TECHNICAL PROJECT REPORT

Analysis of Technical Barriers for Non-Food Rigid Plastic Packaging in Norway
Closed-loop recycling and harmonised material specifications for non-food rigid plastic packaging

Prepared for: Grønt Punkt Norge, Orkla HPC, Unil, Coop Norge, Plastretur and Norsk Formblåsing

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Title

Analysis of Technical Barriers for Non-Food Rigid Plastic Packaging in Norway

Author(s)	Approved by
Karolina Stankiewicz	Tanja Radusin

Background

The project addresses the need to establish more circular material flows for non-food rigid plastic packaging in Norway. It focuses on identifying harmonised material specifications and evaluating the technical barriers that affect the use of post-consumer recycled HDPE in new packaging. The work includes mapping relevant packaging streams, defining key requirements, preparing PCR recyclates from Norwegian HDPE waste fractions and testing bottles produced with different recycled-content levels.

Conclusions/Proposals

The project demonstrated that high-quality HDPE recyclate can be produced from Norwegian household waste collected through both source-separated (SAS) and mixed residual waste (MRF) collection systems. HDPE was identified as the most promising material stream for closed-loop mechanical recycling of non-food rigid packaging in Norway, supported by its strong representation in Home and Personal Care applications and the possibility of developing harmonised material and packaging specifications. The SAS fraction consistently showed higher purity, lower contamination and better colour performance than the MRF fraction, while both streams proved technically suitable for producing packaging-grade PCR HDPE after appropriate washing, sorting and colour separation.

Pilot-scale bottle production confirmed that Norwegian white PCR HDPE can be successfully processed into extrusion blow moulded bottles. Bottles containing 35% PCR showed properties closest to the virgin HDPE reference, while 65% PCR also provided satisfactory performance for many applications. Increasing PCR content reduced impact resistance, ESCR and ductility, although all investigated materials remained processable. The results also demonstrated that recycled material qualification should not rely only on material specifications or supplier TDS values, but must include application-specific testing of the final packaging. The loop recycling simulation, based on 65% material carry-over from the previous recycling cycle with 35% virgin HDPE added in each subsequent cycle, confirmed that the selected HDPE system can maintain stable material quality over repeated mechanical recycling loops. Overall, the key remaining challenge is to establish a coordinated Norwegian value chain that can collect, sort and supply sufficient volumes of packaging-grade recyclate for new packaging production.

Proposal for further work

Attachments

Legal notice[i]

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1. Executive Summary

The project Analysis of Technical Barriers for Non-food Hard Plastics in Norway investigated the technical barriers and requirements for enabling closed-loop recycling of non-food rigid plastic packaging in Norway. The initial work covered non-food rigid plastic packaging more broadly, including the mapping of relevant product categories, packaging requirements and potential for harmonisation. Based on the collected market data and technical results, HDPE was identified as the most promising stream for further closed-loop mechanical recycling work. The subsequent project activities therefore focused on the Norwegian HDPE waste stream.

The work combined market analysis, packaging harmonisation, material characterisation, pilot-scale recycling, bottle production and packaging performance testing. Four Home and Personal Care packaging categories were identified as suitable for harmonisation because they share similar functional requirements and together represent a significant proportion of the Norwegian non-food HDPE packaging stream. Based on these findings, the project developed a harmonised HDPE packaging specification covering material selection, colour, design-for-recycling principles and packaging components.

The project demonstrated that high-quality HDPE recyclate can be produced from Norwegian household waste collected through both source-separated (SAS) and mixed residual waste (MRF) collection systems. Although the SAS fraction consistently exhibited higher purity, lower contamination and better colour performance than the MRF fraction, both waste streams proved technically suitable for producing packaging-grade PCR HDPE after appropriate washing, sorting and colour separation. The work also identified colour variation within the white packaging stream as one of the main factors limiting material recovery, demonstrating the importance of harmonising white shades placed on the Norwegian market.

Pilot-scale bottle production confirmed that recycled white HDPE from Norwegian waste can be successfully processed into extrusion blow moulded bottles. Increasing recycled content gradually reduced mechanical performance, particularly impact resistance and ductility, but bottles containing 35% PCR maintained properties very close to the virgin reference material. Formulations containing 65% PCR also showed promising performance, while 100% PCR remained technically feasible but with a larger reduction in mechanical robustness. The results further demonstrated that packaging performance cannot be predicted solely from supplier material specifications or standard material tests. Application-specific testing, including blow moulding trials, dimensional measurements, drop testing and top-load evaluation, proved essential for assessing the suitability of recycled materials for packaging applications.

Repeated loop recycling simulations further demonstrated that the selected HDPE system can maintain stable material properties over multiple recycling cycles, confirming the technical feasibility of closed-loop mechanical recycling under controlled conditions.

The results demonstrate that cooperation between brand owners, packaging manufacturers, producer responsibility organisations, sorting facilities and recyclers can enable Norwegian household HDPE packaging to be collected, recycled and returned as high-quality PCR material for new packaging production.

Overall, the project provides both the technical evidence and the practical framework required to support future implementation of a Norwegian closed-loop system for non-food HDPE packaging and contributes directly to achieving future recycled-content targets while strengthening domestic circular material flows.

2. Project Background and Objectives

2.1 Background

The project addresses the need to establish more circular material flows for non-food rigid plastic packaging in Norway. Today, closed-loop recycling of plastic packaging is limited by fragmented material specifications, varying packaging requirements and insufficient homogeneous volumes for sorting and recycling. For mechanical recycling to deliver material quality suitable for new packaging applications, larger streams of packaging with similar material compositions and performance requirements are needed.

The project focuses on non-food products packaged in rigid plastic, including categories such as cleaning products, hygiene products and other household-related applications. These packaging types are considered suitable for analysis because they are generally less complex than food-contact packaging from a regulatory perspective and often involve fewer challenges related to printing inks, multilayer structures and advanced barrier materials. By identifying packaging with comparable technical requirements, the project will provide a basis for harmonised material specifications and improved opportunities for closed-loop recycling.

2.2 Background from the Roundtable Meeting 18.04.2024

The project was initiated in response to a shared need identified by the project partners during the roundtable discussions on 18.04.2024. The discussions confirmed strong interest in harmonising material specifications for non-food rigid plastic packaging, while also highlighting practical, technical and commercial barriers that must be addressed before closed-loop recycling can be implemented at scale.

A key reason for creating the project was the partners' need for better access to high-quality recycled material that can support future packaging requirements, internal sustainability goals and credible use of recycled content in packaging. The partners also saw potential benefits from larger volumes of similar packaging materials, including reduced sorting and recycling losses, more homogeneous recycled streams and clearer design guidance for packaging developers.

At the same time, the roundtable identified important partner needs to define the scope of the project. Producers require packaging solutions that allow brand differentiation and consumer navigation, while some product categories may require specific functions such as light protection, oxygen or scent barriers, chemical resistance or higher mechanical performance. This confirmed that the project should identify both common packaging specifications and justified exceptions where specific technical requirements apply.

The project started with a kick-off meeting in January 2025, where the partners reviewed the project scope, objectives and planned activities. As part of the meeting, short workshops were held with the project partners to identify key needs and challenges related to increased use of PCR plastics in packaging. The discussions covered design-for-recycling requirements, material specifications, quality criteria and practical barriers associated with recycled PET, HDPE and PP, providing valuable input for defining the project priorities and guiding the technical work.

Overall, the roundtable and kick-off workshops confirmed that the project should deliver a practical, evidence-based framework for harmonisation. This included collecting confidential volume and polymer data, analysing Norwegian waste streams from different sources, assessing recycled materials, carrying out packaging production trials, developing basic specifications, demonstrating proof of concept and supporting coordinated action among producers, packaging manufacturers, sorting actors and recyclers to enable closed-loop recycling.

2.3 Project Objectives

The overall objective of the project is to identify which non-food rigid plastic packaging applications have similar technical requirements and can therefore potentially use harmonised material compositions. This will support the development of packaging categories that can be sorted and recycled together as homogeneous streams, enabling higher-quality post-consumer recycled material and facilitating its use in new packaging of the same or similar type.

- Map relevant non-food rigid plastic product categories and packaging applications in the Norwegian market.
- Identify key packaging performance requirements.
- Define potential harmonised material and packaging specifications that can cover existing packaging needs with as few categories as possible.
- Assess the suitability of recycled materials for selected packaging applications, including packaging with 35%, 65% and 100% post-consumer recycled content.
- Evaluate technical risks related to odour, migration, colour and other contamination-related effects in recycled plastic materials.
- Generate practical insight into how producers, packaging manufacturers, sorting actors and recyclers can collaborate to enable closed-loop recycling.

2.4 Project Consortium

The project was realised with funding from Handelens Miljøfond (HMF) and was led by Grønt Punkt Norge in collaboration with industrial and technical partners representing key parts of the packaging value chain. Orkla HPC, Unil and Coop contribute market insight, product category data, packaging volumes and information on packaging requirements. Plastretur provides knowledge about sorting and recycling needs, while Norsk Formblåsing contributes packaging production expertise and small-scale HDPE bottle production if needed. Norner was responsible for technical analyses and testing of materials and packaging, including evaluation of virgin and recycled materials and the effects of recycled content.

Project partner	Role
Grønt Punkt Norge	Project owner and coordinator. Responsible for project management, compiling estimates of potential material stream volumes, gathering industrial experiences and facilitating dialogue between companies on harmonised packaging specifications.
Orkla HPC	Contributes information on product categories, packaging volumes and known technical packaging requirements for non-food rigid plastic packaging. Provides input on how harmonised packaging specifications can be developed in collaboration with other market actors.
Unil	Contributes market data, product category information, packaging volumes and known packaging requirements for non-food rigid plastic packaging. Provides input on how harmonised packaging specifications can be developed in collaboration with other market actors.
Coop	Contributes information on relevant non-food product categories, packaging volumes and known technical requirements. Provides input on how harmonised packaging specifications can be developed in collaboration with other market actors.

Plastretur	Provides insight into sorting and recycling requirements and how harmonised packaging materials can be sorted and recycled to enable closed-loop material flows and improved access to high-quality PCR.
Norsk Formblåsing	Contributes packaging production expertise, including insight into the consequences of material harmonisation from a packaging manufacturer perspective. Performs small-scale test production of HDPE bottles using recycled material if needed.
Norner	Responsible for technical analyses and testing. Defines packaging material specifications, maps relevant properties, evaluates virgin and recycled materials and assesses the suitability of packaging with 35%, 65% and 100% PCR content.

3. Project Structure and Work Plan

The project is structured into four interconnected work packages covering data collection, specification development, technical testing, PCR evaluation and industrial learning. The work plan follows a logical sequence from mapping product categories and packaging requirements, through definition and testing of harmonised specifications, to evaluation of recycled-content packaging and collection of industry experience related to harmonisation. In the final part of the project, the behaviour of PET recyclate will also be analysed under multiple-loop recycling conditions to assess how repeated recycling affects material performance and suitability for future packaging applications.

3.1 Overview of Work Packages

WP1 – Collect and analyze the data

WP1 establishes the factual basis for the project by collecting and analysing data from the project partners. This includes information on product categories, polymer types, packaging materials, colours, packaging weights, sales volumes and relevant Norwegian market data. The purpose is to identify the main product categories from which sufficiently homogeneous packaging streams can be created for recycling, and to determine which packaging groups are most relevant for further assessment in the project.

- **WP1.1 Collect and analyse data:** Collect data from project partners on product categories, materials, colour, volumes and facts for the Norwegian market.
- **WP1.2 Identify relevant packaging groups:** Identify the main product categories from which homogeneous packaging streams for recycling can be created.
- **WP1.3 Select packaging groups for further work:** Assess which packaging groups are most relevant for technical evaluation and harmonisation within the project.

WP2 – Investigate, Define and Test Requirements for Selected Packaging

WP2 investigates, defines and tests the technical requirements for selected packaging categories. The work includes confirmation of design-for-recycling requirements from the sorting and recycling perspective, assessment of product-related functional requirements, and development of basic specifications for harmonised packaging that can be used across the widest possible product range. Relevant properties include stacking strength, drop and impact resistance, chemical resistance, odour and barrier properties.

- **WP2.1 Design for recycling:** Confirm needs and requirements from the sorting and recycling parts of the value chain for the selected packaging groups.
- **WP2.2 Design for product:** Investigate whether selected packaging has similar requirements for properties(material and packaging), such as stacking strength, drop and impact resistance, chemical resistance and barrier properties.
- **WP2.3 Basic specification for a wide product range:** Narrow down the number of packaging types and define basic specifications for harmonised packaging that can be used across the widest possible range of products.
- **WP2.4 Analysis of physicochemical properties:** Collect selected packaging from project partners and run tests to confirm whether the packaging meets requirements related to mechanical strength, chemical resistance, odour and barrier performance.

WP3 – Evaluation of Packaging with 100% and 35% PCR Content

WP3 evaluates the feasibility of using post-consumer recycled material in selected packaging applications. The work includes collection of post-consumer packaging waste, cleaning, regrinding and pelletisation, followed by production of packaging with 35%, 65% and 100% PCR content. The produced packaging is subject to basic quality checks and technical testing, including assessment of migration, colour, odour, barrier properties and other performance parameters relevant to the selected product categories.

- **WP3.1 Recyclate preparation:** Collect post-consumer waste from the selected packaging group, clean the packaging and prepare recycled material through regrinding and pelletisation.
- **WP3.2 Packaging with PCR content:** Produce packaging with 35%, 65% and 100% PCR content, perform basic quality checks and define the scope of testing for relevant packaging and product categories.
- **WP3.3 Evaluation:** Compare packaging made from virgin material with packaging made using PCR content and identify deviations from the defined requirements.

- **WP3.4 Loop recycling simulation:** Assess whether HDPE material is susceptible to degradation during multiple-loop recycling under a defined carry-over level, and evaluate how repeated processing may affect key material properties relevant for packaging performance.

WP4 – Collection of Industrial Experiences and Harmonization Activities

WP4 collects and evaluates industrial experiences from the participating companies as they work with potential harmonised packaging specifications. This addresses how harmonisation affects packaging design, branding, differentiation, production, sorting and recycling. Workshops and partner input are used to identify needs, practical barriers and possible solutions, including the distinction between packaging that can follow common specifications and packaging with specific technical requirements.

- **WP4.1 Collection of company experiences:** Collect input from companies on how work with harmonised specifications affects packaging design, material selection, branding and practical decision-making.
- **WP4.2 Workshops and partner dialogue:** Use workshops and discussions to identify industry needs, success factors, barriers and possible solutions for implementing harmonised packaging specifications.
- **WP4.3 Practical recommendations:** Compile the learning from partners and workshops into recommendations for harmonisation, closed-loop recycling and future packaging development.

2.1.1 Work Package Summary

Work package	Main activities	Expected output
WP1	Collect and analyse partner data on product categories, materials, colours, packaging weights, volumes and market facts.	Selection of relevant packaging groups and initial basis for homogeneous recycling streams.
WP2	Confirm sorting and recycling needs, assess product requirements and test selected packaging for mechanical and chemical properties.	Defined basic specifications for harmonised packaging covering a wide product range.
WP3	Prepare PCR from selected packaging waste, produce packaging with 35%, 65% and 100% PCR content and evaluate technical performance.	Comparison between virgin and PCR-based packaging and identification of deviations from requirements.
WP4	Collect partner experiences, organise workshops and assess how harmonisation affects packaging design, production, branding and value-chain collaboration.	Practical recommendations for harmonisation and closed-loop recycling implementation.

3.2 Project Timeline

The project work starts with data collection and product-category mapping, followed by definition of technical requirements and basic harmonised specifications. The later stages focus on PCR preparation, packaging production with recycled content, performance testing and comparison of PCR-based packaging against virgin reference packaging.

Table 1 Project timeline and work package schedule.

WP	Activity	Start	End
WP1	Define product specifications and key packaging material properties.	January 2025	August 2025
WP2	Investigate, define and test requirements for selected packaging	January 2025	November 2025
WP3	Evaluate product-category tolerance to packaging made from contaminated return materials.	April 2025	June 2026
WP3	Test and document virgin and recycled materials and packaging with 35%, 65% and 100% PCR content.	April 2025	May 2026
WP4	Collect industrial experiences and evaluate how harmonisation affects packaging design and value-chain collaboration.	January 2025	June 2026

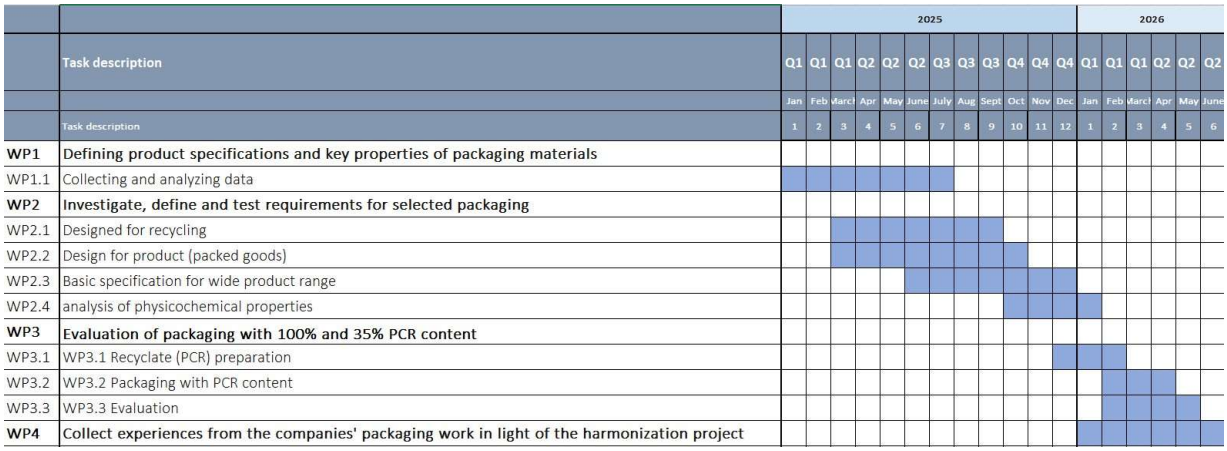


Figure 1 Project Gantt chart showing the planned schedule and overlap of the main work packages from January 2025 to June 2026

4. Technical Work and Results

3.1 Basis for Technical Activities and Workshop-Derived Focus Areas

The technical work in the project was defined through a combination of the original project objectives, partner input from workshops and the evolving evidence base from mapping, sorting and laboratory activities. The workshop conclusions were used as a practical starting point for prioritising the project activities and ensuring that the work addressed the needs of producers, packaging manufacturers, sorting actors and recyclers.

The agreed project activities were organised around six focus areas: mapping and categorisation, specification and harmonisation, testing and analysis, pilot production, collection of industry experience, and communication of results. These activities were selected because they connect the technical requirements of packaging with the practical conditions needed to create homogeneous material streams and enable closed-loop recycling.

Mapping and categorisation provide the basis for identifying non-food products in Norway that use rigid plastic packaging with similar requirements, such as strength, impact resistance, chemical resistance and barrier properties. This mapping supports grouping of packaging types into a limited number of relevant categories, reducing complexity and helping to identify where harmonised material specifications may be realistic.

Specification and harmonisation form the core technical direction of the project. The work focuses on defining product specifications and key material properties for packaging, while facilitating dialogue between companies to support common specifications. The workshop conclusions highlighted the importance of material unification, especially for HDPE packaging, and the potential value of white material streams for sorting efficiency, recyclate purity and PCR availability.

Testing and analysis were defined as necessary to verify whether proposed specifications can meet real packaging requirements. This includes testing selected packaging produced from virgin and recycled materials, evaluating PCR content levels, assessing tolerance to contamination-related effects, and characterising both the material and the final packaging. The analytical scope includes migration, colour, mechanical properties, qualitative analysis, presence of contaminants and rheology.

Pilot production was included to demonstrate practical feasibility, particularly through small-scale production of HDPE bottles using recycled material. This activity creates a bridge between material characterisation and packaging performance by showing how PCR-containing materials behave under realistic processing and product conditions. The work also aimed to assess material processability, including how the material behaves during processing, to test different formulations with varying levels of recycled content, and to evaluate the extent to which production can be adapted by adjusting processing parameters.

Industry experience collection was also defined as a important project activity. The workshops showed that technical harmonisation must be balanced with market and design needs, including brand differentiation, consumer navigation, design-for-recycling requirements and the practical willingness of producers to change packaging solutions. Partner feedback therefore forms an important basis for interpreting technical results and defining realistic next steps.

The focus subjects identified through the workshops and later project discussions provide the foundation for the following technical sections.

4.1 WP1 – Defining Product Specifications and Key Properties of Packaging Materials

Task 1.1 – Collecting and Analysing Data
Objective
The objective of Task 1.1 was to collect and analyse data on relevant non-food rigid plastic packaging in the Norwegian market, with a particular focus on HDPE packaging used in the Home and Personal Care segment. The task aimed to identify packaging categories, polymer types, volumes and material streams.

Activities Performed
The work included analysis of product and packaging information provided by the project partners regarding their product portfolios, review of Norwegian waste-stream data, and assessment of relevant HDPE, PET and PP rigid packaging fractions. Physical packaging samples were not collected from the project partners as part of this activity. Particular attention was given to identifying packaging groups with sufficient similarity in material type, design and functional requirements to support material unification and packaging harmonisation. The activity also included analysis of data from Mepex and Plastretur/Tomra regarding non-food rigid plastic packaging in source-sorted and residual household waste streams.

Methodology
Data were analysed by combining partner portfolio information with external sorting and picking-analysis data. The project considered product categories, polymer type, colour, packaging format, packaging weight, sales volumes and expected availability in the Norwegian waste stream. The analysis focused on identifying categories where a large share of existing packaging could potentially follow common specifications, while recognising that some applications may require specific technical solutions because of barrier, chemical resistance or mechanical performance requirements.

Results

The data analysis identified four main groups of non-food rigid packaging as particularly relevant for the project: HDPE bottles for harsh chemicals, HDPE/PET bottles for laundry care liquids and softeners, HDPE/PET bottles for personal-care wash-off products, and HDPE/PET bottles for non-harsh household cleaners. These categories represent a substantial part of the relevant Home and Personal Care rigid packaging portfolio among the project partners and were therefore considered suitable as the starting point for harmonisation work.
Plastretur/Tomra estimates that the sorting system will recover approximately 2,615 tonnes of HDPE in 2026, corresponding to 8.6% of the total input stream. For PET bottles, approximately 706 tonnes are expected to be sorted, corresponding to 2.3% of the total stream. The project partners are estimated to contribute approximately 16% of the HDPE non-food waste stream in Norway, while around 80% of the Home and Personal Care rigid packaging in the partners' portfolio is covered by the identified categories.

The mapping exercise also highlighted an overlap between HDPE and PET applications within the Home and Personal Care sector. As illustrated in Figure 2 Packaging material overlap and harmonisation potential across selected Home and Personal Care product categories, harsh chemical products (e.g. bleach, ammonia-based cleaners and drain cleaners) are predominantly packaged in HDPE due to its superior chemical resistance, whereas laundry care products, personal-care wash-off products and non-harsh household cleaners are commonly packaged in either HDPE or PET.

