermal desorption GC/MS with calibration standards is planned to address this limitation.

Conflicts of interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Pragti Saini reports financial support was provided by Ministry of Education, India. Tom McDonald has previously received financial support or in-kind support for prior research projects with plastic recycling and packaging companies. For the other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. The raw datasets, including FTIR spectra, GC-MS data, and other analytical results, have been stored securely and can be shared in compliance with institutional and journal guidelines. Additionally, any processed data or SI used for analysis and validation in this study will be made available upon request.

Supplementary information is available. See DOI: **https://doi.org/10.1039/d5su00242g**.

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