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Material flow analysis and recycling performance of an improved mechanical recycling process for post-consumer flexible plastics

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A R T I C L E I N F O

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A B S T R A C T

Increasing the recycling rates for post-consumer flexible plastics (PCFP) waste is imperative as PCFP is considered a difficult-to-recycle waste with only 17 % of PCFP effectively recycled in Europe. To tackle this pressing issue, improved mechanical recycling processes are being explored to increase the recycling rates of PCFP. One interesting option is the so-called *quality recycling process* (QRP) proposed by CEFLEX, which supplements more conventional mechanical recycling of PCFP with additional sorting, hot washing, improved extrusion, and deodorization. Material flow analysis (MFA) model is applied to assess the performance of QRP. Four performance indicators related to quantity (*process yield* and *net recovery*) and quality (*polymer grade* and *transparency grade*) are applied to measure the performance of three PCFP mechanical recycling scenarios. The results are compared against the conventional recycling of PCFP, showing that QRP has a similar *process yield* (64 % – 66 %) as conventional recycling (66 %). The *net recovery* indicator shows that in QRP higher recovery rates are achieved for transparent-monolayer PCFP (>90 %) compared to colored-multilayer PCFP (51 % – 91 %). The quality indicators (*polymer and transparency grades*) demonstrate that the regranulates from QRP have better quality compared to the conventional recycling. To validate the modeling approach, the modeled compositional data is compared with experimental compositional analyses of flakes and regranulates produced by pilot recycling lines. Main conclusions are: (i) although yields do not increase significantly, extra sorting and recycling produces better regranulates' quality (ii) performing a modular MFA gives insights into future recycling scenarios and helps in decision making.

1. Introduction

1.1. Overview of the flexible packaging waste management

Management of post-consumer flexible packaging (PCFP) waste is a pressing issue globally as it is considered as one of the major contributor to the losses of macroplastics to the environment (Ryberg et al. 2019; Peano et al., 2020; OECD, 2022). This is caused by improper treatment and disposal of plastic waste, which is due to the fact that PCFP can be expensive to collect and they have a low market value (SYSTEMIQ, 2022; Peano et al., 2020). On top of the effort to reduce the use of plastics, design for recycling efforts should further be introduced such as

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changing the design from multi- to mono-material, and changing the business model such as building reuse or refill stations (SYSTEMIQ, 2022; OECD 2022; Feber et al., 2020). Next to this, also the waste management infrastructure of PCFP can be further improved such as establishing separate collection, sorting and recycling systems (PRI, 2019; Ellen MacArthur Foundation, 2016; Horodytska et al. 2019).

The current status of PCFP waste treatment is that it is exported, recycled into products like park benches, garden furniture, or bin bags. In this context, there is an urgent need to deploy more recycling capacity that is capable of reprocessing PCFP. To improve this, several options exist, including improved mechanical recycling, chemical recycling (incl. solvent-based recycling such as dissolution-precipitation or delamination), and energy recovery (Horodytska et al. 2019; Ragaert et al. 2017; Simon and Martin, 2019; Vollmer et al. 2020; Ügdüler et al., 2021; Kol et al., 2021). While some promising chemical recycling approaches are still under development such as solvent-based recycling (Simon and Martin, 2019; Schwarz et al., 2021; Vollmer et al., 2020; Hann and Connock, 2020), other technologies can be readily implemented at higher technological readiness level (TRL) and at commercial scale such as improved washing and extrusion (Horodytska et al. 2019; Horodytska et al. 2020). In any case, the requirement for increased recycling rates is urgent, and thus it is crucial to assess how far currently available technologies can be 'pushed' to increase the process yield and regranulates' quality from PCFP recycling. Therefore, this study focuses on assessing the potential improvement in terms of process yield and regranulates' quality of mechanical recycling of PCFP based on potential flowsheets that are proposed by industry with technologies that are commercially used.

PCFP can be sorted into plastic film bales for mechanical recycling in North America (Pressley et al., 2015; Tanguay-Rioux et al., 2022; Kessler Consulting, 2009), Europe (Picuno et al., 2021, Kleinhans et al., 2021; Antonopoulos et al., 2021), and Asia (Wang et al., 2020; Nakatani et al., 2017; Kawai et al., 2022). In the United States and Canada, flexible packaging waste is sorted into a mixed plastic film bales using drum screens, ballistic separators, and optical sorters for recycling (Tanguay-Rioux et al., 2022; Kessler Consulting, 2009; Pressley et al., 2015). Some improvements are also being explored by sorting flexible packaging further by optical sorters (RRS, 2020). Similarly, PCFP is sorted into mixed plastic film bales using a series of mechanical sorting equipment for recycling in Japan and China (Kawai et al., 2022; Nakatani et al., 2017; Wang et al., 2020). In Europe, similar processes are employed to sort and recycle PCFP, which is elaborated in the next section.

1.2. Flexible packaging waste management in Europe

In Europe, plastic packaging accounted for 40 % of the total plastics demand in 2019, which is equivalent to ~20 million tonnes of rigid and flexible packaging. It is estimated that out of 20 million tonnes plastics packaging, nearly 9 million tonnes are flexible plastics (consumer and industrial plastics), in which ~3.7 million tonnes become PCFP (KIDV, 2020; PlasticsEurope, 2021; Eunomia, 2020).