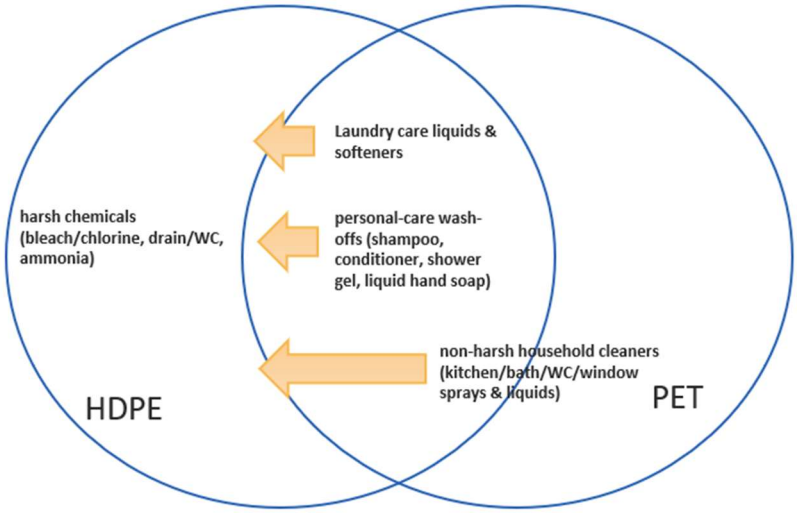


Figure 2 Packaging material overlap and harmonisation potential across selected Home and Personal Care product categories

This indicates that a large share of the identified packaging portfolio could potentially be harmonized around a reduced number of packaging solutions and material specifications. Such harmonization would facilitate larger and more homogeneous recycling streams, improve sorting efficiency, increase the availability of high-quality recyclates, and support the development of closed-loop recycling systems for non-food rigid packaging.

The Mepex analysis was conducted to characterize the composition of non-food rigid plastic packaging present in Norwegian household waste streams and to identify material fractions with the greatest potential for closed-loop recycling. Approximately 80–90 kg of plastic waste originating from both source-sorted household collections and residual waste streams was manually sorted and analyzed. The objective was to quantify the occurrence of non-food rigid HDPE, PP, and PET packaging and to assess the availability of homogeneous material streams.



Figure 3 Manual sorting and categorisation of non-food rigid plastic packaging during the Mepex waste composition analysis.

The results demonstrate substantial differences between source-sorted and residual waste streams. As shown in Figure 4, rigid plastic packaging represents nearly 40% of the source-sorted plastic waste fraction, whereas it accounts for only 3.1% of the residual waste stream. This finding confirms that

source sorting remains the primary pathway for recovering significant volumes of recyclable rigid plastic packaging in current system. Furthermore, the material composition analysis revealed that HDPE and PET constitute a considerable share of the non-food packaging fraction, supporting their selection as priority materials for further investigation within the project.

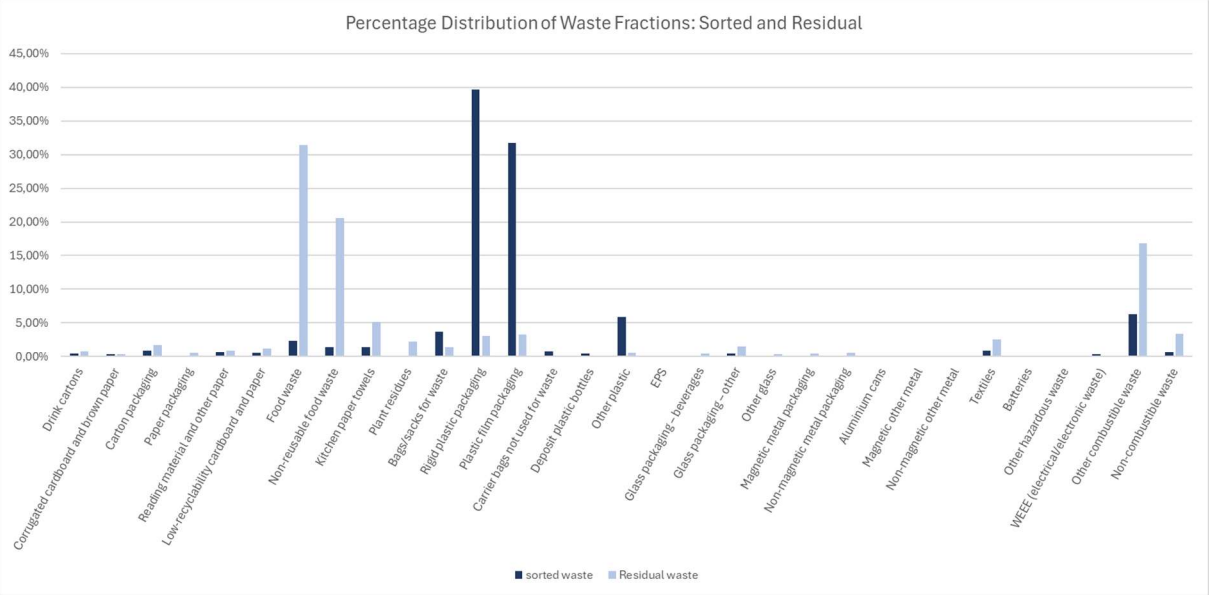


Figure 4 Distribution of Waste Fractions: Sorted and Residual

The distribution of food and non-food packaging by polymer type is presented in Figure 5 for source-sorted waste and Figure 6 for residual waste. The results show that non-food rigid HDPE packaging forms a distinct and identifiable stream in both collection systems. Within the HDPE packaging group, 86.2% of the packaging was identified as non-food packaging, indicating that HDPE represents the largest potential material stream for this project. This high non-food share is important because non-food HDPE packaging is generally less constrained by food-contact requirements, is strongly represented in Home and Personal Care applications, and can potentially be grouped into more homogeneous material streams. In addition, HDPE packaging often has comparable bottle formats and functional requirements, which supports specification harmonisation, improved sorting efficiency and the development of higher-quality PCR for closed-loop recycling. Although the quantities recovered from residual waste are significantly lower, the presence of HDPE and PET packaging in both streams indicates that future recycling systems should consider material originating from multiple collection routes. The analysis also confirms that the Home and Personal Care sector contributes substantially to the available HDPE and PET packaging volumes, providing a sufficiently large material base for harmonization initiatives.

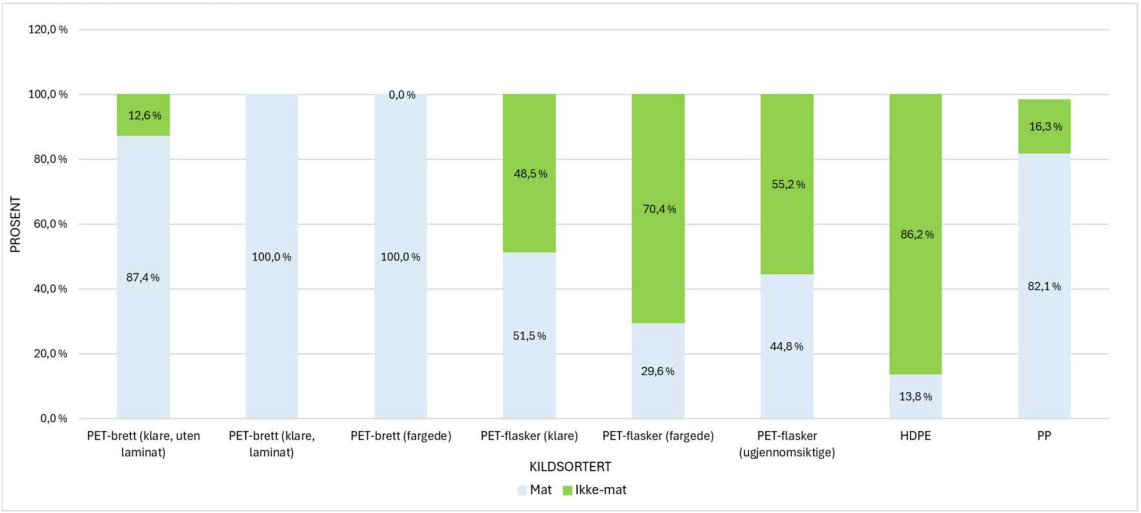


Figure 5 Distribution of food and non-food packaging by material type.

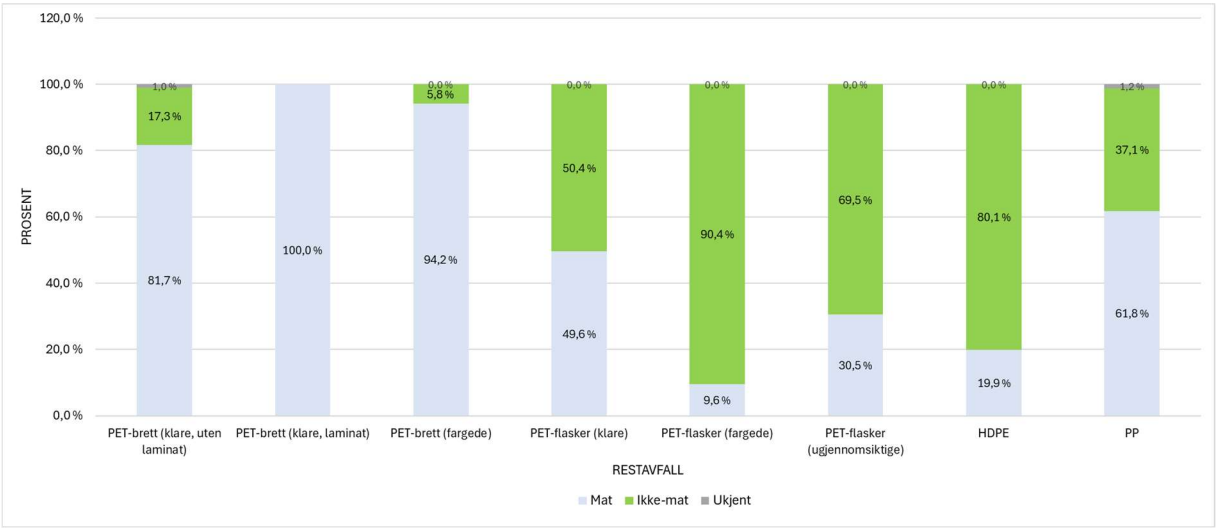


Figure 6 Distribution of food and non-food packaging by material type. Residual waste

Washing and color sorting of HDPE fraction

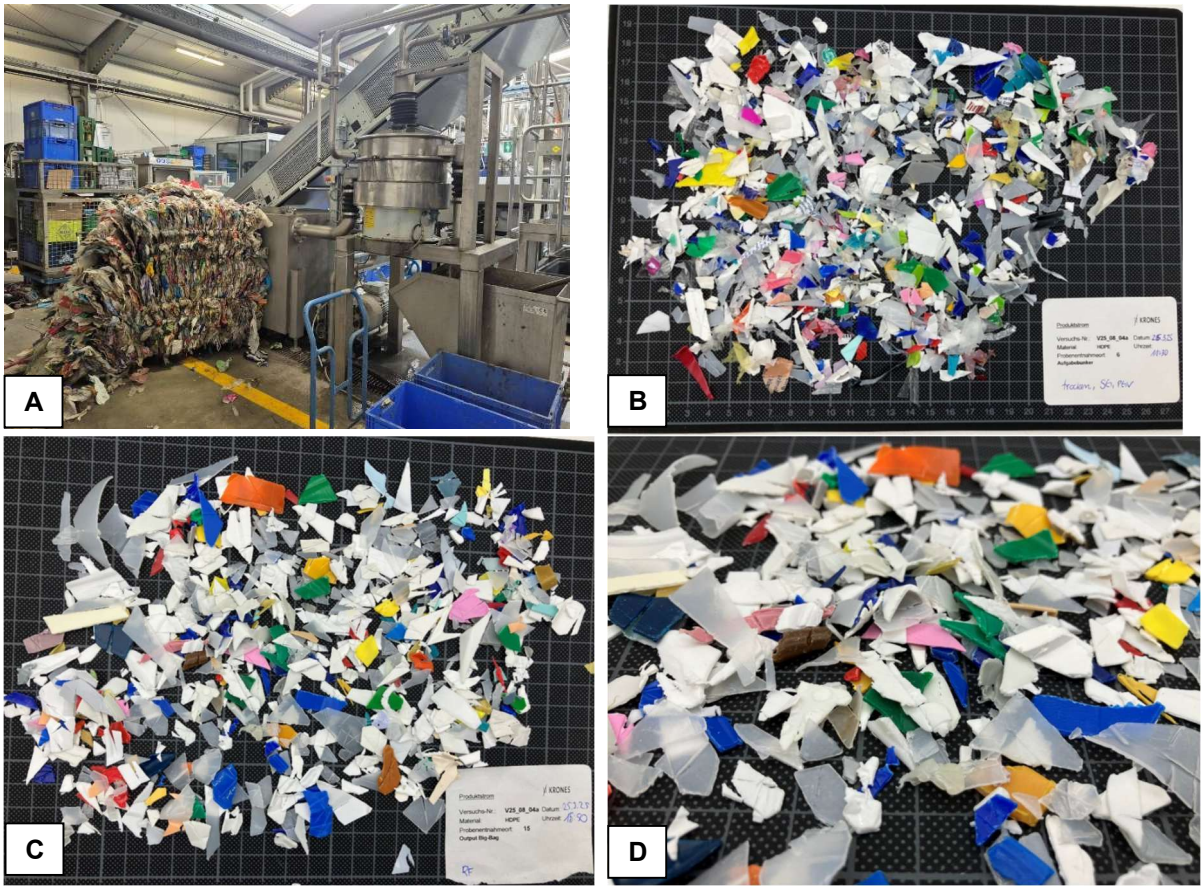
Based on these findings, the project focused further work on the HDPE fraction, as it was identified as the most promising non-food waste stream with potential relevance for cosmetic packaging and household cleaning product packaging. The prioritisation of HDPE was supported by its high non-food share, its strong representation in Home and Personal Care applications, the availability of a relatively large and identifiable material stream, and the possibility of developing more uniform material specifications for packaging with similar functional requirements.

The next step was therefore to evaluate how the selected HDPE fraction could be sorted and prepared for further recycling trials. The sorting approach presented in the project meeting on 18.11.2025 showed how the material stream was divided into relevant output fractions after processing. This provided a practical basis for understanding whether a sufficiently clean and homogeneous HDPE fraction could be obtained for subsequent recyclate preparation and packaging evaluation.

For both SAS and MRF material streams, the material was first washed and then subjected to colour sorting. HDPE packaging waste collected from Norwegian household waste streams was sourced from two collection systems: source-sorted household plastic waste (SAS) and mixed residual waste (MRF). Prior to further processing, both fractions were mechanically shredded into flakes and treated on a pilot-scale washing line designed to remove dirt, product residues, labels, adhesives and other contaminants.

The washing process included several sequential operations, such as grinding, friction washing, pre-washing, intensive hot washing, sink-float separation and drying, resulting in clean HDPE flakes suitable for further sorting and recycling trials.
The pilot-scale washing trials demonstrated that both material streams could be cleaned effectively. The washed SAS fraction achieved material purity of 93.4%, while the MRF fraction reached a purity of 90.5%. Representative examples of the washed flakes are shown in Table 2

Table 2 Pilot-scale washing of HDPE packaging waste from Norwegian household waste streams. (A) Pilot-scale washing line and baled HDPE packaging waste before processing. (B–D) Examples of washed HDPE flakes obtained after shredding, washing and drying, prior to colour sorting and recyclate production.



This sequence was selected because the white HDPE flake represented the largest and most relevant output fraction after washing, and separation of this fraction was necessary to improve colour consistency and material quality. The composition of the output after the washing process was assessed visually and by fraction distribution, providing input for selecting the most relevant material stream for continued work.

The composition of the output fractions after washing is shown in Table 3

Table 3 Composition of output after the washing process for the SAS and MRF fractions

The material composition of the output can be seen in the following tabl

Name	Area share	Area share
ABS	0,00	2
HDPE	93,42	934155
LDPE	2,21	22141
PA	0,00	2
PC	0,00	2
PET	0,05	536
PET G	0,00	2
PLA	0,01	73
PP	3,02	30187
PS	0,00	12
PVC	0,01	123
Silicon rubber	0,00	0
Undefined	1,27	12721
Wood	0,00	45

SAS fraction

The material composition of the output can be seen in the following tabl

Name	Area share [%]	Area share [ppm]
ABS	0,00	0
HDPE	90,53	905272
LDPE	1,65	16513
PA	0,00	0
PC	0,00	0
PET	0,01	134
PET G	0,00	1
PLA	0,00	47
PP	5,86	58571
PS	0,00	3
PVC	0,00	14
Silicon rubber	0,00	0
Undefined	1,94	19444
Wood	0,00	0

MRF fraction

The comparison of the washed SAS and MRF fractions showed generally high washing efficiency in both trials. The MRF fraction contained more soil on the flake surface. Particle size distribution did not show a major shift towards smaller particles; however, the MRF material was more concentrated in the 4–6.3 mm size range. This was also reflected in the bulk density results, where the SAS fraction had a lower bulk density of 282 kg/m³, while the MRF fraction reached 313 kg/m³, most likely due to a lower proportion of larger particles above 10 mm. Overall, the washing quality was considered very high for both fractions, although the material purity of the MRF fraction was approximately 3% lower than that of the SAS fraction.

Color sorting of HDPE flakes

Following the washing process, the HDPE flake fraction obtained from the source-sorted (SAS) stream was subjected to optical color sorting. The sorting process was performed using an optical sorting system equipped with NIR and RGB sensors, enabling simultaneous polymer identification and color discrimination. To maximize the purity of the white fraction, two consecutive sorting steps were applied. During both stages, flakes differing in polymer type as well as flakes exhibiting color deviations from the target white shade were rejected, while no recovery step was included in the process.

The mass balance (Figure 7) demonstrated that the input material contained approximately 73% white HDPE flakes. After the two-stage sorting process, a white HDPE product with a measured purity of 98.6 wt% PE was obtained. The overall recovery of the white HDPE fraction reached 70.4%. Approximately 26% of the initial white fraction was rejected during sorting due to variations in whiteness ("different shades of white"), highlighting the significant impact of color heterogeneity on material recovery. Although these rejects consisted largely of polyethylene, they did not meet the predefined optical criteria required for producing a uniform white recyclate.

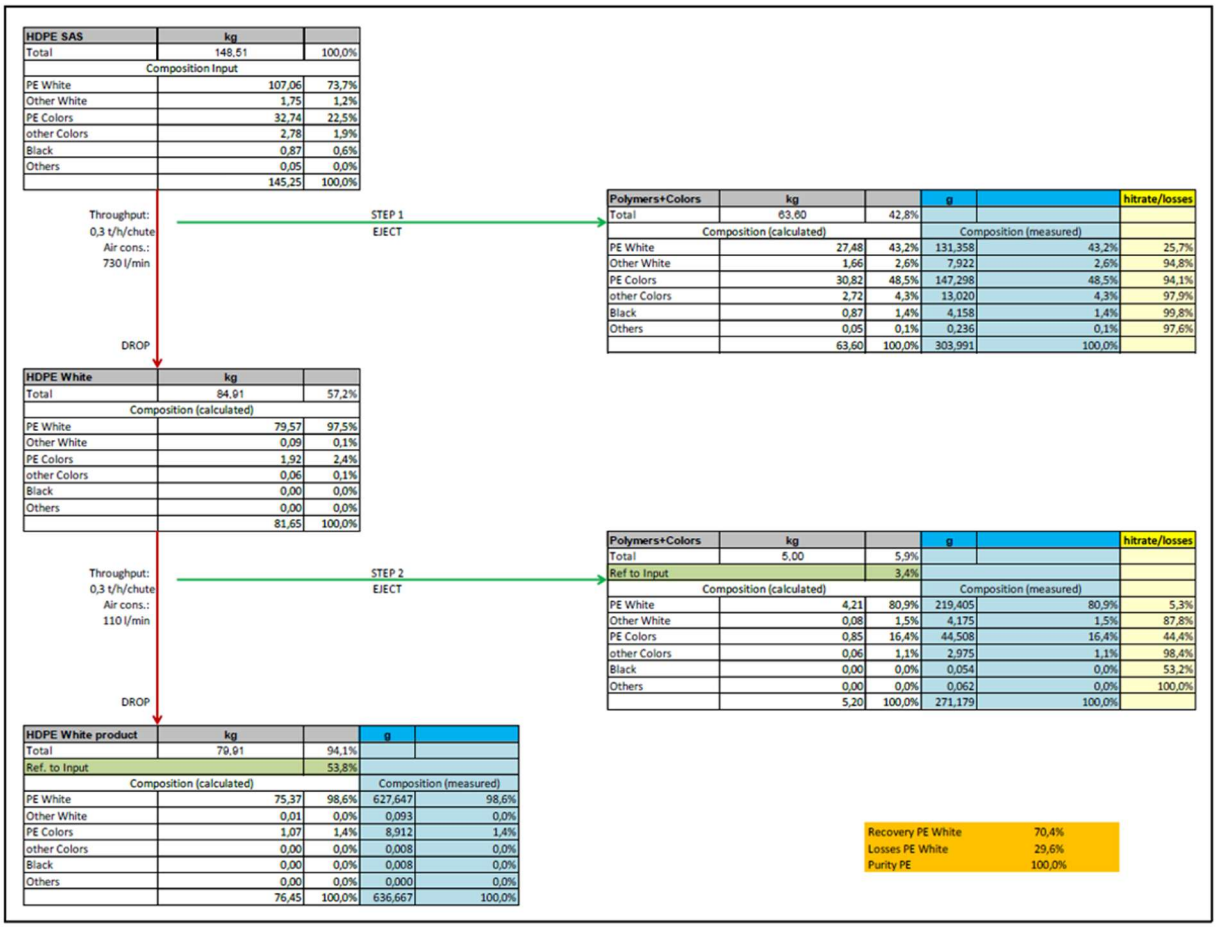


Figure 7 Mass Balance of test 2 for SAS fraction

These results demonstrate that optical color sorting is capable of producing a packaging-grade white HDPE fraction with very high polymer purity. However, they also identify color variation within nominally white packaging as one of the main factors limiting material recovery.



Figure 8 Two-stage optical color sorting of the SAS HDPE flake fraction. Step 1 removed colored flakes and non-target polymers, while Step 2 eliminated remaining off-white flakes, producing the final high-purity white HDPE fraction

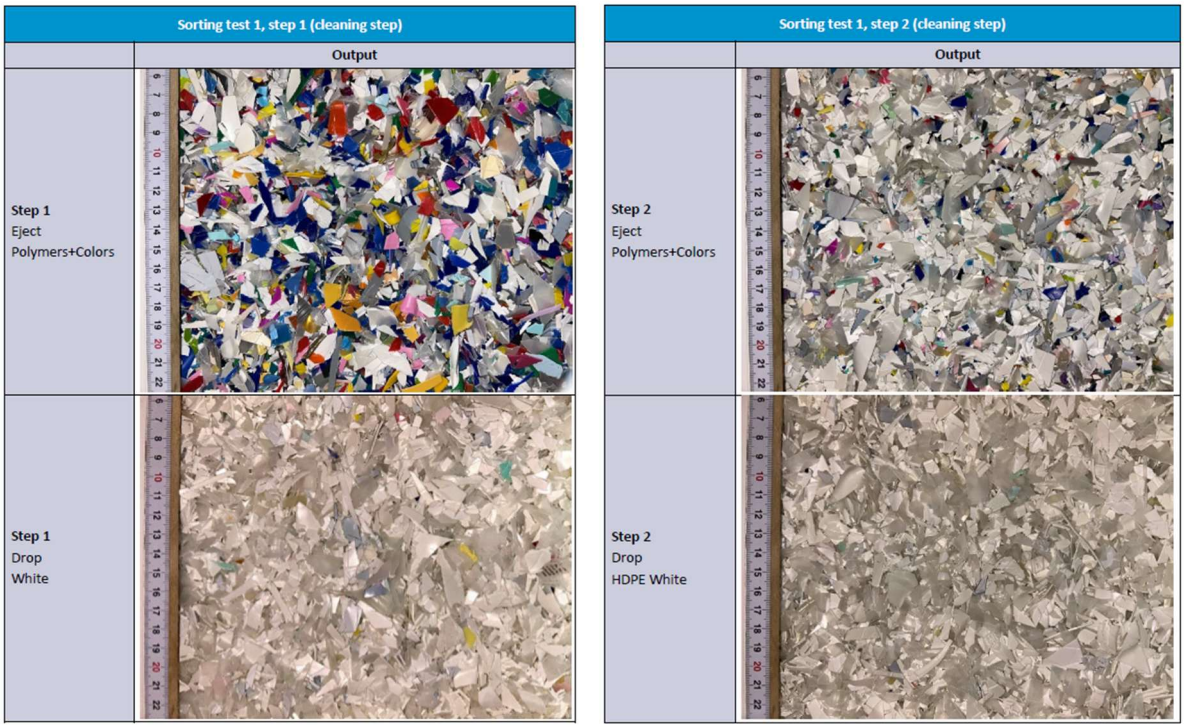


Figure 9 Two-stage optical color sorting of the MRF HDPE flake fraction. Step 1 removed colored flakes and non-target polymers, while Step 2 eliminated remaining off-white flakes, producing the final high-purity white HDPE fraction.

Discussion

The results of WP1 showed that harmonisation of non-food rigid plastic packaging should focus on packaging streams that combine high market relevance with the potential to generate sufficiently large and homogeneous recycling streams. The identified Home and Personal Care categories fulfil these criteria, as they represent a significant share of Norwegian non-food rigid packaging while also exhibiting similarities in functional requirements and packaging design. Concentrating on a limited number of packaging groups therefore provides a realistic pathway towards reducing unnecessary material diversity without compromising product functionality.

Among the investigated materials, HDPE emerged as the most suitable candidate for the development of a closed-loop recycling system. Its strong representation in the selected product categories, together with the high proportion of non-food packaging within the HDPE stream, provides a favorable basis for establishing a dedicated recycling loop capable of supplying packaging-grade recyclate. The findings therefore support the project strategy of prioritizing HDPE as the reference material for further material qualification and packaging evaluation.

The comparison between source-sorted (SAS) and mixed residual waste (MRF) fractions highlights the influence of collection systems on recyclate quality. Although the differences between the two streams were relatively small, the SAS fraction consistently exhibited slightly higher purity and lower visible contamination than the MRF fraction. Nevertheless, both fractions produced technically suitable washed HDPE flakes following the washing process. These findings indicate that both collection routes represent relevant feedstocks for the project and have the potential to supply packaging-grade HDPE recyclate, provided that appropriate washing and sorting technologies are applied.

One of the most significant findings concerns the influence of colour consistency on recycling efficiency. Optical colour sorting produced a high-purity white HDPE fraction suitable for further recycling trials; however, a substantial proportion of nominally white flakes had to be rejected because of differences in whiteness. This demonstrates that polymer harmonisation alone is insufficient to maximize material recovery. Future closed-loop systems will also require greater alignment of packaging colour specifications, particularly for white packaging, to reduce unnecessary losses during optical sorting. The findings therefore support the development of harmonised packaging specifications that address not only material selection but also colour, design-for-recycling principles and compatibility with existing sorting technologies.

Overall, the WP1 results establish both the technical and strategic foundation for the subsequent work packages. They demonstrate that harmonisation at the design stage, combined with appropriate collection, washing and sorting technologies, has the potential to increase the availability of high-quality PCR HDPE and improve the feasibility of closed-loop recycling for non-food rigid packaging.

4.2 WP2 – Investigate, Define and Test Requirements for Selected Packaging

4.2.1 WP2.1 Design for Recycling

Work Package 2 focused on translating the findings from WP1 into a harmonized technical specification for HDPE packaging intended for non-food applications. The work addressed both packaging functionality and recyclability by defining common material requirements, packaging design criteria, dimensional specifications, and Design for Recycling principles. These specifications served as the technical foundation for the production and evaluation of bottles containing virgin and post-consumer recycled (PCR) HDPE in WP3.

The starting point was the analysis of the Norwegian HDPE waste stream performed in WP1, which demonstrated that the selected Home and Personal Care packaging categories constitute a substantial share of the available non-food HDPE stream. Based on these findings, HDPE was confirmed as the priority material for further harmonisation, while colour harmonisation was identified as one of the most effective measures for improving sorting efficiency and increasing the availability of packaging-grade recycled HDPE.

The washing and sorting trials carried out on source-separated (SAS) and mixed residual waste (MRF) fractions provided practical information on the quality of the recovered material. Both fractions produced technically usable HDPE flakes after washing. Subsequent colour sorting demonstrated that high-purity white HDPE could be recovered from both waste streams. However, approximately one quarter of the incoming white fraction was rejected because of differences in white shades, illustrating the practical challenge referred to during the project as the "50 shades of white" effect. This finding highlighted that harmonisation should address not only the selection of white packaging but also the standardisation of acceptable white colour shades to minimise material losses during colour sorting.

The recycling assessment was complemented by a review of RecyClass Design for Recycling recommendations for rigid HDPE packaging. These guidelines were used together with the project's own experimental observations to define recommendations for packaging materials, colours, labels, adhesives, closures and other components affecting sorting and mechanical recycling.

4.2.2 WP2.2 Design for Product

The purpose of WP2.2 was to determine whether the selected packaging categories require substantially different material performance or whether a common material specification could satisfy the functional requirements of multiple product groups.

The assessment focused on packaging used for harsh household chemicals, laundry care products, personal care products and non-harsh household cleaners identified during WP1. Existing packaging specifications from project partners together with technical data sheets for commercially available HDPE grades were reviewed and compared.

The comparison demonstrated considerable overlap between the functional requirements of the investigated packaging categories. Although certain products require enhanced chemical resistance or specific barrier properties, most rigid HDPE bottles share similar requirements regarding stiffness, processability, stacking performance, drop resistance and environmental stress cracking resistance (ESCR). This finding supported the concept of harmonising packaging materials across a broad range of Home and Personal Care applications.

Based on the comparison of commercially available materials, a common reference specification for virgin HDPE was established. Material properties including density, melt flow rate, tensile modulus and ESCR were used to define the target property window. A commercial virgin HDPE blow-moulding grade was subsequently selected as the reference material for experimental validation because its properties were considered representative of HDPE grades currently used for both harsh and non-harsh applications.

4.2.3 WP2.3 Basic Specification for a Wide Product Range

Based on the outcomes of WP2.1 and WP2.2, a draft harmonised specification for rigid HDPE packaging was developed.

The specification was intended to provide a common technical framework rather than prescribe one specific bottle design. Its purpose was to harmonise the packaging features that have the greatest influence on recyclability while maintaining sufficient flexibility for different products and brand owners.

The specification addressed several complementary areas:

- material selection and target material properties;
- Design for Recycling requirements;
- packaging component compatibility;
- colour strategy;
- packaging design recommendations;
- recycled content;
- documentation and traceability.

A central element of the specification was the recommendation to prioritize natural and white HDPE packaging wherever technically feasible. The specification also recommended limiting the number of white shades, avoiding incompatible polymers, selecting recyclable packaging components and designing packaging that supports efficient emptying, washing and mechanical recycling.

The packaging component recommendations included the use of HDPE or compatible polyolefin labels, releasable adhesives, HDPE closures and limited use of polypropylene components. Barrier layers, incompatible polymers, dark pigments and problematic additives were identified as features that should be avoided because of their negative impact on recycling efficiency.

The specification was discussed with the project partners, and a jointly acceptable version was established. This version provides a practical compass for market participants seeking to achieve a larger and higher-quality stream of recycled HDPE material. The full version of the specification has been shared with the project partners and is included as an appendix 1 to this report.

4.2.3 WP2.4 Analysis of Physicochemical Properties

The final task of WP2 focused on preparing the experimental program required to verify the proposed harmonised specification and to generate comparable data on packaging produced with recycled HDPE from the Norwegian waste stream.

Originally, the analysis was planned to include packaging collected from the project partners and to evaluate its performance through tests such as stacking strength, drop resistance, impact strength, chemical resistance and other relevant functional requirements. However, the partner packaging portfolio varied considerably in design, wall thickness, dimensions, closure systems, geometry and intended use. Direct comparison of such diverse packaging would therefore have made it difficult to distinguish the effect of material composition from the influence of packaging design. In addition, the available volumes of recycled HDPE were limited and too small for use in industrial-scale machines covering several formulations.

For these reasons, the project approach was adjusted, and the testing programme was based on standardised packaging produced by Norner. One-litre HDPE bottles were manufactured by extrusion blow moulding using the selected virgin reference material and recycled HDPE fractions from the Norwegian waste stream. Keeping the bottle format constant enabled a more reliable comparison of material performance at different recycled-content levels.

The experimental program included the preparation of white and coloured PCR materials originating from both SAS and MRF waste streams. Bottles were produced using formulations containing virgin HDPE together with 35%, 65% and 100% PCR content. This approach made it possible to evaluate how increasing PCR content affects material processability, packaging performance and key functional properties, while also providing direct information on the suitability of PCR derived from the Norwegian HDPE waste stream for future packaging applications.
The planned evaluation covered both material characterisation and packaging testing. Material characterisation included density, melt flow rate, FTIR identification, rheological behaviour, tensile properties and thermal analysis. Packaging performance testing included dimensional stability, wall thickness distribution, top-load resistance, drop resistance, ESCR, colour measurements and migration analysis. Barrier-related requirements were considered during the specification work but were not assessed through dedicated barrier testing in the final experimental programme.

material	type	[ml]	PCR content	description	mass
Hostalen ACP 5831D	bottle	1000	0% PCR	Hostalen ACP 5831D bottle 0% PCR	33
SAS HDPE WHITE	bottle	1000	100% PCR	SAS HDPE WHITE bottle 100% PCR	33
SAS HDPE WHITE	bottle	1000	65% PCR	SAS HDPE WHITE bottle 65% PCR	33
SAS HDPE WHITE	bottle	1000	35% PCR	SAS HDPE WHITE bottle 35% PCR	33
SAS HDPE COLOR	bottle	1000	100% PCR	SAS HDPE COLOR bottle 100% PCR	33
SAS HDPE COLOR	bottle	1000	65% PCR	SAS HDPE COLOR bottle 65% PCR	33
SAS HDPE COLOR	bottle	1000	35% PCR	SAS HDPE COLOR bottle 35% PCR	33
MRF HDPE WHITE	bottle	1000	100% PCR	MRF HDPE WHITE bottle 100% PCR	33
MRF HDPE WHITE	bottle	1000	65% PCR	MRF HDPE WHITE bottle 65% PCR	33
MRF HDPE WHITE	bottle	1000	35% PCR	MRF HDPE WHITE bottle 35% PCR	33
MRF HDPE COLOR	bottle	1000	100% PCR	MRF HDPE COLOR bottle 100% PCR	33
MRF HDPE COLOR	bottle	1000	65% PCR	MRF HDPE COLOR bottle 65% PCR	33
MRF HDPE COLOR	bottle	1000	35% PCR	MRF HDPE COLOR bottle 35% PCR	33

Figure 10 Bottle matrix showing the different formulations produced (virgin, 35%, 65% and 100% PCR; SAS and MRF; white and coloured fractions).

4.3 WP3 – Evaluation of Packaging with 100%, 65% and 35% PCR Content

The recycled HDPE used in this study was produced from packaging waste collected from the Norwegian market. Washed HDPE flakes from both the SAS and MRF fractions were regranulated on a twin-screw extruder to obtain pelletised recyclates. These materials were then used to produce HDPE bottles containing 35%, 65% and 100% PCR, enabling the evaluation of packaging performance at different recycled-content levels.
The objective was to assess whether bottles with increasing PCR content met the technical and functional requirements and to identify the key factors affecting their suitability for closed-loop recycling. The evaluation was divided into two complementary parts: material testing and bottle testing. Material testing focused on the intrinsic properties of the recycled polymers, including their chemical composition, processing behaviour, thermal characteristics and mechanical performance. These analyses were intended to determine whether the recycling process affected the fundamental properties of HDPE and whether the recycled materials remained suitable for extrusion blow moulding. Particular attention was given to polymer purity, melt behaviour, stiffness and the presence of contaminants or additives originating from the post-consumer waste stream.

Bottle testing evaluated the performance of the final packaging produced from virgin and recycled materials. Since the ultimate objective of the project is to demonstrate the feasibility of using PCR HDPE in commercial packaging, the assessment extended beyond material characterisation to include the functional behaviour of the finished bottles. The testing programme therefore covered dimensional stability, wall thickness distribution, colour consistency, stacking strength, drop resistance, environmental stress cracking resistance (ESCR). These properties represent the key performance requirements for rigid HDPE packaging used in home and personal care applications and provide a direct comparison between bottles manufactured from virgin material and those containing different levels of recycled content.

In addition to the evaluation of individual PCR formulations, the testing program included analyses supporting the assessment of long-term circularity. Advanced analytical techniques, including Fourier Transform Infrared Spectroscopy (FTIR), Differential Scanning Calorimetry (DSC), Thermogravimetric Analysis (TGA), rheological characterisation were applied to investigate changes in polymer composition and material stability. These methods also formed the basis for the subsequent loop recycling simulation, where the effect of repeated mechanical recycling on the material properties was evaluated.
The overall scope of material and bottle testing is summarised in the tables below.

Test Name	Method / Standard
MFR 190°C / 2.16 kg	Internal method (Melt Flow Index)
Density	ISO 1183-1
FTIR Identification	Internal method (FTIR)
Dynamic Rheology	ISO 6721-10:2015
Tensile Test	ISO 527-1 / 527-2
Charpy Impact (23°C N)	ISO 179
Ash Content + EDS	ISO 3451-1 Method A

Figure 11 Material characterization methods and test standards used for the evaluation of virgin and PCR HDPE materials

Test Name	Method / Standard
Dimensions	ASTM D2911
ESCR Bottle Test	M731014
Top Load	M730091
Color CIE L*, a*, b*	Internal method (Color CIE L*, a*, b*)
Drop Test	M730782

Figure 12 Bottle performance tests and applicable test standards used for the evaluation of virgin and PCR HDPE bottles

4.3.1 WP3.1 Recyclate (PCR) preparation

The PCR recyclates were prepared in pellet form using a twin-screw extruder. Cleaned and colour-sorted HDPE flakes, including both white and mixed-colour fractions, were extruded and pelletised to obtain recycled HDPE materials suitable for further processing. The resulting pellets were subsequently used to produce HDPE bottles with defined PCR contents.

Within this work package, material characterisation of the prepared recyclates was also carried out to assess their composition, processing behaviour and suitability for HDPE bottle production.

4.3.1.1 Material analysis

Identification of contaminants in HDPE flake

Following colour sorting, an additional assessment was performed to identify potential contaminants remaining in the HDPE flake fractions. The objective was to evaluate the effectiveness of the colour sorting process and determine whether foreign polymers or visually atypical flakes could still be present in the recycled material.
The analysis was carried out on representative quantities of colour-sorted HDPE flakes from both the SAS and MRF streams. For each fraction, a predefined volume of flakes was manually inspected for 10 minutes, during which visually atypical flakes were separated and subsequently identified by FTIR analysis. This approach was intended to simulate a practical quality control procedure capable of detecting contaminants that may not have been removed during automated sorting. The results for the individual fractions are presented below.

<u>SAS fraction</u>

The results for the SAS fraction are presented in Figure 13. All manually selected flakes were identified as polyethylene, confirming the high polymer purity of the colour-sorted SAS stream. No foreign polymers were detected among the analysed flakes.
Although polymer contamination was not observed, several flakes exhibited pearly, cream or greyish shades rather than the target white colour. While these flakes are chemically compatible with the HDPE stream, they may negatively affect the colour consistency of the recyclate and reduce the yield of the high-quality white fraction during colour sorting.

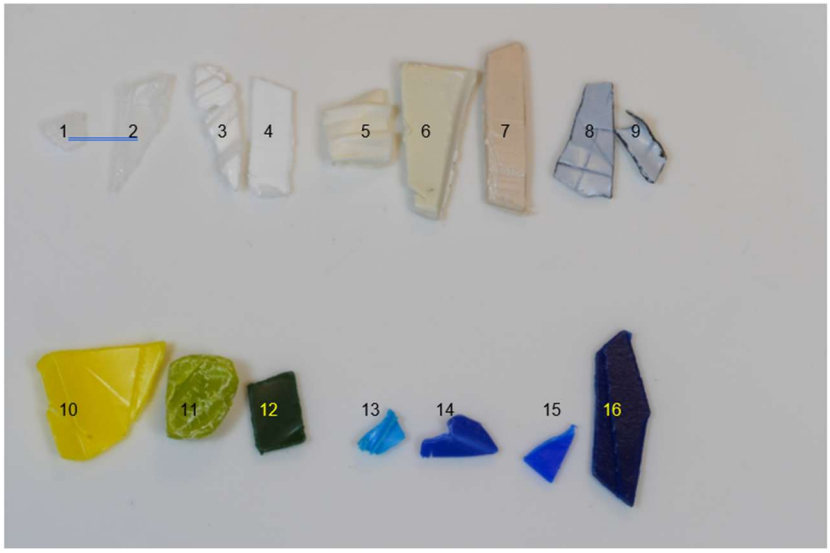


Figure 13 Manually selected flakes and potential contaminants from the white HDPE stream. SAS fraction

Description	Search Best Hit Description
S-250829-002, HDPE SAS T2S2 PROD. (1. natural)	Polyethylene
S-250829-002, HDPE SAS T2S2 PROD. (2. natural)	Polyethylene
S-250829-002, HDPE SAS T2S2 PROD. (3. white)	Polyethylene
S-250829-002, HDPE SAS T2S2 PROD. (4. white)	Polyethylene
S-250829-002, HDPE SAS T2S2 PROD. (5. white)	Polyethylene
S-250829-002, HDPE SAS T2S2 PROD. (6. grey)	Polyethylene
S-250829-002, HDPE SAS T2S2 PROD. (7. grey)	Polyethylene
S-250829-002, HDPE SAS T2S2 PROD. (8. white, outer surface)	Polyethylene
S-250829-002, HDPE SAS T2S2 PROD. (9. white, outer surface)	Polyethylene
S-250829-002, HDPE SAS T2S2 PROD. (10. yellow)	Polyethylene
S-250829-002, HDPE SAS T2S2 PROD. (11. green)	Polyethylene, (wax)
S-250829-002, HDPE SAS T2S2 PROD. (12. dark green)	Polyethylene
S-250829-002, HDPE SAS T2S2 PROD. (13. blue)	Polyethylene
S-250829-002, HDPE SAS T2S2 PROD. (14. blue)	Polyethylene
S-250829-002, HDPE SAS T2S2 PROD. (15. blue)	Polyethylene
S-250829-002, HDPE SAS T2S2 PROD. (16. dark blue)	Polyethylene

Figure 14 Identification of manually selected flakes from the colour-sorted SAS HDPE fraction

MRF fraction

The results for the MRF fraction are presented in Figure 15. Similar to the SAS material, the majority of the manually selected flakes were identified as polyethylene, confirming that the colour sorting process produced a predominantly HDPE stream. However, unlike the SAS fraction, several foreign polymers were detected among the analysed flakes.
FTIR analysis identified (Figure 16) isolated flakes of polystyrene (PS), polyisoprene, and ethylene-based copolymers (ethylene ethyl acrylate and ethylene vinyl acetate), indicating that a small number of contaminants remained in the HDPE fraction after automated sorting. In addition, pearly and cream-coloured HDPE flakes were observed, which may negatively affect the colour consistency of the recycled material despite being chemically compatible with the HDPE stream.

These results demonstrate that the MRF-derived HDPE fraction contains a higher level of cross-contamination than the SAS fraction, reflecting the greater heterogeneity of material collected from mixed residual waste. Their presence indicates a risk of such contaminants occurring in MRF-based collection systems.

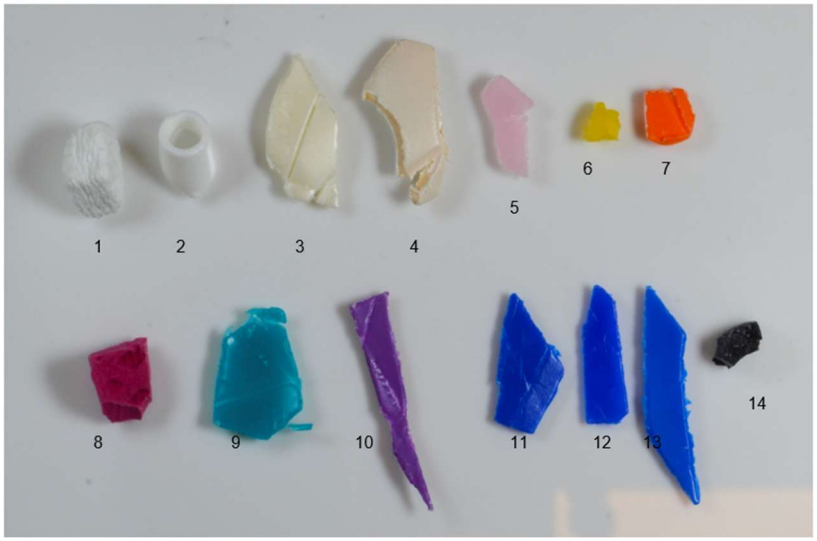


Figure 15 Manually selected flakes and potential contaminants from the white HDPE stream.MRF fracion

Description	Search Best Hit Description
S-250829-001, HDPE MRF T1S2 PROD. (1. white)	Polystyrene
S-250829-001, HDPE MRF T1S2 PROD. (2. white)	Polyethylene
S-250829-001, HDPE MRF T1S2 PROD. (3. white)	Polyethylene
S-250829-001, HDPE MRF T1S2 PROD. (4. white)	Polyethylene
S-250829-001, HDPE MRF T1S2 PROD. (5. pink)	Poly (ethylene ethyl acrylate)
S-250829-001, HDPE MRF T1S2 PROD. (6. yellow)	Ethylene/vinyl acetate copolymer ~14 wt%
S-250829-001, HDPE MRF T1S2 PROD. (7. orange)	Poly (ethylene ethyl acrylate)
S-250829-001, HDPE MRF T1S2 PROD. (8. red)	Ethylene/vinyl acetate copolymer ~18 wt%
S-250829-001, HDPE MRF T1S2 PROD. (9. green)	Poly (ethylene ethyl acrylate)
S-250829-001, HDPE MRF T1S2 PROD. (10. magenta)	Polyethylene
S-250829-001, HDPE MRF T1S2 PROD. (11. blue)	Polyethylene
S-250829-001, HDPE MRF T1S2 PROD. (12. blue)	Polyethylene
S-250829-001, HDPE MRF T1S2 PROD. (13. blue)	Polyethylene
S-250829-001, HDPE MRF T1S2 PROD. (14. black)	Poly(isoprene), 1,4-cis

Figure 16 Identification of manually selected flakes from the colour-sorted MRF HDPE fraction

Density and Melt Flow Rate

Density and melt flow rate (MFR) were measured to evaluate the basic physical and processing properties of the virgin HDPE reference material and the recycled HDPE fractions. The results are presented in Figure 17

Sample name	Density kg/m3	MFR @190°c, 2.16kg
Hostalen ACP5831D	958	0,30
SAS HDPE white	961	0,16
SAS HDPE color	956	0,21
MRF hDPE white	961	0,13
MRF HDPE color	951	0,29

Figure 17 Density and melt flow rate of virgin HDPE and recycled SAS and MRF fractions

Both white PCR fractions (SAS and MRF) exhibited identical densities of 961 kg/m³, slightly higher than the virgin HDPE (958 kg/m³), indicating a relatively homogeneous HDPE stream. The coloured fractions showed lower densities, reflecting their more heterogeneous composition.
The white recycled fractions also exhibited lower MFR values (0.13–0.16 g/10 min) than both the virgin material (0.30 g/10 min) and the coloured fractions, indicating higher melt viscosity. This lower MFR is most likely associated with the presence of white masterbatch in the original packaging.
Overall, the results confirm that the white recycled HDPE fractions possess consistent material properties and are suitable for subsequent bottle production.

Tensile properties

The mechanical performance of the virgin HDPE reference material and the recycled HDPE fractions was evaluated by tensile testing.

Tensile modulus
All recycled HDPE fractions retained a tensile modulus above 1000 MPa, indicating that the stiffness of the material remained suitable for rigid packaging applications. The white fractions exhibited slightly higher modulus values than the coloured fractions, although all recyclates showed lower stiffness than the virgin reference.

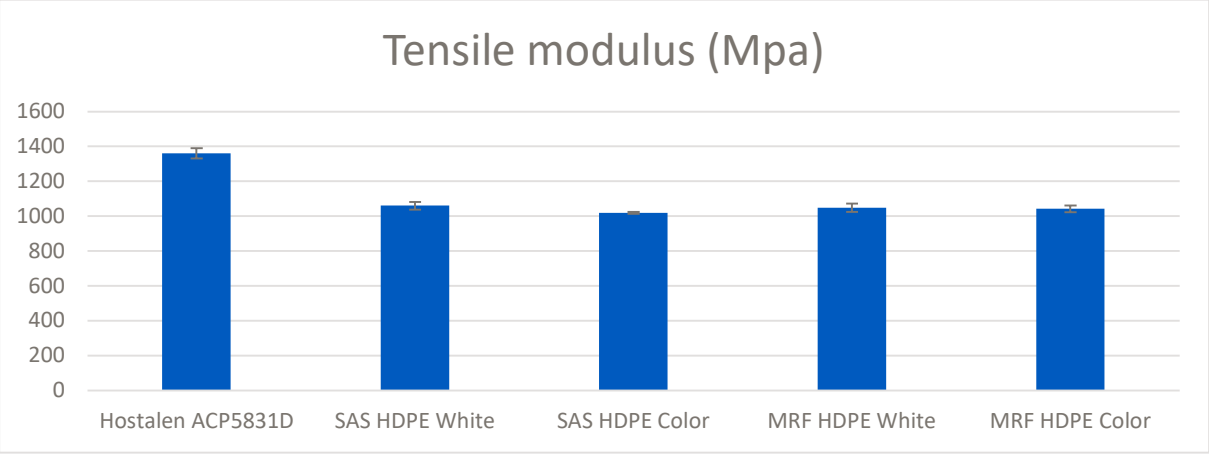


Figure 18 Tensile modulus of virgin HDPE and recycled SAS and MRF fractions

Stress at yield

The stress at yield of all recycled materials was only slightly lower than that of the virgin HDPE. The white fractions (SAS and MRF) showed marginally higher values than the coloured fractions, indicating that the recycling process had only a limited effect on the yield strength of the material.

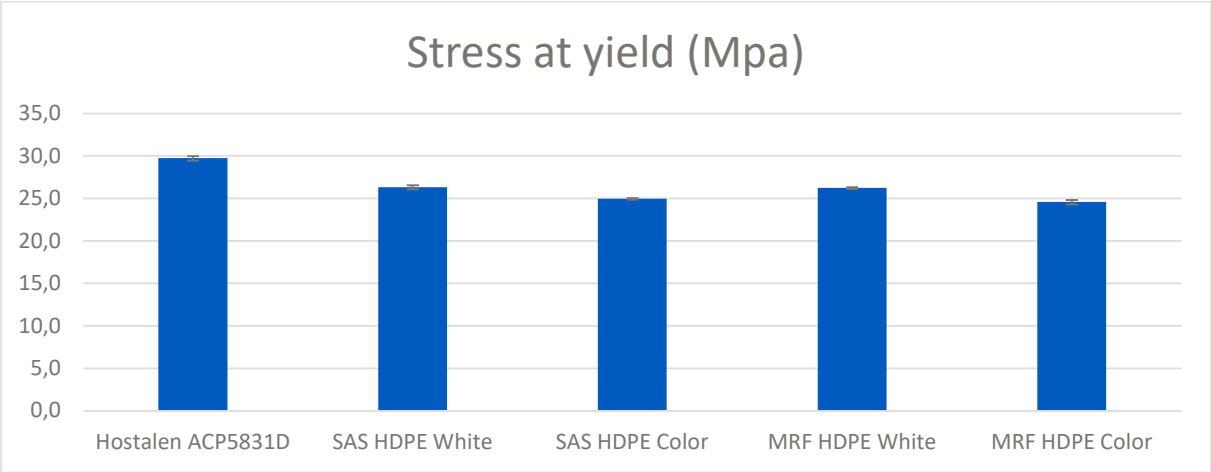


Figure 19 Stress at yield of virgin HDPE and recycled SAS and MRF fractions

Strain at break

The largest differences were observed for strain at break. All recycled materials exhibited substantially lower ductility than the virgin reference, with the coloured fractions showing the greatest reduction. In particular, the coloured MRF fraction fractured at very low elongation, indicating significantly increased brittleness.

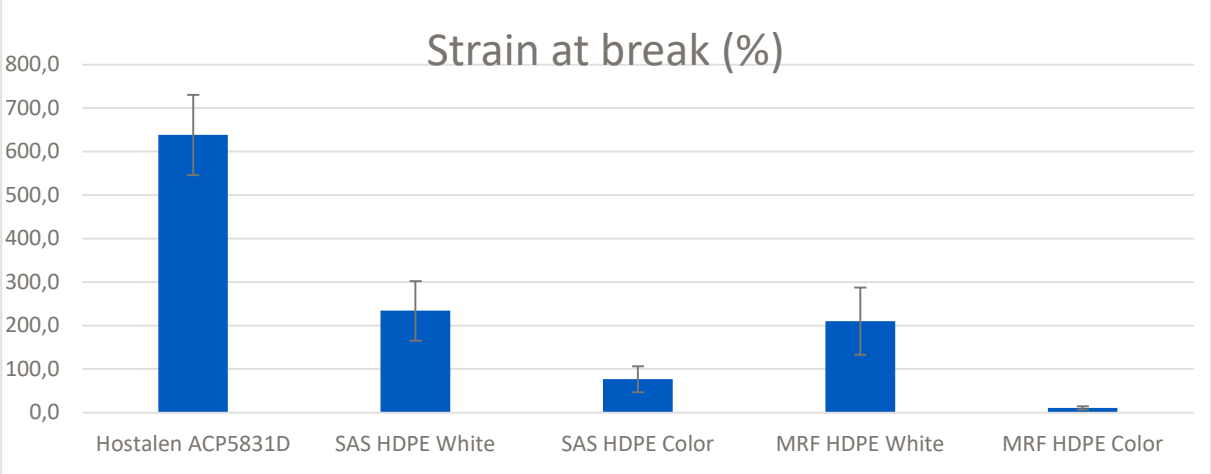


Figure 20 Strain at break of virgin HDPE and recycled SAS and MRF fractions

Summary of tensile properties

Overall, the mechanical properties indicate that the white recycled HDPE fractions provide more consistent performance than the mixed-colour fractions, regardless of the waste collection system. Both SAS and MRF white fractions exhibited slightly higher stiffness, higher yield strength and substantially better ductility than the corresponding coloured fractions. The differences between SAS and MRF were relatively small, whereas the separation of the white fraction had a much greater positive effect on the mechanical properties.

Notched impact strength

The notched impact strength of the virgin HDPE and the recycled HDPE fractions is presented in Figure 21

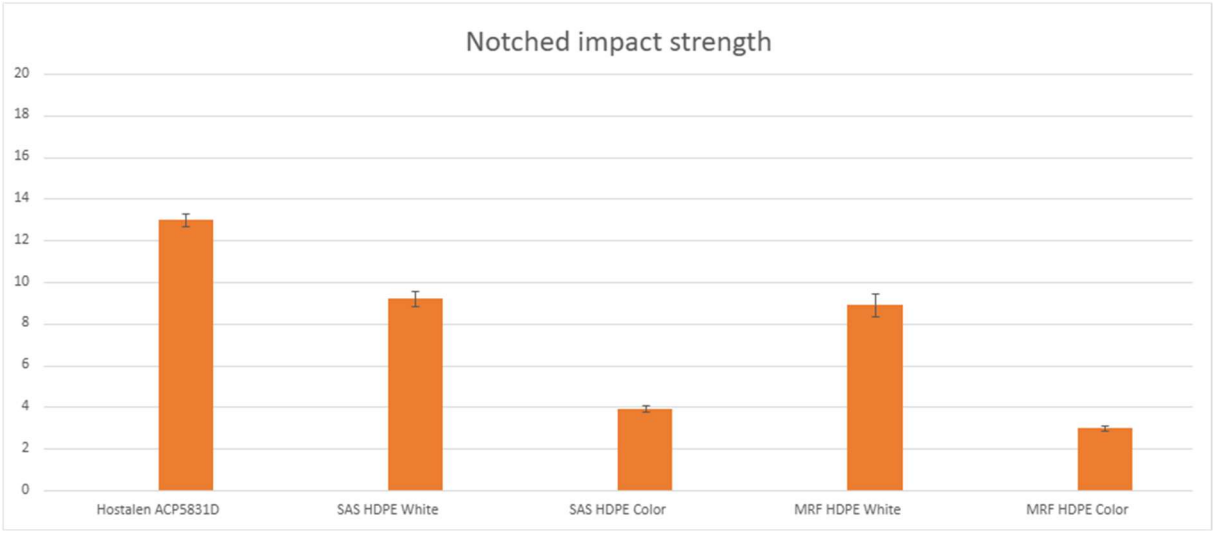


Figure 21 Notched impact strength of virgin HDPE and recycled SAS and MRF fractions

The virgin HDPE exhibited the highest impact strength, as expected. Among the recycled materials, the white fractions from both SAS and MRF showed comparable impact resistance, reaching approximately 70% of the virgin material. In contrast, the mixed-colour fractions exhibited substantially lower impact strength, with the MRF coloured fraction showing the lowest value of all tested materials.
The pronounced reduction in impact strength of the coloured fractions is consistent with the tensile test results, which also showed significantly lower ductility. The presence of mixed pigments, additives and minor polymer contamination is likely to contribute to the increased brittleness of these materials.

Overall, the results indicate that colour sorting has a much greater influence on impact performance than the collection system itself. Both SAS and MRF white fractions exhibited similar impact resistance, whereas the mixed-colour fractions showed a marked deterioration in toughness. These findings further support the production of a homogeneous white HDPE recyclate for applications requiring good mechanical performance.

Dynamic Rheology

The rheological behaviour of the virgin HDPE and the white PCR materials from the SAS and MRF streams was evaluated using oscillatory frequency sweep measurements. The results are presented in Figure 22 and Table 4

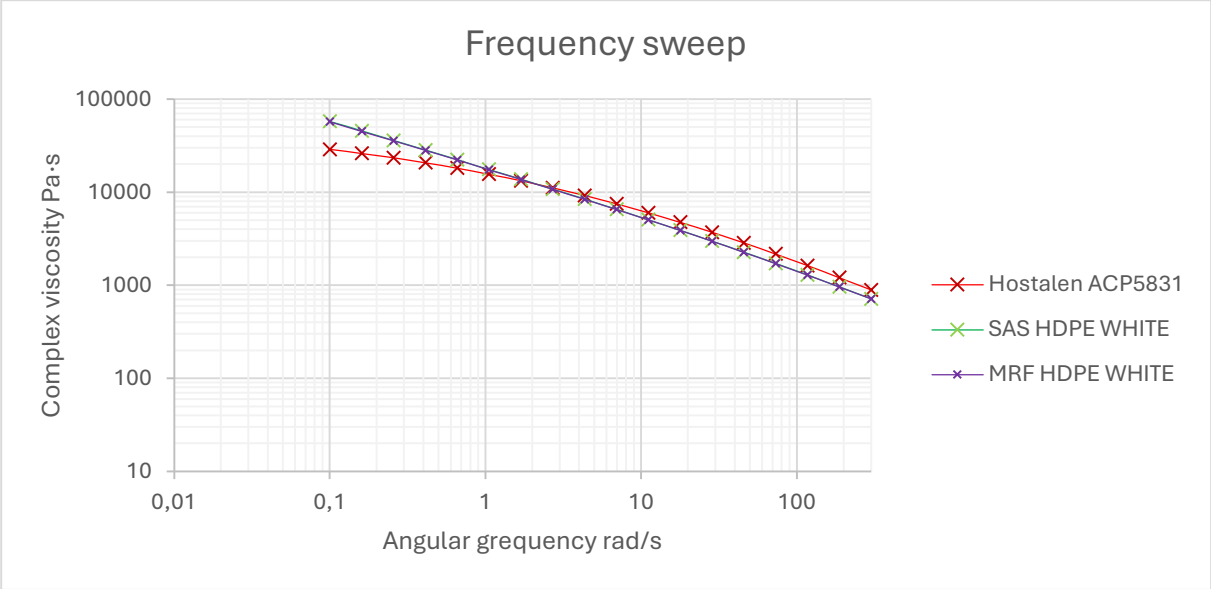


Figure 22 Frequency sweep showing complex viscosity of virgin HDPE, SAS white PCR and MRF white PCR

Table 4 Rheological parameters (η, G', G" and tan δ) for virgin HDPE and white PCR materials

Parameter	ACP5831 (Virgin)	SAS White PCR	MRF White PCR
Complex viscosity, η* (Pa·s)	28 844	57 157	57 281
Storage modulus, G' (Pa)	897	3 906	3 924
Loss modulus, G" (Pa)	2 741	4 173	4 173
Loss factor, tanδ (-)	3,06	1.07	1.06

Both recycled materials exhibited higher complex viscosity than the virgin HDPE, particularly at low angular frequencies, which is consistent with the lower melt flow rate (MFR) measured previously. The SAS and MRF white fractions showed almost identical viscosity curves, indicating very similar processing behaviour.
The storage modulus (G′) and loss modulus (G″) were also comparable for both PCR materials, while the lower tan δ values relative to the virgin material indicate a more pronounced elastic melt response. Despite these differences, no significant rheological differences were observed between the SAS and MRF white fractions.

Overall, the results demonstrate that the white PCR materials from both collection systems exhibit close rheological behaviour and can be expected to perform similarly during extrusion blow moulding.

FTIR analysis

FTIR analysis was performed on pellets produced from the colour-sorted HDPE fractions to determine polymer composition and identify potential contaminants. Virgin HDPE was included as a reference material. The results are presented in Table 5

Table 5 FTIR quantification of polymer composition for virgin HDPE and recycled SAS and MRF fractions

Description	PE	PP	PA	PET	CaCO3	TiO2	Talc
S-251024-001, Hostalen ACP5831D	99,9	0,0	0,0	0,0	0,0	0,0	0,0
S-251024-002, SAS HDPE WHITE	98,9	0,3	0,0	0,0	0,0	0,8	0,0
S-251024-003, SAS HDPE COLOR	93,2	6,0	0,0	0,0	0,1	0,6	0,0
S-251024-004, MRF HDPE WHITE	98,8	0,3	0,0	0,0	0,0	0,8	0,0
S-251024-005, MRF HDPE COLOR	85,0	14,1	0,1	0,1	0,1	0,7	0,0

The virgin HDPE reference consisted of 99.9 wt.% polyethylene, confirming its high purity. Both white recycled fractions (SAS and MRF) exhibited similarly high polyethylene contents (98.8–98.9 wt.%) with only 0.3 wt.% polypropylene and approximately 0.8 wt.% TiO_2, the latter originating from the white masterbatch commonly used in packaging applications. No significant amounts of other polymers or mineral fillers were detected, indicating that these fractions are chemically very similar to virgin HDPE.

The coloured fractions showed noticeably lower purity. The SAS coloured fraction contained 93.2 wt.% polyethylene and 6.0 wt.% polypropylene, whereas the MRF coloured fraction exhibited the lowest polyethylene content (85.0 wt.%) and the highest polypropylene content (14.1 wt.%). Small amounts of PA, PET and mineral fillers were also detected in the MRF coloured fraction, confirming a higher degree of material heterogeneity.

Overall, the FTIR results demonstrate that the white recycled fractions from both SAS and MRF provide a highly homogeneous HDPE stream with comparable chemical composition, while the coloured fractions—particularly the MRF material—contain significantly higher levels of polymer contamination.

4.3.2 WP3.2 Packaging with PCR content

Following the characterization of the recycled HDPE materials in WP3.1, the next stage of the project focused on evaluating their performance in a representative packaging application. The objective was to determine whether mechanically recycled HDPE obtained from Norwegian household waste could be successfully used in extrusion blow moulding and to assess how increasing PCR content affects bottle quality, processability and functional performance.
One-litre HDPE bottles were selected as the reference packaging format, representing a typical application within the Home and Personal Care sector. A commercial virgin blow-moulding grade was used as the reference material, while bottles containing 35%, 65% and 100% PCR were produced using white and coloured HDPE recyclates recovered from both source-separated (SAS) and mixed residual waste (MRF) streams. This experimental design enabled the influence of both PCR content and recycle origin on bottle performance to be evaluated under identical processing conditions.
The produced bottles were subjected to a comprehensive evaluation programme combining dimensional measurements, mechanical testing and visual assessment with complementary material characterization. Particular attention was given to properties identified in WP2 as critical for harmonized HDPE packaging, including dimensional stability, wall thickness distribution, top-load performance, drop resistance, colour and environmental stress crack resistance (ESCR). The objective was to compare bottles produced with increasing PCR content against the virgin reference and to identify practical limitations associated with high recycled content.

4.3.2.1 Bottle analysis

Dimensional stability/ processability

The processability of the different PCR formulations was assessed through pilot-scale extrusion blow moulding of 1 L HDPE bottles. As only approximately 20 kg of each formulation was available, the production trials were carried out without full process optimisation. Consequently, the dimensional evaluation (Figure 23) focused on the repeatability of the production process rather than compliance with industrial dimensional tolerances.

Instead of comparing the measured dimensions with specification limits, the relative variation of each parameter was calculated according to Equation:

$$Relative\ variation = \frac{Max - Min}{Average} \times 100\%$$

This approach normalises the variation with respect to the average dimension, allowing parameters with different absolute sizes (e.g., bottle diameter, bottle height and neck dimensions) to be directly compared. The relative variation therefore provides a measure of process consistency, where lower values indicate more stable bottle production and better processability under identical manufacturing conditions. This methodology is particularly suitable for pilot-scale trials, where the objective is to compare the influence of different PCR formulations rather than to assess compliance with commercial product specifications.

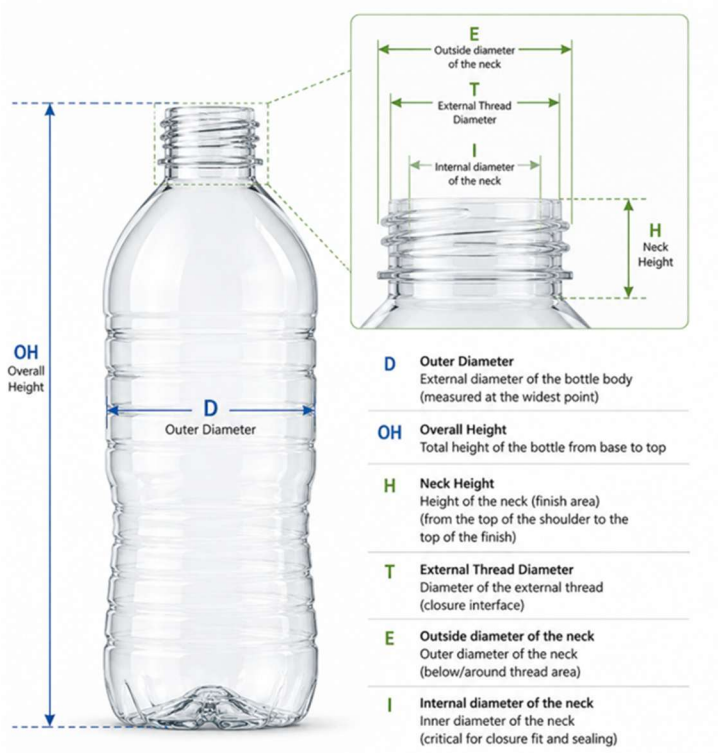


Figure 23 Dimensional parameters used for the evaluation of bottle dimensional stability, including bottle body (D, OH) and neck dimensions (H, T, E and I)

The dimensional evaluation included measurements of the bottle body (outer diameter, overall height and weight) as well as critical neck dimensions (neck height, thread diameter, outside and inside neck diameters, and neck ovality), which are directly related to mould filling, parison stability and closure compatibility.

Bottle body dimensional consistency

The dimensional consistency of the bottle body was evaluated using the outer diameter (D), overall height (OH) and bottle weight. The results are presented in Table 6

All formulations produced bottles with low dimensional variation, indicating stable blow moulding performance. Comparable repeatability was observed for both SAS and MRF materials across all PCR contents, with no systematic deterioration as the recycled content increased. The measured variations in bottle diameter, overall height and weight remained low for all formulations, demonstrating that the bottle body geometry could be reproduced consistently under the applied processing conditions in pilot scale.

Table 6 Relative variation of bottle body dimensions (outer diameter, overall height and bottle weight) for SAS and MRF white formulations

Sample	D (%)	OH (%)	Weight (%)
SAS White 35%	0,39	0,16	0,19
SAS White 65%	0,56	0,17	0,44
SAS White 100%	0,57	0,14	0,62
MRF White 35%	0,53	0,41	0,62
MRF White 65%	0,44	0,07	0,25
MRF White 100%	0,54	0,12	0,25

Neck dimensional consistency

The neck dimensions, including neck height (H), external thread diameter (T), outside neck diameter (E), internal neck diameter (I) and neck ovality, exhibited greater variability than the bottle body measurements. The results are shown in Table 7

Table 7 Relative variation of neck dimensions for SAS and MRF white formulations

Sample	H (%)	T (%)	E (%)	I (%)	Ovality (%)
SAS White 35%	**2,70**	0,55	1,13	6,90	1,13
SAS White 65%	0,76	0,35	1,10	6,98	1,08
SAS White 100%	0,87	0,68	0,59	7,04	0,58
MRF White 35%	0,87	**1,31**	**1,42**	**7,93**	**1,42**
MRF White 65%	**2,94**	0,65	0,93	**8,74**	0,90
MRF White 100%	**2,22**	0,83	**1,43**	**7,38**	**1,42**

The SAS formulations generally demonstrated better dimensional consistency than the corresponding MRF materials. The largest variations were observed for the internal neck diameter and neck ovality, particularly for the MRF formulations. Since these dimensions are influenced by parison positioning and mould alignment, the observed variability is likely to reflect the increased sensitivity of the neck region to processing conditions during pilot-scale production.

Despite the increased variation, all formulations could be successfully processed into bottles, indicating that the recycled materials remained suitable for extrusion blow moulding.

Wall thickness distribution

Wall thickness distribution was evaluated to assess the uniformity of material distribution during extrusion blow moulding. Since the average wall thickness differed slightly between formulations, the results were expressed as relative wall thickness variation (%), calculated using Equation:

$$Relative\ Wall\ Thickness\ Variation = \frac{Max - Min}{Average} \times 100\%$$



Figure 24 Schematic illustration of the bottle sections used for wall thickness measurements

This normalized parameter allows direct comparison between bottle formulations and provides an indication of process consistency, where lower values represent a more uniform wall thickness distribution. Measurements were performed at three characteristic bottle regions: the top (neck/shoulder), middle (body) and bottom (base), as illustrated in Figure 24

The wall thickness distribution results are summarised inTable 8, Table 9, while the trend for the white formulations is illustrated in Figure 25

Table 8 Wall thickness measurements and relative wall thickness variation of bottles produced from white HDPE recyclates (SAS and MRF) with 35%, 65% and 100% PCR content.

Sample	Bottom	Middle	Top	Average	Relative Variation (%)
ACP 5831	0,515	0,497	0,510	0,507	3,60
SAS White 35%	0,512	0,477	0,482	0,490	7,10
SAS White 65%	0,540	0,478	0,457	0,491	16,90
SAS White 100%	0,539	0,465	0,417	0,474	25,70
MRF White 35%	0,500	0,496	0,520	0,505	4,80
MRF White 65%	0,534	0,493	0,488	0,505	9,10
MRF White 100%	0,527	0,484	0,472	0,494	11,10

Table 9 Wall thickness measurements and relative wall thickness variation of bottles produced from mixed-colour HDPE recyclates (SAS and MRF) with 35%, 65% and 100% PCR content

Sample	Bottom	Middle	Top	Average	Relative Variation (%)
SAS Color 35%	0,528	0,499	0,516	0,514	5,60
SAS Colour 65%	0,528	0,493	0,501	0,507	6,90
SAS Color 100%	0,542	0,476	0,476	0,498	13,30
MRF Color 35%	0,52	0,486	0,528	0,511	8,20
MRF Color 65%	0,533	0,497	0,497	0,509	7,10
MRF Color 100%	0,556	0,473	0,439	0,489	24,00

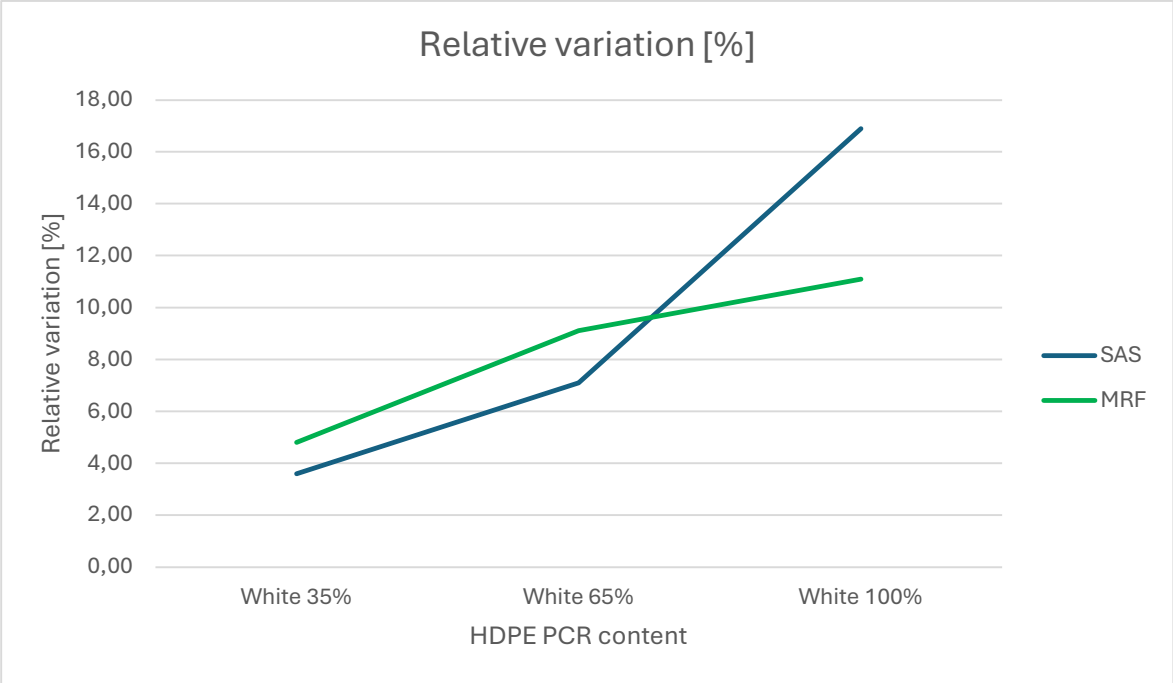


Figure 25 Relative wall thickness variation of bottles produced from white SAS and MRF recyclates at different PCR contents

For the white HDPE formulations, the relative wall thickness variation increased progressively with increasing PCR content for both SAS and MRF materials, indicating a gradual reduction in wall thickness uniformity. At 35% PCR, both recyclates showed values close to the virgin reference, suggesting that the incorporation of a moderate amount of recycled material had only a limited effect on material distribution during blow moulding. At higher PCR contents, the variation increased, with the largest increase observed for the 100% SAS white formulation. In contrast, the MRF white formulations exhibited a more gradual increase in variation, resulting in a more uniform wall thickness profile at high PCR contents.

The wall thickness distribution results should be interpreted together with the dimensional consistency measurements presented previously. While the SAS formulations generally exhibited lower variability in bottle body and neck dimensions, the MRF white formulations showed a more uniform wall thickness

profile, particularly at higher PCR contents. These observations indicate that dimensional repeatability and wall thickness distribution are influenced by different aspects of the blow moulding process. External bottle dimensions primarily reflect process repeatability and mould filling, whereas wall thickness distribution is more sensitive to parison stability and melt behaviour during inflation. Since the rheological measurements showed nearly identical frequency sweep responses for the SAS and MRF materials, the observed differences are likely related to properties not captured by conventional linear viscoelastic measurements, such as melt strength or parison sag behaviour. Additional characterisation using dedicated melt-strength methods, such as Rheotens or parison sag measurements, would help clarify the processing behaviour of these materials. Further industrial-scale trials under optimised process conditions would also be beneficial to validate product performance.

Colour

The colour of the bottles was evaluated using the CIELAB colour space to assess the influence of PCR content and recyclate source on the visual appearance of the final packaging. The L* value represents lightness (0 = black, 100 = white), while the b* value describes the blue–yellow colour axis, where higher positive values indicate a more yellow appearance. The results are presented in Figure 26, Figure 27.

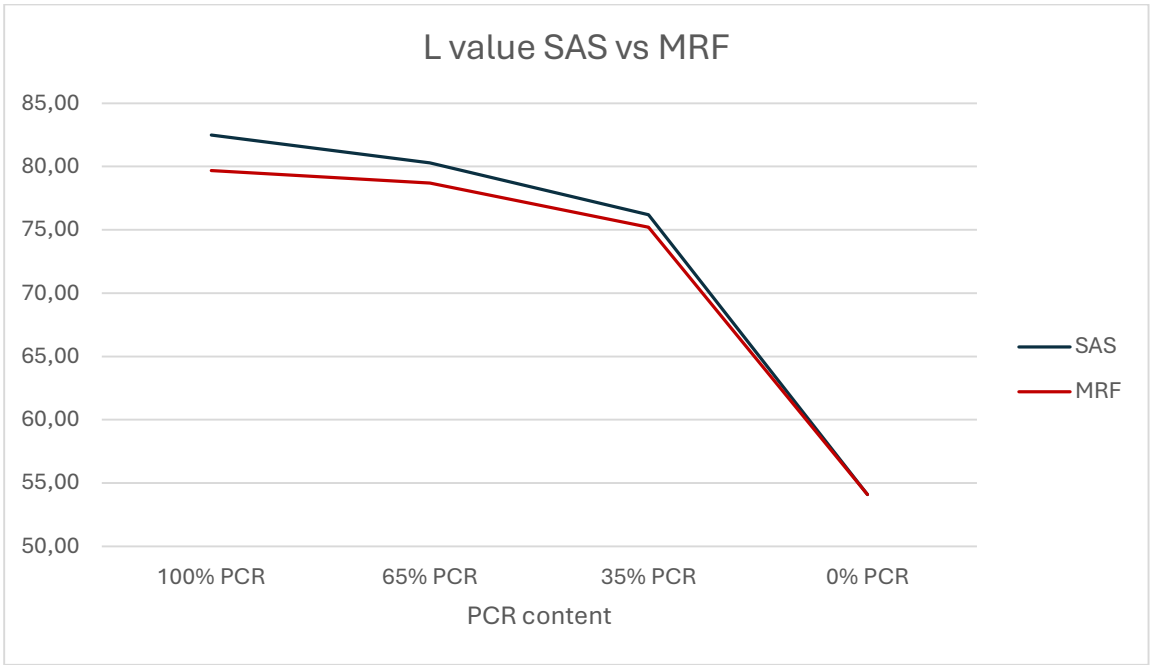


Figure 26 Effect of PCR content on the CIELAB L value of bottles produced from SAS and MRF white HDPE recyclates.]*

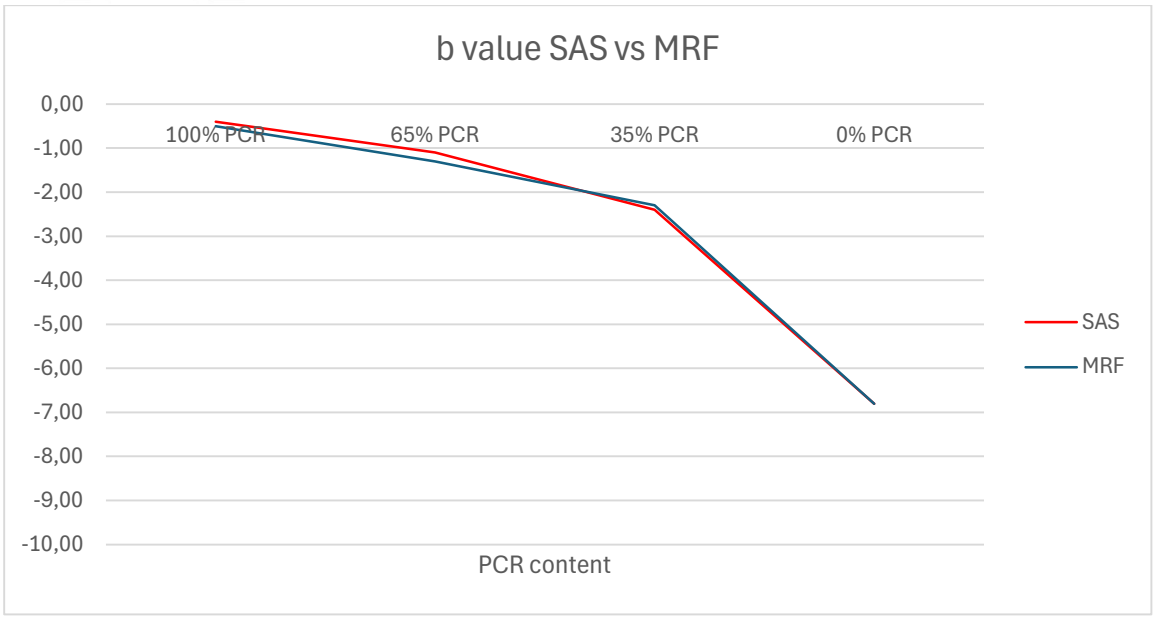


Figure 27 Effect of PCR content on the CIELAB b value of bottles produced from SAS and MRF white HDPE recyclates*

The effect of PCR content on the L* value is shown in Figure 26. For both SAS and MRF materials, the lightness increased with increasing PCR content, reflecting the presence of titanium dioxide (TiO_2) in the white recycled HDPE fractions. At all PCR levels, bottles produced from SAS recyclate exhibited consistently higher L* values than those produced from MRF recyclate. This difference remained evident for the 100% PCR bottles, indicating that the SAS-derived recyclate possesses a slightly higher inherent whiteness.
The b* values for the different formulations are presented in Figure 27. Increasing PCR content resulted in progressively higher b* values, indicating that bottles became less blue and more yellow as the proportion of recycled material increased. However, the differences between the SAS and MRF recyclates were small, and both materials followed similar trends across the investigated PCR contents.

Overall, the colour measurements show that PCR content was the main factor influencing bottle colour, while the effect of the waste collection system was relatively limited. No additional white masterbatch was used during the bottle production trials in order to avoid masking the visual effect of the recycled material itself. The consistently higher L* values obtained for the SAS formulations indicate that source-separated HDPE produced a slightly brighter white recyclate than material recovered from mixed residual waste. Both recyclate streams showed similar trends in b* values, indicating comparable increases in yellowness as PCR content increased. It is expected that the addition of white colour masterbatch would improve the visual colour quality of the bottles, particularly by increasing brightness and reducing the apparent colour variation associated with recycled-content formulations.

Bottle drop test

The drop test was performed to evaluate the impact resistance of bottles produced with increasing PCR content. Virgin HDPE bottles were used as the reference material. For each formulation, the average failure height together with the minimum and maximum values were recorded. The results for the white and mixed-colour formulations are presented in Figure 28, Figure 29, respectively.

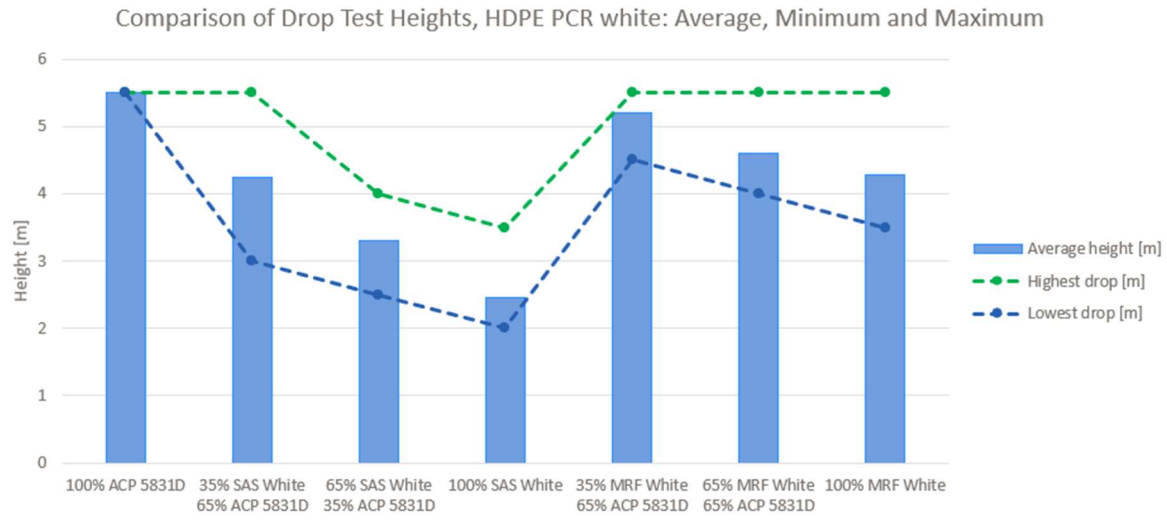


Figure 28 Comparison of drop test results for white HDPE bottle formulations

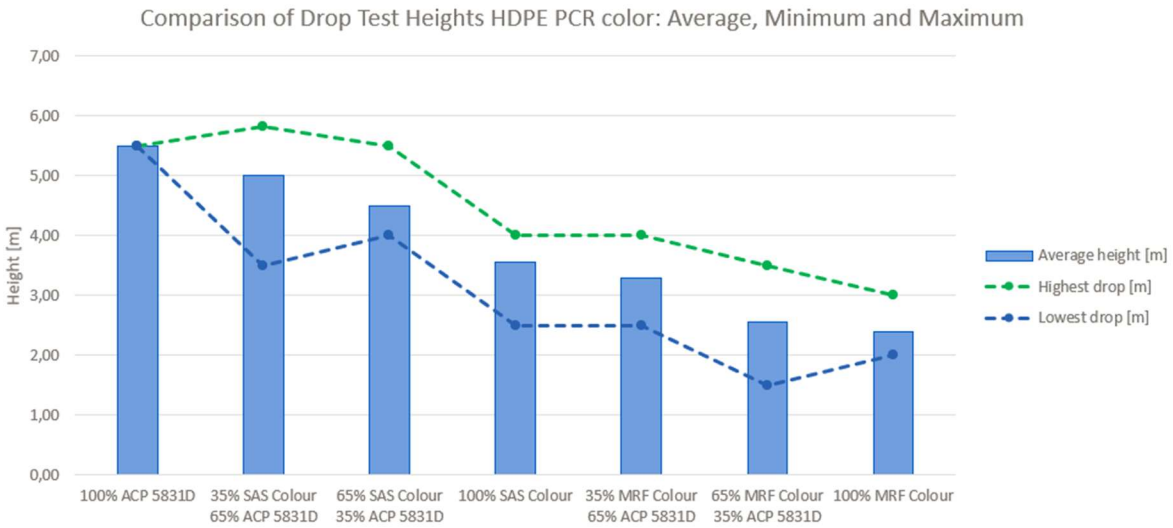


Figure 29 Drop test results for bottles produced from mixed-colour HDPE formulations

White HDPE formulations

The results for the white formulations are shown in Figure 28. The virgin HDPE bottles exhibited the highest drop resistance, with all specimens surviving the maximum test height of 5.5 m. For the SAS formulations, the average failure height decreased progressively with increasing PCR content, reaching approximately 2.5 m for the 100% PCR bottles. In contrast, the MRF white formulations retained considerably higher impact resistance, maintaining average failure heights above 4 m even at 100% PCR. This indicates that the MRF white recyclate provided better drop performance than the corresponding SAS material despite the increasing recycled content.

Mixed-colour HDPE formulations

The coloured formulations showed a different behaviour (Figure 29). For both SAS and MRF materials, the average drop height decreased with increasing PCR content, indicating reduced impact resistance at higher levels of recycled material. The reduction was more gradual for the SAS formulations, whereas the MRF coloured bottles exhibited a steeper decline, particularly at 65% and 100% PCR, where the lowest average drop heights were recorded. Consequently, unlike the white formulations, the coloured SAS bottles outperformed the corresponding MRF bottles at high PCR contents.

Discussion

The drop test results demonstrate that the effect of PCR content on bottle impact resistance depends on the type of recyclate. For both white and coloured formulations, increasing PCR content generally reduced the average drop height, indicating a gradual decrease in impact resistance. However, the influence of the waste collection system differed between the two material streams.

For the white fractions, bottles produced from MRF recyclate consistently exhibited higher drop resistance than those produced from the corresponding SAS material. In contrast, the mixed-colour fractions showed the opposite trend, with the SAS recyclate providing better impact performance than the MRF material at higher PCR contents.

These differences cannot be explained solely by the intrinsic material properties. Tensile testing and rheological characterization showed only minor differences between the SAS and MRF white recyclates, suggesting comparable material behaviour. Instead, the drop test results correlate more closely with the wall thickness distribution observed after blow moulding. In particular, the MRF white formulations exhibited a substantially more uniform wall thickness profile than the corresponding SAS formulations, especially at 100% PCR, while no significant differences were observed in the overall bottle dimensions. Since local wall thinning is a critical factor governing impact failure, the improved wall thickness uniformity is considered the most probable explanation for the superior drop performance of the MRF white bottles.

Overall, the results demonstrate that the impact resistance of the finished bottle is governed not only by the quality of the recycled material but also by the material distribution achieved during extrusion blow moulding. Consequently, bottle performance cannot be predicted from material characterization alone, highlighting the importance of combining laboratory testing with full-scale packaging evaluation when assessing the suitability of PCR materials for demanding packaging applications.

Top-load performance

The top-load test was performed to evaluate the compressive strength of bottles containing different levels of PCR. The maximum compressive force (Fmax) sustained by each bottle before deformation was recorded. Virgin HDPE bottles served as the reference material. The results for the white and mixed-colour formulations are presented in Figure 30, Figure 31 respectively.

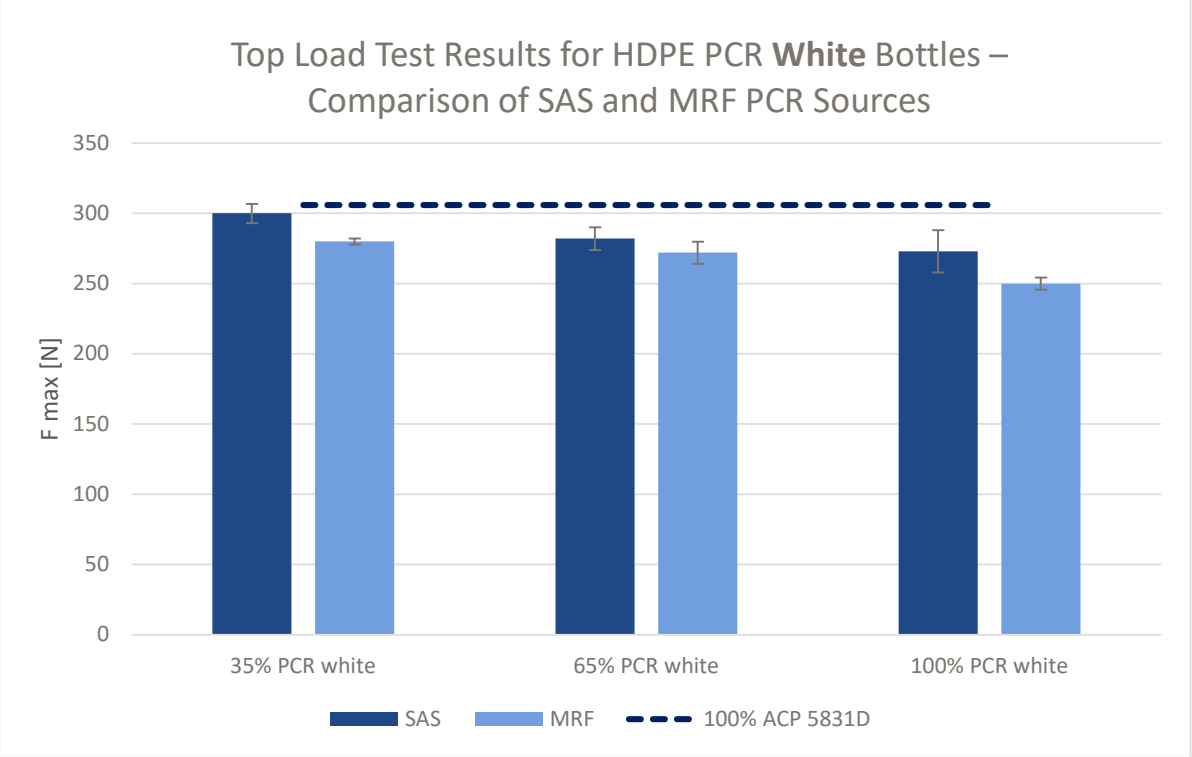


Figure 30 Top-load performance of bottles produced from white HDPE formulations

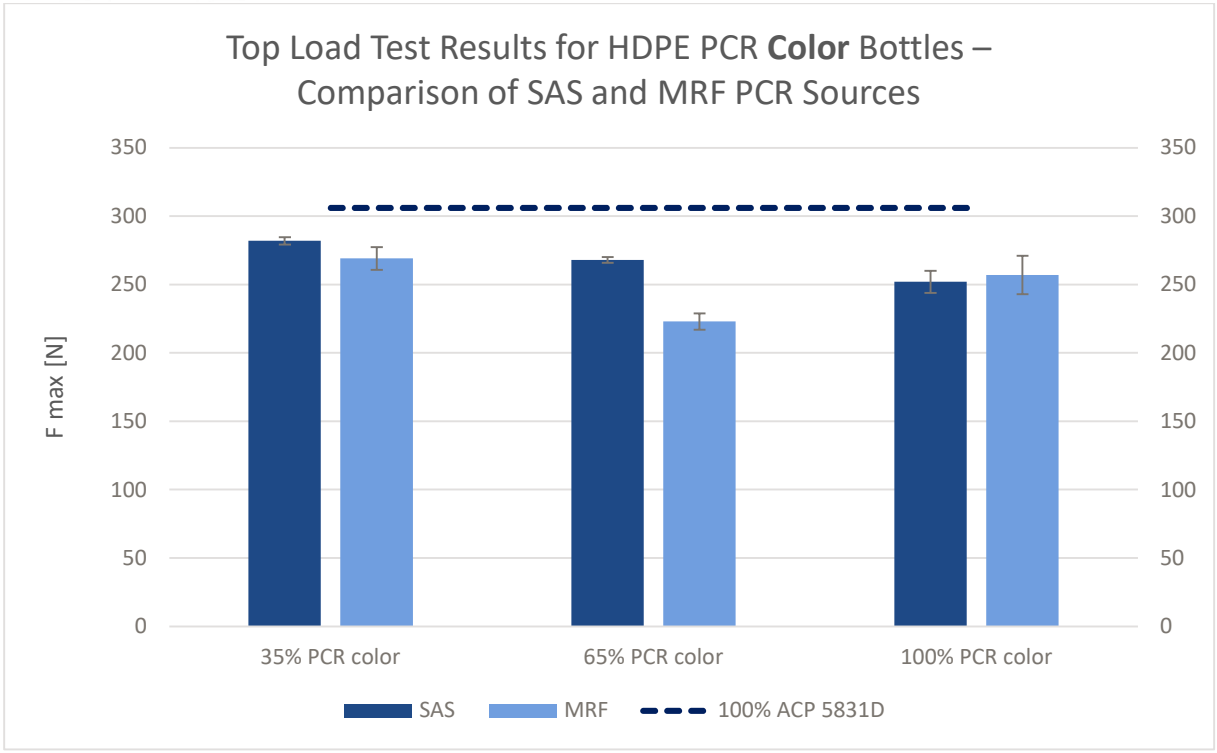


Figure 31 Top-load performance of bottles produced from mixed-colour HDPE formulations

White HDPE formulations

The results for the white formulations are shown in Figure 30. As expected, all bottles containing PCR exhibited slightly lower top-load resistance than the virgin reference. The reduction in compressive strength became more pronounced with increasing PCR content.

For all PCR contents, the SAS white bottles showed slightly higher top-load values than the corresponding MRF white bottles. The difference was relatively small at 35% and 65% PCR, while a larger reduction was observed for the 100% MRF white formulation. Nevertheless, all white formulations retained a high compressive strength, remaining close to the performance of the virgin bottles.

Mixed-colour HDPE formulations

The results for the mixed-colour formulations are presented in Figure 31. Similar to the white bottles, compressive strength generally decreased with increasing PCR content. However, a different trend was observed between the SAS and MRF recyclates.

At 35% PCR, the SAS and MRF bottles exhibited comparable top-load performance. At 65% PCR, the MRF coloured formulation showed the largest reduction in compressive strength of all tested bottles, whereas at 100% PCR, the MRF bottles recovered to a level comparable to, or slightly higher than, the corresponding SAS formulation. Considering the measurement variability, the differences between the two 100% PCR formulations are relatively small.

Discussion

The top-load results demonstrate that increasing PCR content has only a moderate influence on the compressive strength of HDPE bottles. Even at 100% PCR, all formulations retained approximately 80–90% of the top-load capacity of the virgin reference, indicating that the bottles maintained sufficient structural rigidity for typical handling and stacking conditions.

Unlike the drop test, no consistent advantage of either the SAS or MRF recyclate was observed across all formulations. The white SAS bottles consistently exhibited slightly higher compressive strength than

the corresponding MRF bottles, whereas the mixed-colour formulations showed no systematic trend. These observations are consistent with the material characterization results, where only small differences in tensile modulus were measured between the recycled materials. Since bottle compression is governed primarily by stiffness and bottle geometry rather than local stress concentrations, the top-load performance appears to be less sensitive to variations in wall thickness distribution than the drop test.

Overall, the results indicate that PCR content has a relatively limited effect on bottle compressive strength, confirming that both SAS- and MRF-derived HDPE recyclates can produce bottles with adequate load-bearing capacity, even at high recycled content. In contrast to impact resistance, the top-load performance is controlled by the global stiffness of the bottle.

Migration (NIAS Screening)

Migration testing was performed on HDPE pellets prepared from the white SAS and MRF recycled fractions in order to evaluate the chemical suitability of the recycled materials for potential packaging applications. The study included overall migration, screening of specific migrating substances (SML), and non-intentionally added substances (NIAS).

Migration experiments were carried out using 95% ethanol (60°C, 10 days) and isooctane (40°C, 2 days). The migration extracts were analyzed by GC-MS to identify and quantify both regulated substances and unknown compounds.

Overall migration

The overall migration values for both recycled HDPE materials remained well below the applicable specific migration limit of 60 mg/kg. (Figure 32)

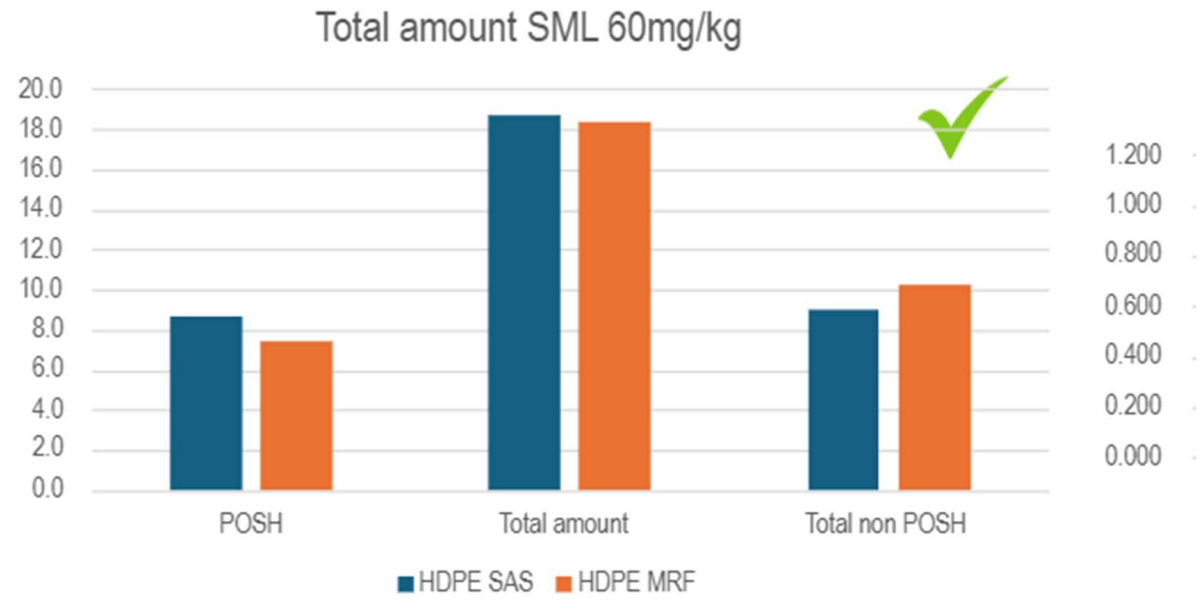


Figure 32 Overall Migration, POSH and Non-POSH Fractions (SML = 60 mg/kg)

The total migrated amount was 18.64 mg/kg for the SAS material and 18.32 mg/kg for the MRF material, demonstrating comparable overall migration behavior and compliance with the regulatory limit. The detected migration consisted of both POSH (Polyolefin Oligomeric Saturated Hydrocarbons) and non-POSH compounds.

These results show that both recycled HDPE streams have satisfactory overall migration performance and that overall migration does not limit further material evaluation.

Specific Migration and NIAS Screening

Screening of the migration extracts identified several compounds exceeding the default analytical screening threshold of 0.01 mg/kg used for unidentified substances (NIAS). (Figure 33)

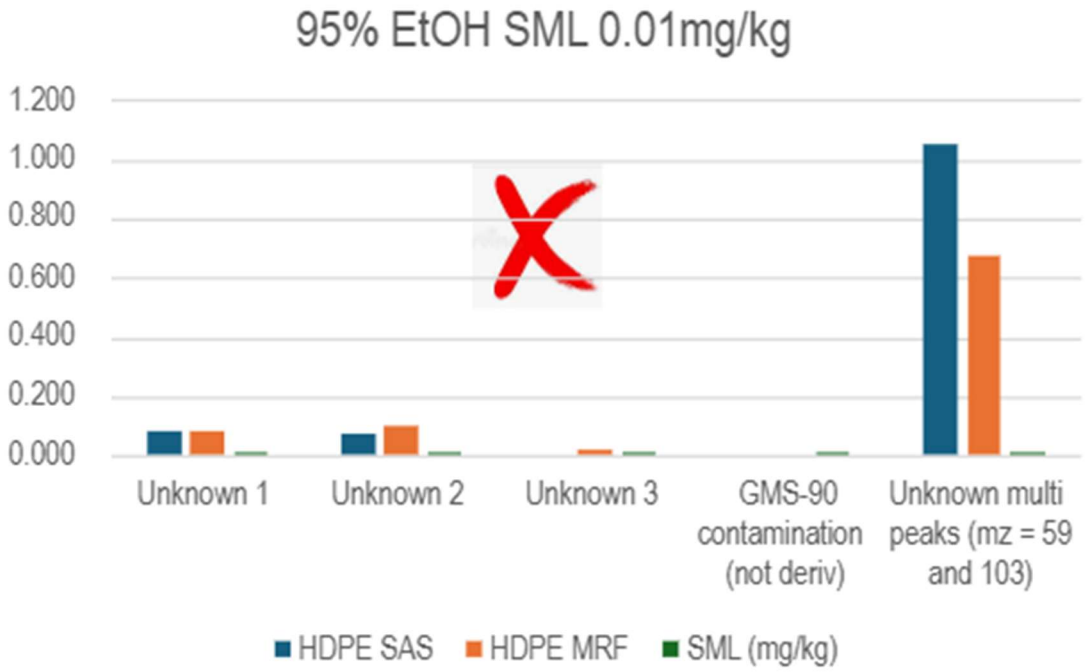


Figure 33 NIAS Screening Results in 95% Ethanol (Screening Threshold = 0.01 mg/kg)

Several unidentified compounds ("Unknown 1", "Unknown 2", "Unknown 3", and an unidentified group of compounds characterized by ions m/z 59 and 103) were detected above the analytical screening threshold in both SAS and MRF materials. As these compounds have not yet been identified, no toxicological assessment can currently be performed.

The results therefore indicate the need for further chemical identification and risk assessment of these substances before their significance can be fully evaluated.

Hexanamide Residue

Hexanamide, 3,5,5-trimethyl-N-2-ethylhexyl-, exceeded its specific migration limit (SML = 0.09 mg/kg), with measured concentrations of 1.72 mg/kg for the SAS material and 1.20 mg/kg for the MRF material. (Figure 34)

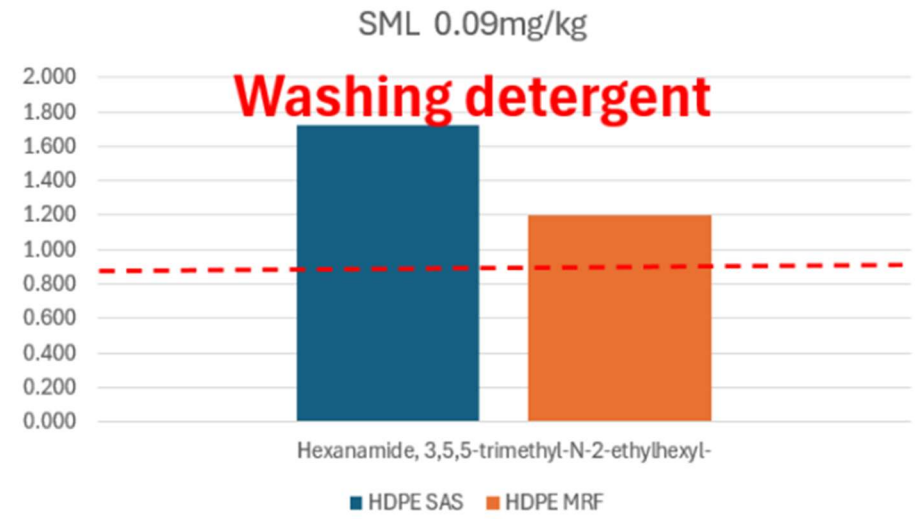


Figure 34 Specific Migration of Hexanamide, 3,5,5-trimethyl-N-2-ethylhexyl

Based on process knowledge, this substance was identified as originating from the washing process, where it is associated with a foaming agent used in the industrial washing system (Krones), rather than from the recycled HDPE itself. Consequently, its presence is considered process-related and may be minimized or eliminated through optimization of the washing procedure. This also highlights the importance of such assessments for recyclates that may originate from different washing lines, depending on the facility where they are processed.

Ethyl cis-9-octadecenoate

Ethyl cis-9-octadecenoate was detected in both recycled materials at concentrations of 0.162 mg/kg (SAS) and 0.102 mg/kg (MRF), remaining below the applicable specific migration limit. (Figure 35)

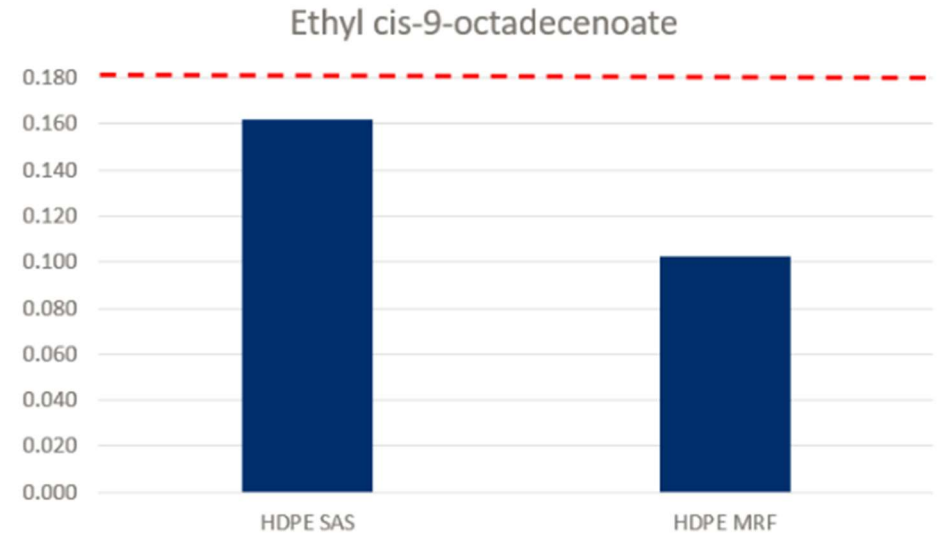


Figure 35 Migration of Ethyl cis-9-octadecenoate

This compound is not typically derived from the HDPE polymer itself but is more likely associated with processing additives, lubricants, or substances introduced through the recycled material stream.

Discussion

Overall, the migration results confirm the good chemical cleanliness of both recycled HDPE streams and demonstrate that overall migration is not a limiting factor for their use in non-food packaging applications. The remaining challenges are primarily related to the identification of unknown migrating substances (NIAS) and the elimination of process-related residues introduced during recycling operations. Future qualification of recycled HDPE for closed-loop applications should therefore include comprehensive NIAS characterization together with continuous optimization of recycling and washing processes to further improve the chemical quality of the recyclate.

4.3.2 WP3.3 Evaluation

WP 3.3 Discussion

The results obtained in WP3 demonstrate that recycled HDPE produced from Norwegian post-consumer packaging waste is suitable for the production of extrusion blow-moulded bottles. Both the source-separated (SAS) and mixed residual waste (MRF) streams yielded recyclates with properties compatible with rigid packaging applications. Overall, the SAS recyclate exhibited slightly higher material quality, including higher polyethylene purity, improved colour performance and marginally better tensile properties, whereas the MRF recyclate showed comparable rheological behaviour and satisfactory processability.

Increasing the PCR content influenced both the material and the finished package. While stiffness, yield strength and compressive strength were only moderately affected, higher PCR contents resulted in reduced bottle whiteness, lower ductility and lower impact resistance. Bottles containing 35% PCR showed only minor deviations from the virgin reference and can therefore be considered suitable for applications requiring properties close to those of virgin HDPE. Bottles containing 65% PCR also demonstrated satisfactory performance, although progressive changes in colour, impact resistance and process variability became evident. The successful production of bottles containing 100% PCR confirms the technical feasibility of using fully recycled HDPE; however, the increased variability observed for several performance parameters indicates that the applicability of such materials should be assessed according to the functional requirements of the intended packaging.

An important finding of the study is that the performance of the finished bottle cannot be predicted from standard laboratory material characterization alone. Although the SAS and MRF white recyclates exhibited very similar rheological behaviour and only small differences in tensile properties, differences were observed during pilot-scale bottle production. For example, the MRF white formulations produced bottles with a more uniform wall thickness distribution and higher drop resistance under the selected processing conditions. However, these observations should not be interpreted as an intrinsic material advantage. The production trials were performed under pilot-scale conditions using only approximately 20 kg of material per formulation, which limited the possibility for process optimisation. The observed differences are therefore likely to be influenced by processing-related factors such as parison stability, melt strength, material homogeneity and machine settings, in addition to the material itself. Full industrial-scale production trials should therefore be considered to verify process stability for both materials under more representative manufacturing conditions.

These findings demonstrate the importance of complementing laboratory material characterization with pilot-scale processing and application-specific bottle testing. Material properties reported in supplier technical data sheets, such as density, melt flow rate, tensile properties or conventional rheological measurements, provide valuable information about the polymer but are not sufficient to predict the behaviour of the finished package. Pilot-scale trials revealed differences in wall thickness distribution and drop performance that were not apparent from the laboratory results alone. Consequently, qualification of recycled materials for high-PCR packaging should combine laboratory characterization with representative processing trials and functional bottle tests. Furthermore, the results suggest that additional characterization methods directly related to blow moulding performance, such as melt strength, parison sag or Rheotens measurements, could improve the prediction of processing stability and finished-package performance.

4.3.3 WP3.4 Loop recycling simulation

The objective of this study was to evaluate whether HDPE packaging can maintain adequate material performance during repeated closed-loop mechanical recycling. The simulation reproduced a realistic recycling scenario in which each processing cycle consisted of 65 wt.% material recovered from the previous loop and 35 wt.% virgin HDPE. To better represent industrial recycling conditions, controlled levels of typical contaminants (6 wt.% PP, 2 wt.% LDPE and 0.5 wt.% PET) were introduced together with the virgin material in each subsequent loop. The material was recycled through five consecutive extrusion cycles and evaluated with respect to rheological, thermal, mechanical and ESCR properties.

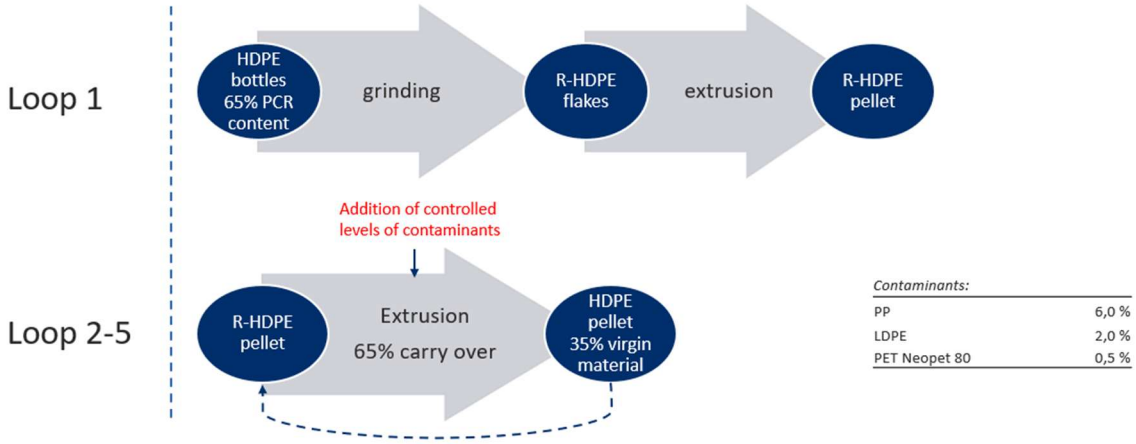


Figure 36 Experimental design of the multi-loop HDPE recycling simulation, showing the 65 wt.% material carry-over strategy with 35 wt.% virgin HDPE addition and controlled contaminant incorporation (PP, LDPE and PET) in each recycling loop

Rheological Properties

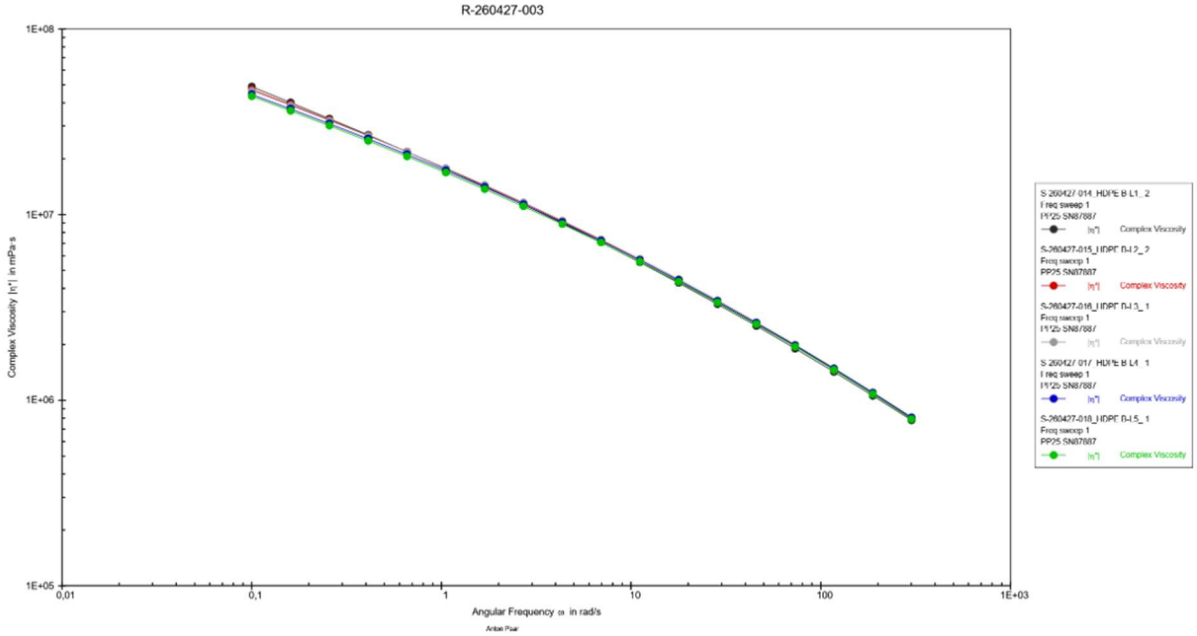


Figure 37 Complex viscosity as a function of angular frequency for HDPE after five consecutive closed-loop recycling cycles (L1–L5). The nearly overlapping frequency sweep curves indicate stable melt rheology and good retention of processing properties throughout

All samples exhibited the characteristic shear-thinning behaviour of HDPE, with complex viscosity decreasing continuously as the angular frequency increased. The frequency sweep curves for all five loops were highly similar and almost completely overlapped over the entire measured frequency range, indicating that repeated processing did not significantly alter the viscoelastic behaviour of the material.

A small reduction in low-frequency complex viscosity was observed after repeated recycling. The complex viscosity at 0.1 rad/s decreased from approximately 49.0 kPa·s in Loop 1 to 43.5 kPa·s in Loop 5, corresponding to a reduction of about 11%. No significant differences were observed at higher frequencies relevant to extrusion processing.

Overall, the rheological results indicate that the closed-loop recycling strategy maintained stable melt properties throughout five recycling cycles. The combination of 65 wt.% recycled material from the previous loop with 35 wt.% virgin HDPE effectively compensated for the effects of repeated melt processing, while the controlled addition of contaminants did not produce measurable changes in the linear viscoelastic response of the material. Consequently, the recycled HDPE retained melt behaviour comparable to that of the initial material, suggesting good processability during repeated mechanical recycling.

Differential Scanning Calorimetry (DSC)

Representative DSC thermograms for Loop 1 (L1) and Loop 5 (L5) are presented in Figure 38 and Figure 39.

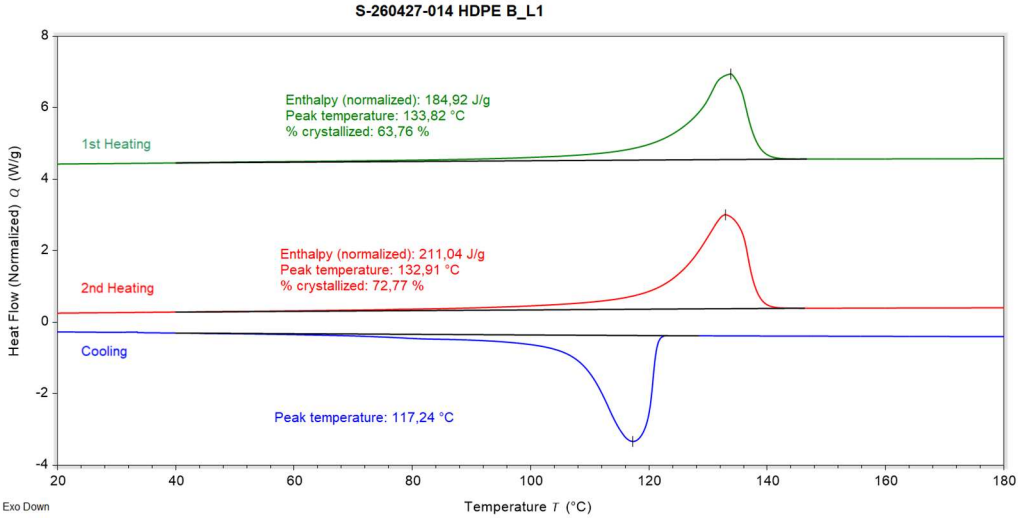


Figure 38 DSC thermogram of the HDPE material after the first recycling loop (L1)

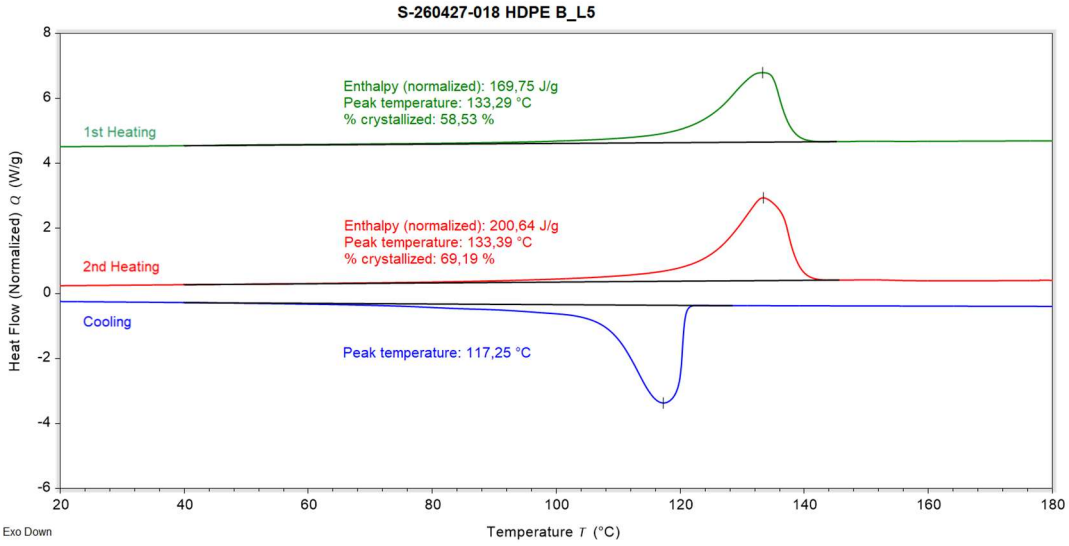


Figure 39 DSC thermogram of the HDPE material after the fifth recycling loop (L5)

Both samples exhibited nearly identical melting and crystallization profiles, indicating that repeated mechanical recycling did not significantly affect the thermal behaviour of the HDPE material. The melting endotherms remained narrow and well-defined, while the crystallization exotherms occurred at nearly the same temperature, suggesting that the crystalline structure of the polymer was largely preserved throughout the recycling process.

The melting temperature remained essentially constant at 133–134 °C for all recycling loops, whereas the crystallization temperature varied only between 117 and 118 °C. A small decrease in the enthalpy of melting was observed, from 211 J/g in Loop 1 to 201 J/g in Loop 5, indicating a slight reduction in the

degree of crystallinity after repeated processing. However, the change was relatively small and was not accompanied by any measurable shift in melting or crystallization temperatures.

Overall, the DSC results demonstrate that the applied closed-loop recycling strategy preserved the thermal characteristics of the HDPE material over five recycling cycles. The stable melting and crystallization behaviour indicates that repeated extrusion did not induce significant structural changes in the polymer and confirms the good thermal stability of the recycled HDPE.

Mechanical Properties

The tensile properties of the HDPE material after five consecutive recycling loops are presented in Figure 40, Figure 41 and Figure 42. Tensile modulus, tensile strength and strain at break were measured to assess the effect of repeated mechanical recycling on material stiffness, strength and ductility.

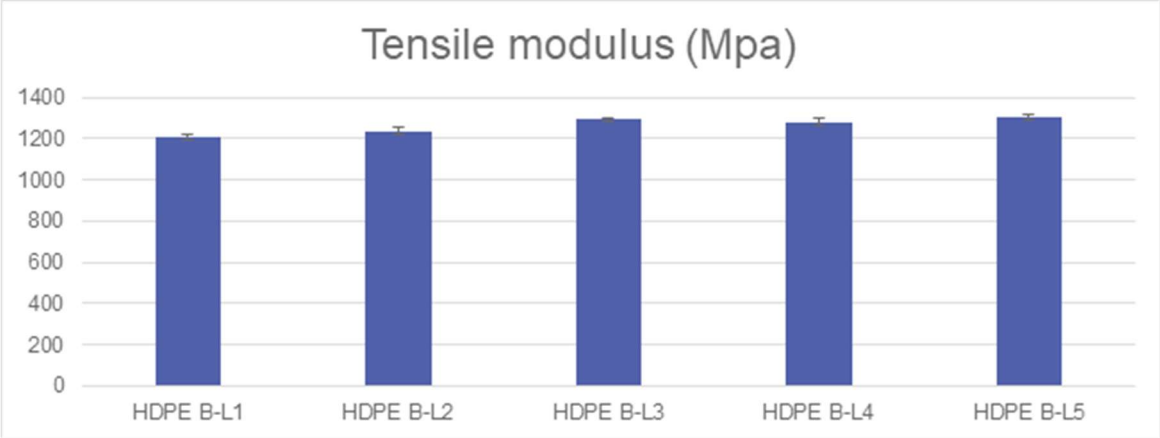


Figure 40 Tensile modulus of HDPE after five consecutive recycling loops, showing a gradual increase in material stiffness during repeated recycling

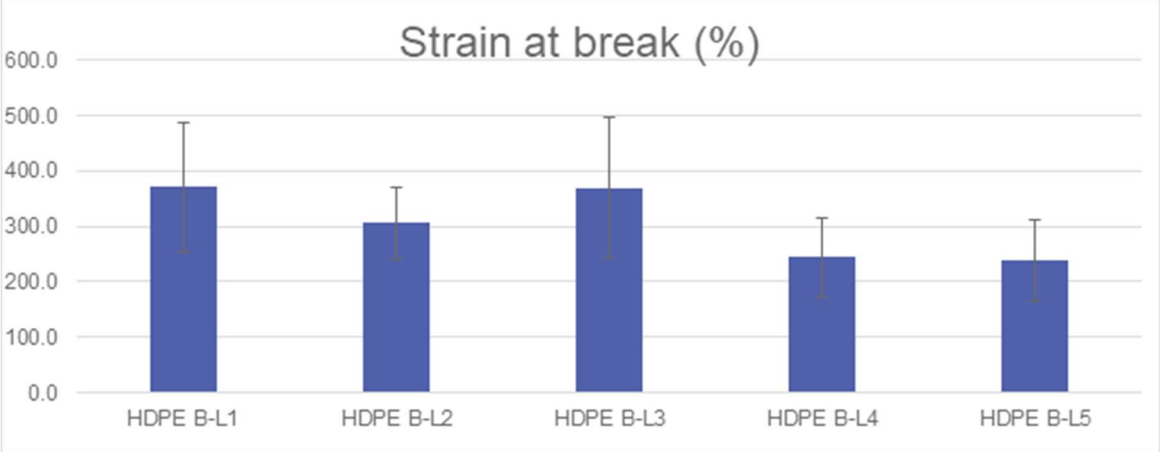


Figure 41 Strain at break of HDPE after five recycling loops, illustrating a gradual reduction in ductility while maintaining acceptable elongation for packaging applications

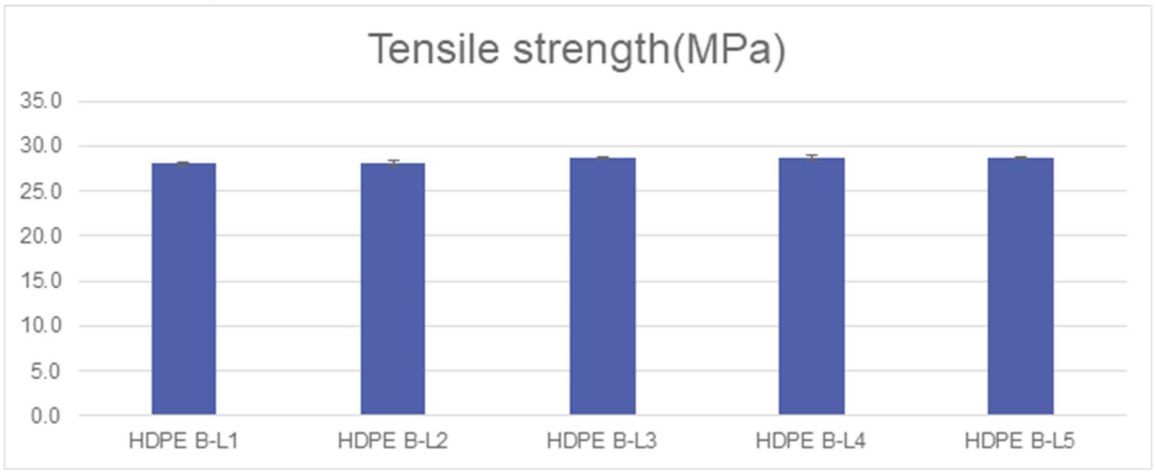


Figure 42 Tensile strength of HDPE after five recycling loops, demonstrating stable strength throughout repeated mechanical recycling

A gradual increase in tensile modulus was observed with increasing recycling loop number, rising from approximately 1206 MPa in Loop 1 to 1303 MPa in Loop 5. This increase indicates a moderate stiffening of the material during repeated processing. The increase in stiffness is consistent with the slight reduction in crystallinity observed by DSC and may also reflect limited molecular changes occurring during repeated extrusion.

In contrast, tensile strength remained essentially unchanged throughout the recycling simulation, varying only between approximately 28 and 29 MPa. The stable yield strength indicates that the material retained its load-bearing capability despite repeated melt processing and the controlled accumulation of contaminants.

The largest change was observed for strain at break, which decreased from approximately 371% in Loop 1 to 239% in Loop 5. This reduction indicates a gradual loss of ductility and reduced ability of the material to undergo large plastic deformation before failure. Nevertheless, even after five recycling loops the elongation remained within the range typically reported for blow-moulding grades of recycled HDPE.

Overall, the mechanical test results demonstrate that repeated recycling mainly affected material flexibility, while stiffness increased moderately and tensile strength remained stable. The combination of 65 wt.% recycled material with 35 wt.% virgin HDPE effectively limited the deterioration of mechanical performance, supporting the suitability of the material for repeated closed-loop recycling of rigid HDPE packaging.

Impact Properties

The notched Charpy impact strength of the HDPE material after five consecutive recycling loops is presented in Figure 43.

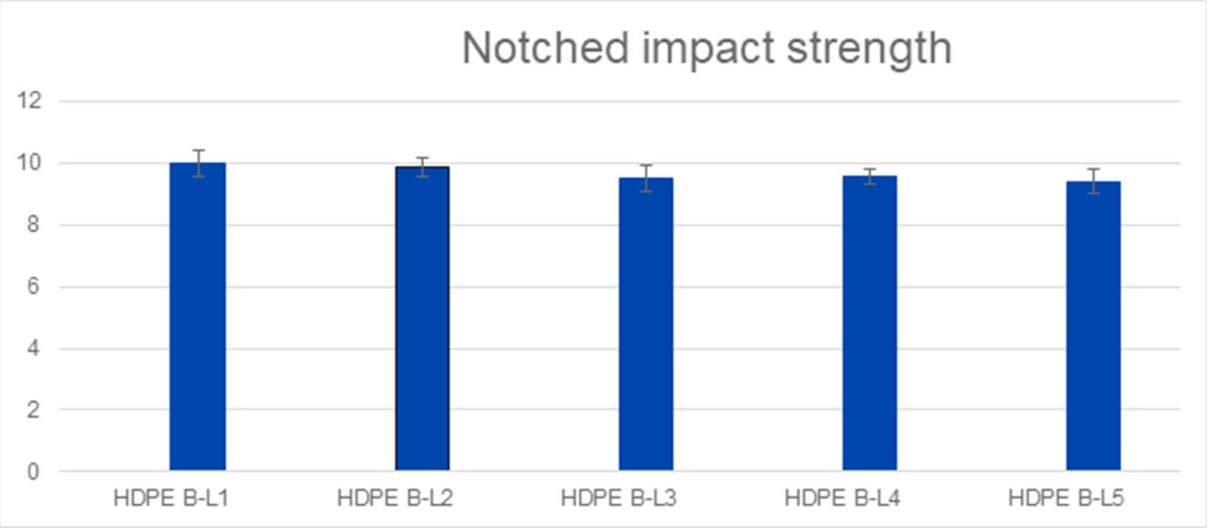


Figure 43 Notched Charpy impact strength of HDPE after five consecutive closed-loop recycling cycles.

Only minor changes were observed throughout the recycling simulation. The impact strength decreased slightly from approximately 10 kJ/m² in Loop 1 to about 9 kJ/m² in Loop 5, corresponding to a reduction of approximately 10%.

Despite the gradual decrease, the impact performance remained relatively stable over the five recycling loops. The limited reduction indicates that repeated extrusion and the controlled accumulation of contaminants had only a minor influence on the material's ability to absorb impact energy. Furthermore, all specimens exhibited the same fracture behaviour during testing, indicating consistent failure characteristics throughout the recycling simulation.

Overall, the results demonstrate that the closed-loop recycling strategy preserved the impact resistance of the HDPE material over repeated recycling cycles. Together with the stable tensile strength observed in the tensile tests, these findings indicate that the recycled material retained mechanical performance suitable for rigid HDPE packaging applications.

FTIR Analysis

FTIR analysis was performed to compare the polymer composition of the regenerated HDPE obtained after the loop recycling simulation with the original SAS HDPE white recyclate used as the starting material. The objective was to determine whether repeated recycling and controlled contaminant addition resulted in significant changes in polymer composition.

Table 10 FTIR quantification of the original SAS HDPE white recyclate and the regenerated HDPE after the loop recycling simulation.

Description	PE (%)	PP (%)	PA (%)	PET (%)	$CaCO_3$ (%)	TiO_2 (%)	Talc (%)
S-251024-001, Hostalen ACP5831D	99,9	0	0	0	0	0	0
S-251024-002, SAS HDPE WHITE	98,9	0,3	0	0	0	0,8	0
S-251024-003, SAS HDPE COLOR	93,2	6	0	0	0,1	0,6	0
S-251024-004, MRF HDPE WHITE	98,8	0,3	0	0	0	0,8	0
S-251024-005, MRF HDPE COLOR	85	14,1	0,1	0,1	0,1	0,7	0
S-260414-014, regenerat 030 0080 white (avg.)	98,6	0	0	0	0,1	1,3	0

As shown in Table 10, both materials exhibited very similar compositions. The regenerated material contained 98.6 wt.% polyethylene, compared with 98.9 wt.% for the original SAS HDPE white recyclate. No detectable PP or PET contamination was identified in the regenerated material, whereas the initial recyclate contained approximately 0.3 wt.% PP. Small differences were observed only in the inorganic additive content, with TiO_2 increasing slightly from 0.8 to 1.3 wt.% and $CaCO_3$ increasing from 0 to 0.1 wt.%.

Overall, the FTIR results show that repeated recycling did not significantly change the chemical composition of the HDPE matrix. The regenerated material remained comparable to the original white SAS recyclate, with very high polyethylene content and no detectable PP or PET contamination. The only minor differences were small variations in pigment and mineral additive content, which are typical for recycled HDPE and are not expected to significantly affect recyclability or processing performance.

Environmental Stress Cracking Resistance (ESCR)

The environmental stress cracking resistance (ESCR) of the HDPE materials after five consecutive recycling loops was evaluated using the F50 parameter, defined as the time required for 50% of the test specimens to fail under the specified test conditions. For samples where only 0% and 100% failure data were available, the F50 value was estimated as the midpoint between the two consecutive observation times.

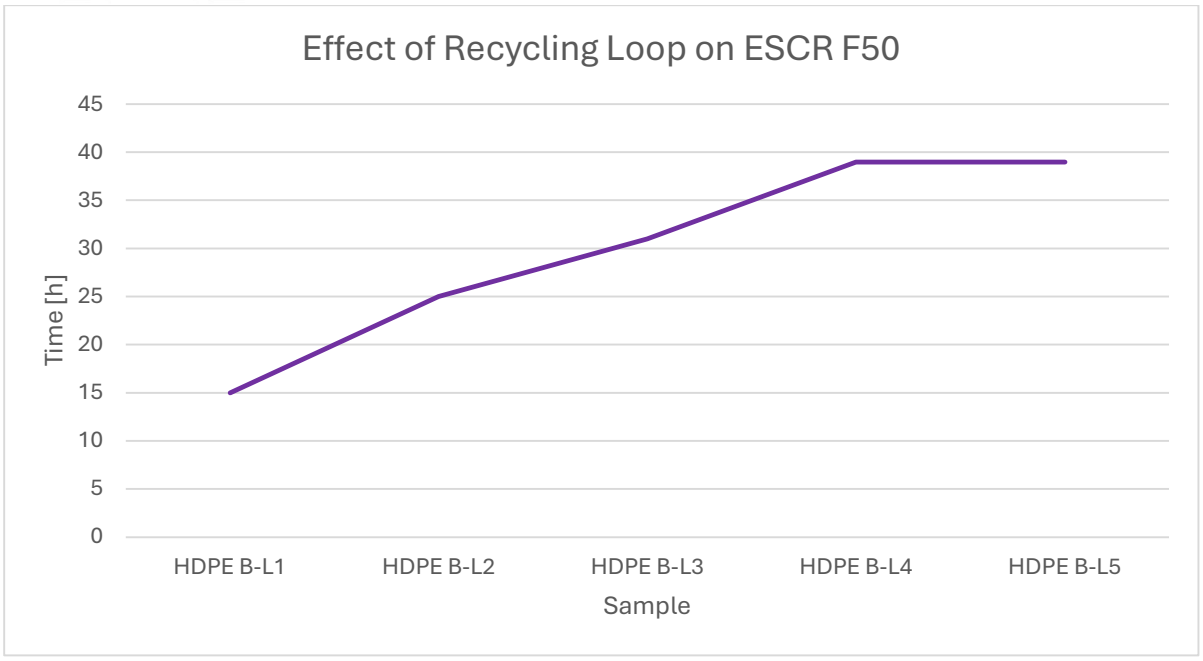


Figure 44 Environmental stress cracking resistance (ESCR) expressed as the F50 value for HDPE after five consecutive closed-loop recycling cycles.

As shown in Figure 44, the ESCR performance improved progressively during the recycling simulation. The estimated F50 increased from 15 h for Loop 1 to 25 h and 31 h for Loops 2 and 3, respectively, reaching 39 h for Loops 4 and 5. No decrease in ESCR was observed despite repeated extrusion and the controlled addition of contaminants throughout the recycling process.

The improved ESCR performance is attributed primarily to the continuous addition of 35 wt.% virgin HDPE in each recycling loop, which appears to have compensated for any potential degradation associated with repeated melt processing. Furthermore, the results indicate that the controlled levels of PP, LDPE and PET introduced during the simulation did not adversely affect the stress crack resistance of the recycled HDPE within the investigated number of recycling cycles.

Overall, the ESCR results demonstrate that the applied closed-loop recycling strategy successfully maintained, and even improved, resistance to environmental stress cracking over five recycling loops.

Discussion

The loop recycling simulation demonstrated that the proposed closed-loop strategy is technically feasible for HDPE packaging produced from Norwegian post-consumer waste. Throughout five consecutive recycling loops, the material retained stable rheological and thermal behaviour, indicating that repeated extrusion did not result in significant molecular degradation or changes in the crystalline structure of the polymer. FTIR analysis further confirmed that the regenerated material remained chemically comparable to the initial white SAS recyclate, with only minor differences in additive content.

Repeated recycling caused moderate changes in the mechanical properties. The material became slightly stiffer and less ductile, as reflected by the increase in tensile modulus and reduction in strain at break. However, tensile strength and impact resistance remained largely unchanged, demonstrating that the structural integrity of the material was preserved. The observed changes are consistent with the expected effects of repeated melt processing and remained within a range considered acceptable for blow-moulded HDPE packaging applications.

An important outcome of the study was that the controlled accumulation of representative contaminants (PP, LDPE and PET) did not produce measurable deterioration of the investigated material properties. In addition, the ESCR performance improved throughout the recycling simulation, indicating that the continuous addition of 35 wt.% virgin HDPE effectively stabilized the material despite repeated processing.

Overall, the results indicate that the selected recycling strategy, combining 65 wt.% recycled material from the previous loop with 35 wt.% virgin HDPE, can maintain material quality over multiple recycling cycles. The findings support the feasibility of closed-loop recycling for Norwegian HDPE packaging, provided that high-quality recyclate from well-sorted waste streams is available and contamination remains effectively controlled. While longer recycling sequences may eventually lead to further material degradation, no critical deterioration was observed within the five recycling loops investigated in this study.

4.4 WP4 Industrial Feedback and Implementation Perspectives

Industrial Evaluation of the Harmonised HDPE Packaging Specification

The final project meeting brought together the industrial partners to review the technical results of the project and evaluate the proposed harmonised HDPE packaging specification. The discussions confirmed that the specification is regarded as an important first step towards establishing a more circular HDPE packaging system in Norway. Rather than being considered a fixed standard, the specification was viewed as a common technical framework that can support future packaging development, facilitate dialogue across the value chain and provide practical guidance for improving recyclability and the use of post-consumer recycled (PCR) materials.

The partners agreed that harmonisation should not limit product innovation or branding but should instead focus on those packaging characteristics that directly influence recyclability and recyclate quality. Material selection, colour harmonisation, packaging components and Design for Recycling principles were identified as areas where common specifications could create significant benefits for the entire recycling system while still allowing sufficient flexibility for individual product differentiation.

Opportunities

The technical results generated during the project provided confidence that Norwegian household HDPE waste can become an important domestic source of high-quality recycled material for new non-food packaging applications. The laboratory investigations confirmed that high-purity white HDPE fractions can be recovered from Norwegian waste streams and successfully processed into new packaging with mechanical properties suitable for demanding applications.

The partners recognised that harmonisation of HDPE packaging, particularly through increased use of natural and white HDPE, could significantly improve sorting efficiency, increase the availability of packaging-grade recyclate and reduce material losses during recycling. The project also demonstrated that PCR contents between approximately 35 and 65 wt.% can be technically feasible, depending on the performance requirements of the final application. Together with the successful loop recycling simulation, these findings support the long-term potential for establishing closed-loop recycling systems for HDPE non-food packaging.

The harmonised specification was therefore considered not only a technical document but also a practical tool for facilitating future collaboration between companies aiming to increase recycled content while maintaining packaging performance and compliance with emerging regulatory requirements.

Barriers

Despite the positive technical results, the discussions highlighted several barriers that currently limit wider industrial implementation.

The most significant technical challenge remains the variability of post-consumer recycled materials. The project confirmed that differences in colour, contamination level and material composition directly influence recyclate quality. In particular, the large variation in white shades currently used for HDPE packaging ("50 shades of white") leads to considerable material losses during colour sorting, reducing both the recovery yield and the availability of high-quality white recyclate. In addition, increasing recycled content generally increases variability in material behaviour, requiring careful optimisation of packaging design, processing conditions and product specifications.

The partners also emphasised that economic factors currently represent one of the main obstacles to wider PCR implementation. High-quality PCR HDPE remains considerably more expensive than virgin material while simultaneously introducing additional production risks related to colour consistency, process stability and packaging performance. Consequently, companies are often expected to pay more for a material that may require additional process adjustments and quality control measures. Although

regulatory requirements are driving increased use of recycled content, these economic challenges continue to influence implementation decisions throughout the packaging industry.

Building a Closed-Loop Value Chain

One of the most important conclusions from the final project discussion was that the technical feasibility of producing high-quality PCR HDPE from Norwegian household waste has already been demonstrated. The remaining challenge is therefore not primarily related to material performance but to establishing an efficient value chain capable of delivering sufficient volumes of packaging-grade recyclate with consistent quality.

At present, the limited availability of high-quality PCR HDPE on the Norwegian market means that packaging producers often rely on recyclates sourced from other European countries. While this provides access to recycled material, it does not represent a true closed-loop recycling system for Norwegian packaging. Instead, both waste and recycled materials are traded across national borders, making it difficult to maintain material traceability and consistent control over the quality and composition of recyclates entering the Norwegian market.

The discussions highlighted the opportunity to establish a collaborative Norwegian value chain involving brand owners, packaging manufacturers, producer responsibility organisations, waste management companies, sorting facilities and recyclers. Such cooperation would make it possible to identify, collect and sort suitable Norwegian HDPE packaging and convert it into dedicated high-quality white PCR HDPE for use in new packaging by participating companies. This would support a genuine closed-loop system idea, where packaging placed on the Norwegian market is, as far as possible, recycled back into new packaging for the same market.

The harmonised HDPE packaging specification developed within the project could play a central role in enabling such a system. By defining common requirements for material selection, colour, packaging design and recyclate quality, the specification would facilitate more efficient sorting, improve recyclate consistency and increase the recovery of packaging-grade white HDPE. Over time, this could help secure stable volumes of high-quality PCR HDPE for Norwegian companies, reduce dependence on imported recyclates and strengthen the circular use of materials within Norway.

Although establishing such a value chain will require organisational coordination, commercial agreements and long-term commitment from all stakeholders, the project demonstrated that the concept is technically achievable. The combination of harmonised packaging design, efficient collection and sorting systems and dedicated recycling infrastructure provides a realistic pathway towards a more robust and transparent Norwegian closed-loop recycling system for HDPE packaging.

Future Perspectives

The project clearly demonstrated that successful implementation of circular HDPE packaging systems requires considerably more than simply increasing recycled content. Future progress will depend on simultaneous improvements in packaging design, harmonisation of material specifications, efficient collection and sorting systems, high-quality recycling processes and close collaboration throughout the entire value chain.

The harmonised HDPE specification developed during the project provides an important starting point for this transition. As regulatory requirements under the Packaging and Packaging Waste Regulation (PPWR) become increasingly demanding, common material specifications and coordinated recycling systems will become essential for ensuring reliable access to high-quality PCR suitable for packaging applications.

Overall, the project confirms that the transition towards closed-loop HDPE packaging is technically feasible. The primary challenge now lies in transforming the demonstrated technical solutions into an industrially coordinated system capable of delivering consistent, high-quality recycled material at the scale required by the Norwegian packaging market.

5. Methodology

5.1 Density

The density of virgin and recycled HDPE pellets was determined according to ISO 1183-1:2012 Method A (Immersion method). Density was calculated from the relationship between specimen mass and displaced liquid volume.

Equipment

Mettler Toledo analytical balance equipped with density kit
Immersion liquid: isododecane

Sample preparation

Pellet samples without visible voids.

Test conditions

Temperature: 22°C
Immersion liquid: isododecane
Three replicate measurements were performed for each material.

Reported parameter

Density (kg/m³)

5.2 Melt Flow Rate (MFR)

The melt flow rate was determined according to NS-EN ISO 1133-1:2011 to evaluate melt viscosity and processability of the HDPE materials.

Equipment

MFR instrument (Norner M730003).

Test conditions

Temperature: 190°C
Load: 2.16 kg
Preheating time: 5 min
Die diameter: 2.095 mm
Die length: 8.000 mm

Reported parameter

Melt Flow Rate (g/10 min).

5.3 Dynamic Rheology

Dynamic rheological measurements were performed according to ISO 6721-10:2015 using oscillatory frequency sweep measurements to characterize melt viscoelastic behaviour.

Compression moulded plates (1.5 mm thickness, Ø30 mm) were prepared prior to testing.

Equipment

Anton Paar MCR302e rotational rheometer using plate-plate geometry.

Test conditions

Plate diameter: 25 mm
Gap: 1.2 mm
Temperature: 190°C
Nitrogen atmosphere
Preheating: 300 s
Strain: 10 %
Frequency range: 0.1–300 rad/s
Plate geometry: fixed plate-plate

Reported parameters

Storage modulus (G′)
Loss modulus (G″)
Complex viscosity (η*)
Crossover point
Tan δ

5.4 Differential Scanning Calorimetry (DSC)

Thermal properties were determined according to ISO 11357-3 using Differential Scanning Calorimetry.

Equipment

TA DSC instrument.

Sample preparation

Compression moulded specimens.

Reported parameters

Melting temperature
Crystallization temperature
Melting enthalpy
Crystallization enthalpy

5.5 Fourier Transform Infrared Spectroscopy (FTIR)

Polymer identification was carried out using FTIR spectroscopy (Norner method M730849).

Hot-pressed films were prepared from the investigated materials before analysis.

Reported information

Polymer identification
Detection of possible contaminants
Comparison of characteristic absorption bands.

5.6 Colour Measurements

Colour was evaluated using the CIELAB colour system by measuring spectral reflectance in the visible wavelength range (400–700 nm).

Measurements were performed both on pellets and finished bottles, depending on the investigated sample.

Reported parameters

L*
a*
b*

5.7 Ash Content

Ash content was determined according to ISO 3451-1 Method A (Direct Calcination).

Test conditions

Furnace temperature: 600°C
Holding time: 60 min

The remaining ash was subsequently subjected to elemental analysis (EDS) to identify inorganic contaminants.

Reported parameters

Ash content (wt%)
Ash composition (EDS).

5.8 Tensile Properties

Mechanical properties were determined according to ISO 527-1/-2 using Type 1B specimens produced by compression moulding.

Equipment

Zwick Z010 universal testing machine equipped with extensometer.

Test conditions

Gauge length: 50 mm
Gripping distance: 115 mm
Modulus speed: 1 mm/min
Test speed: 50 mm/min
Temperature: 22°C

Reported parameters

Tensile modulus
Yield stress
Yield strain
Tensile strength
Stress at break
Strain at break

5.9 Charpy Impact

Impact resistance was measured according to ISO 179-1 using notched Type A specimens.

Ten specimens were tested for each material.

Reported parameter

Charpy impact strength (kJ/m²).

5.10 Environmental Stress Crack Resistance (ESCR)

Material ESCR was determined according to ASTM D1693 Method B (Bell test).

Compression moulded specimens were immersed in 10% Igepal solution and tested at 50°C.

Reported parameter

F50 (time for 50% specimen failure).

5.11 Bottle ESCR Test

Stress crack resistance of blow-moulded bottles was evaluated according to Norner method M731014, based on ASTM D2561-95.

The bottles were partially filled with 10% Acropal solution, conditioned at 60°C, and pressurized to 350 mbar.

The test continued for a maximum of 360 h, while pressure loss and leakage were monitored continuously.

Reported parameter

Time to leakage/failure.

5.12 Blow Moulding

Experimental bottles (1000 mL) were produced using a Magic ME-L2-3/ND-LS420 three-layer co-extrusion blow moulding machine.

The machine consisted of three 38-mm single screw extruders with a 24 L/D ratio. Bottles were produced using virgin HDPE and recycled HDPE blends containing 35%, 65% and 100% PCR.

Typical processing conditions were:

Melt temperature: 184–192°C
Cycle time: 18 s
Three-layer co-extrusion
Single cavity mould.

5.13 Bottle Top Load

Top-load resistance was measured according to Norner method M730091.

Equipment

Zwick Z050 universal testing machine.

Test conditions

Load cell: 5 kN
Preload: 4 N
Compression speed: 10 mm/min
Test temperature: 22°C

Reported parameters

Maximum compressive force (Fmax)
Deflection at maximum load.

5.12 Bottle Drop Test

Drop resistance was evaluated according to Norner method M730782.

Filled bottles were dropped from increasing heights onto a rigid surface until failure occurred.

Test conditions

Test liquid temperature: 23°C

Reported parameters

Failure height
Calculated impact energy.

5.13 Bottle Dimensions

The dimensional stability of the blow-moulded bottles was evaluated after conditioning according to ASTM D618. Bottles were conditioned at 23 ± 2°C and 50 ± 5% relative humidity for a minimum of 40 h prior to testing. Randomly selected bottles from each material variant were measured using a digital caliper (accuracy ±0.1 mm) and an analytical balance (accuracy ±0.01 g). The following dimensions were recorded: overall bottle height, outer bottle diameter, neck height, external thread diameter, internal thread diameter, and bottle weight.

5.14 Wall Thickness Distribution

Wall thickness distribution was determined to evaluate the material distribution in the blow-moulded bottles. Measurements were performed using a magnetic wall thickness gauge on conditioned bottles. The bottle wall thickness was measured at three predefined locations representing the top, middle, and bottom sections of the bottle. Multiple measurements were recorded at each location for every bottle, and the average wall thickness and standard deviation were calculated for each bottle type to assess the uniformity of material distribution following blow moulding.

5.15 Migration Analysis (Overall and Specific Migration)

Migration testing was performed according to EN 1186 (overall migration) and EN 13130 (specific migration) to evaluate the chemical safety of recycled HDPE materials intended for non-food packaging applications.

Migration experiments were carried out on HDPE pellets using food simulants representing severe extraction conditions. Samples were exposed to 95% ethanol at 60°C for 10 days and isooctane at 40°C for 2 days. Following migration, extracts were analysed by gas chromatography–mass spectrometry (GC–MS) using a non-target screening approach to identify both intentionally added substances (IAS) and non-intentionally added substances (NIAS).

The analytical evaluation included determination of the overall migration, screening of compounds with established Specific Migration Limits (SML), identification of NIAS, and quantification of polyolefin oligomeric saturated hydrocarbons (POSH) where applicable.

6. Appendices

Appendix 1. Material and Packaging Specifications for HDPE Containers in the Norwegian Market (Non-Food Applications)

Appendix 2. Simplified Material and Packaging Specifications for HDPE Containers in the Norwegian Market (Non-Food Applications)

[1] ***Legal notice***
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Appendix 1

Material and Packaging Specifications for HDPE Containers in the Norwegian Market

(Non-Food Applications)

Date: 31.07.2026
Version: 2

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1. Introduction and purpose

This document defines the material and packaging specifications which HDPE containers placed on the Norwegian market should comply with.
In Norway, approximately 86% of the HDPE plastic waste stream consists of non-food packaging, primarily originating from cosmetics, personal care products, household cleaners and detergents. As a result, packaging design choices made in these sectors have a decisive influence on the overall quality, homogeneity and recyclability of the Norwegian HDPE stream. To create value for Norwegian companies and support a circular use of materials, it would be optimal to organize the HDPE recycling system in a way that enables the recovery of high-quality material fractions. In such a model, collected HDPE packaging from the Norwegian market is is first sorted at the Områ facility, where HDPE packaging is separated from mixed plastic waste streams. The sorted HDPE fraction is then supplied to specialized recyclers where advanced sorting, including color separation, allows the recovery of high-quality white HDPE. This material can then be recycled into post-consumer recycled (PCR) HDPE and supplied back to Norwegian producers for use in new packaging. The organization of such system would be based on the principle that participating companies are enabled to access volumes of recycled HDPE that are, to the extent possible, equivalent to the quantities of HDPE packaging they place on the Norwegian market.

The specifications serve as:

- a design and approval guide for producers, fillers and importers
- a reference framework for packaging manufacturers and recyclers
- and a tool to protect the efficiency, quality and long-term stability of the Norwegian HDPE recycling stream

The purpose of the specifications is to ensure that:

- HDPE containers can be efficiently collected, sorted and recycled
- material quality is preserved across multiple recycling loops
- contamination and degradation of recycled HDPE are minimized
- that packaging design supports high-value mechanical recycling
- the recycling system is enabled to deliver increased volumes of high-quality recycled HDPE suitable for use on the Norwegian market

The specifications apply to single-use HDPE containers for non-food products, including cosmetics, personal care, household and industrial applications.

2. System scope and general principles

HDPE containers placed on the Norwegian market are collected through mixed post-consumer collection systems, sorted at material recovery facilities, and processed by mechanical recycling companies.

HDPE system relies on:

- optical polymer recognition
- float-sink separation
- washing and extrusion with melt filtration

Therefore, design for recycling is essential to achieving high-quality recycled HDPE
General principles:

- Mono-material HDPE packaging is preferred
- Natural and white HDPE must be preserved as high-value streams
- Packaging features that hinder sorting, washing or extrusion shall be avoided

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3. HDPE container material specifications

3.1 Polymer type

Only high-density polyethylene (HDPE) is permitted as the material of the bottle/container body.

The following materials are not allowed in the main body:

- PET, PETG, PVC, PS, PLA, PA
- multilayer structures with non-polyolefin layers

Resin Identification Code “2” (HDPE) shall be used where feasible

3.2 Material properties (general)

HDPE used for containers shall be compatible with existing mechanical recycling processes.

Material properties shall be within ranges that:

- allow stable extrusion and filtration
- do not generate excessive odors or fumes
- do not impair recyclate quality

Recycled HDPE may show broader variability than virgin HDPE and shall be assessed based on functional performance and recyclability, not on virgin equivalence alone.

Table 11HDPE Material Properties – Virgin and Recycled Content

Property	Virgin material – target values	PCR material – performance requirements	Unit	Test method
Polymer type	HDPE homopolymer or copolymer for packaging application	HDPE (post-consumer recycled)	–	–
Density	0.952 – 0.958	Comparable to virgin; within HDPE recycling range	g/cm^3	ISO 1183-1
Melt Index (190 °C / 2.16 kg)	0.2 – 0.3	Functional equivalence required; broader range acceptable recommended 0.1-0.3	g/10 min	ISO 1133
Tensile modulus	1300 – 1400	Functional performance shall be met, recommended not less than 1000	MPa	ASTM D638
ESCR F_{50} (10% igepal)	≥ 150	Recommended ≥ 150 or equivalent performance demonstrated	h	ASTM D1693
Color	Natural or white HDPE, L value ≥95	Natural or white HDPE, L value ≥80	–	CIElab scale
Ash	0,03%	≤1,5% recommended		SEM EDS
PP content	0%	≤0,5% recommended		FTIR
Odor	No noticeable odor	No strong or persistent odor	–	Sensory assessment during extrusion

3.3 Color requirements for HDPE containers

Reference colors

To protect recyclate quality and market value, the following color strategy applies:

- Natural (unpigmented) HDPE
- White HDPE

HDPE containers placed on the Norwegian market are collected and initially sorted as a single HDPE stream, without color differentiation. Subsequent color sorting is performed at later stages of the recycling process by mechanical recyclers. At the recycling stage, color homogeneity of the HDPE material has a significant impact on sorting efficiency and recyclate yield. In particular, wide variation in white and off-white shades leads to increased rejection of flakes during color sorting and results in material losses. To support efficient color sorting and maximize recycling yield, the use of limited and harmonized white shades is recommended. For HDPE packaging containing recycled content, it is therefore recommended that:

- the lightness parameter L* (CIELAB scale, transmission) is above 80
- packaging designs avoid excessive variation in white and off-white tones

These measures contribute to improved color sorting efficiency, reduced reject rates, and increased availability of high-quality recycled HDPE.

3.4 Not-recommended colors

The following colors are not recommend:

- black or carbon-black pigmented HDPE
- dark or opaque colors
- metallic or pearlescent pigments

The use of colors other than white is not recommended, as it reduces the available volume of white recycled HDPE suitable for further recycling. Where the use of non-white colors cannot be avoided, it is recommended that colors are selected which are clearly distinguishable from white, in order to enable efficient color sorting and to facilitate the separation of such packaging from the white HDPE stream.
Light, off-white or pearlescent colours that are visually close to white (e.g. ivory, cream, greyish or effect whites) are discouraged, as they increase sorting losses and negatively affect the yield and quality of white recycled HDPE.

3.5 Packaging design and functional requirements

Geometry and emptying behavior

HDPE containers shall be designed to:

- allow efficient emptying of contents
- minimize residues after use
- avoid complex internal geometries and trapped volumes

Containers with excessive product residues negatively impact recyclability.

Wall thickness and robustness

Containers shall maintain sufficient wall thickness to:

- withstand handling, compaction and transport
- avoid excessive fines formation during shredding
- ensure acceptable recycling yield

Extremely thin or fragile containers are discouraged, as reduced wall thickness negatively affects the processability of HDPE flakes due to lower bulk density, which may hinder stable handling, feeding and processing in mechanical recycling operations
This recommendation is aligned with the RecyClass Recyclability Evaluation Protocol for HDPE Containers, which assesses flake yield, handling and process stability throughout mechanical recycling operations.

3.6 Barriers

Barrier layers are generally not recommended in HDPE containers.
Only barrier technologies explicitly approved under recognized recycling guidelines may be considered and shall be subject to separate approval. Where barrier layers are applied, their compatibility with mechanical recycling shall be demonstrated in accordance with the RecyClass Design for Recycling Guidelines and the Recyclability Evaluation Protocol for HDPE Containers.

3.7 Additives and fillers

The following are recommended:

- processing additives that are unavoidable (stabilizers, antioxidants, lubricants)
- limited mineral fillers provided material density remains compatible with HDPE recycling

The following are not recommended:

- additives increasing density above recycling limits
- flame retardants
- oxo-, bio- or photo-degradable additives

4. Packaging components and associated materials

4.1 Labels and sleeves

Label and sleeve materials should:

- be polyolefin-based (PE or PP)
- have a density below 1 g/cm^3
- not hinder optical recognition of HDPE

The following are not recommended:

- PVC, PET, PS or metallized labels or sleeves
- Fiber losing paper labels
- non-separable full-body sleeves that block polymer recognition

4.2 Adhesives and printing

- Adhesives should be releasable in the recycling process and non-reactivating
- Hot-melt pressure-sensitive adhesives are discouraged
- Inks shall comply with EuPIA guidelines and must not bleed during washing
- Direct printing on the HDPE container body is not recommended, except for limited functional marking (e.g. laser marking or date coding)

4.3 Closures, liners and attachments

Closures and attached components shall be compatible with HDPE recycling.
Permitted materials include:

- HDPE, LDPE, LLDPE, MDPE
- PP in limited proportions

The following are not recommended:

- silicone components
- PVC, PET, PS
- metal or glass attachments

5. Recycled content

The use of mechanically recycled HDPE of documented origin, derived from post-consumer waste streams sorted within Norway, is recommended.
No fixed maximum recycled content is defined. However, to support long-term material recovery and recycling efficiency across multiple loops, the use of recycled content above 65% is not recommended.
Higher recycled content levels may:

- increase color variation and lead to darker or greyer white shades, which may be rejected during color sorting
- reduce the effective recovery of white HDPE material in subsequent recycling loops
- and contribute to accelerated degradation of material quality within the recycling stream over time

Recycled content shall not compromise recyclability, processing stability or product performance.
Chemical recycling inputs are not recommended unless full polymer equivalence to HDPE can be demonstrated.

6. Documentation

Documentation and traceability of recycled content are recommended.
Companies placing HDPE packaging on the Norwegian market should ensure that the packaging complies with this specification and should request appropriate documentation confirming compliance, either from their suppliers or from internal production processes, as applicable.
The supplier or manufacturer should provide documentation for the materials used (container material, material properties, recycled content, closures, labels, adhesives, etc.). Such documentation can be requested from raw material or packaging manufacturers.

Appendix 2 *Simplified Material and Packaging Specifications for HDPE Containers in the Norwegian Market (Non-Food Applications)*

Object	Clear / white HDPE	Colored HDPE	Not recommended
Bottle / container body	HDPE	HDPE	PET, PETG, PVC, PS, PLA, PA; multilayer structures with non-polyolefin layers.
Color strategy	Natural (unpigmented) HDPE and white HDPE are the preference colors.	If non-white colors cannot be avoided, they should be clearly distinguishable from white to support color sorting.	Black or carbon-black pigmented HDPE, dark or opaque colors, metallic or pearlescent pigments, and off-white shades visually close to white (ivory, cream, greyish or effect whites).
Barriers	Only barrier technologies explicitly approved under recognized recycling guidelines may be considered		Barrier solutions without demonstrated compatibility with mechanical recycling.
Additives and fillers	Unavoidable processing additives such as stabilizers, antioxidants and lubricants are acceptable. Limited mineral fillers may be used if density remains compatible with HDPE recycling.	Same principle applies to colored HDPE, but fillers or additives	Additives increasing density above recycling limits; flame retardants; oxo-, bio- or photo-degradable additives.
Labels and sleeves	PE or PP labels / sleeves with density below 1 g/cm3 and without interference with optical recognition of HDPE are preferred.		PVC, PET, PS or metallized labels / sleeves; fiber losing paper labels; non-separable full-body sleeves that block polymer recognition.
Adhesives	Adhesives should be releasable in the recycling process		Hot-melt pressure-sensitive adhesives
Printing	Inks shall comply with EuPIA guidelines and must not bleed during washing. Direct printing is not recommended		Extensive direct printing on the HDPE container body
Closures / attachments	Compatible materials include HDPE, LDPE, LLDPE, MDPE; PP in limited proportions.		Silicone components; PVC, PET, PS; metal or glass attachments.
Packaging design	Mono-material HDPE packaging is preferred. Packaging should allow efficient emptying, minimize residues, avoid trapped volumes, and maintain sufficient wall thickness and robustness.		Features that hinder sorting, washing or extrusion; excessively thin or fragile containers.
Recycled content	Mechanically recycled HDPE of documented origin derived from Norwegian post-consumer waste streams is recommended. Recycled content of up to 65% PCR may be used, provided packaging performance and processing stability are maintained.	Higher recycled content may be used in colored packaging, provided processing and product performance are maintained.	Natural and white rHDPE should be reserved for natural/white applications, as colored HDPE cannot return to the white material pool.