Flexible plastics, also referred as films, includes bags, pouches, envelopes, sachets, and wraps which are widely used as consumer packaging with main the function to ensure proper product delivery to the customers. This type of packaging can provide excellent barriers against aspects such as microorganisms, light, oxygen, carbon dioxide, and water vapor, which increases the shelf life of the product and reduce (food) waste (KIDV, 2020; Hou et al., 2018; Wagner & Marks, 2010). The market for flexible plastics is also continuously growing due to its low cost, versatility, light weight, resistance, and printability (Ügdüler et al., 2021; Grant et al., 2020a; Horodytska et al., 2018).

The main polymers for PCFP are the polyolefins (PO) low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), and polypropylene (PP) (CEFLEX, 2020; Horodytska et al., 2018; Faraca & Astrup, 2019). Flexible plastics can be produced from a single component or can be multi-layered, consisting of different material types such as polymers (e.g., PO, Polyethylene Terephthalate (PET), Polyamide (PA), Ethylene Vinyl Alcohol (EVOH), …), paper, aluminum, or any combination of these. These films may be transparent, printed, coated and/or laminated. It is estimated that around 20 % (750 kilo tonne) of the total PCFP are multi-material and between 70 and 80 % (~3 million tonne) are reported as mono-material PO packaging (CEFLEX, 2020; KIDV, 2020; Faraca & Astrup, 2019).

To enable a circular economy for plastics, including PCFP waste, the European Union (EU) has set a target to recycle 55 % of plastics packaging waste by 2030 (European Commission, 2018). To realize this ambition, the Commission has recently launched the Circular Plastics Alliance (CPA) to support and boost the EU market for recycled plastics to 10 million tonnes by 2025 (European Commission, 2021). The EU has also recently passed a tax on plastics waste that charges €800 per tonne of non-recycled plastic packaging waste (European Commission, 2020). However, up to now most of the waste management infrastructure is developed to process rigid plastics (e.g., HDPE and PET bottles). In many countries, PCFP is still not correctly source separated and is usually sent to landfill or incineration, or is exported (Lopez-Aguilar et al., 2022). In Europe, only in a limited number of countries, for example in The Netherlands, Germany, and recently Belgium, PCFP is source separated typically together with rigid plastics packaging, metals, and beverage carton. When source separated, PCFP are sent for sorting and recycling (Kleinhans et al., 2021; Picuno et al., 2021; Horodytska et al., 2018; Brouwer et al., 2018).

A typical PCFP waste treatment can be seen in Fig. 1. Correctly source separated PCFP waste are sent to material recovery facilities (MRFs) for sorting. At MRFs, PCFP are sorted into different bales for recycling. Typical bales for PCFP waste are: (i) *bale rich in PE film* and (ii) *bale rich in PO film*, in which > 70 % of PCFP is forwarded to these two bales at MRF level (Antonopoulos et al., 2021; Kleinhans et al., 2021; Picuno et al., 2021; Mastellone et al., 2017; Cimpan et al., 2016). One of the standards used for bales specification is 'Duales System Deutschland (DSD) GmbH', which is commonly used and accepted specifications to benchmark quality of the sorted bales in Europe (Der Grüne Punkt – Duales System Deutschland GmbH, 2018). Using this standard, hereafter the bale rich in PE film and PO film is referred as DSD 310-1 and DSD 323-2 bales, respectively.

Thereafter, the two sorted bales are sent to recycling facilities to be reprocessed into regranulates, in which the 'r' is added to the nomenclature referring to different regranulate types (Fig. 1). Mechanical recycling is to date the most commonly used technique to process PCFP waste. A typical conventional mechanical recycling (will be called 'conventional recycling' from hereafter) of DSD 310-1 bale consists of shredding, additional (yet limited) optical sorting based on near-infrared (NIR) technology, washing, density separation, mechanical and thermal drying, and extrusion (Ragaert et al., 2017; Faraca & Astrup, 2019; Brouwer et al., 2018; Faraca et al., 2019; Civancik-Uslu et al. 2021). In the conventional recycling, PCFP waste is shredded into flakes and washed to remove the contaminants such as organic remnants, wood, rocks, sand, and metals. In the water-based medium, PO will mostly float and the other materials will mostly sink. After being dried using mechanical and thermal drying, PCFP waste undergoes a final regranulation step by extrusion (Ragaert et al., 2017; Larrain et al., 2021). Regranulation of PCFP flakes is usually processed at 180–220 °C, which would remove the remaining paper, woods, metals, and polymers with higher melting temperature (e.g., PET) by a melt filter (Stenvall et al., 2013). The process yield of a typical conventional recycling for PE and PO films ranges from 60 to 80 % depending on the input quality (sorted bales) and efficiency of the recycling equipment (Picuno et al., 2021; Brouwer et al., 2018; Faraca & Astrup, 2019; Larrain et al., 2021).

However, there are still many challenges in the conventional recycling of PCFP waste. Despite recent technological innovation, regranulates from PCFP are often considered inferior to virgin plastics, partly due to inefficient sorting at MRFs, complex polymer compositions, and inadequate contamination removal. For example miscibility can become

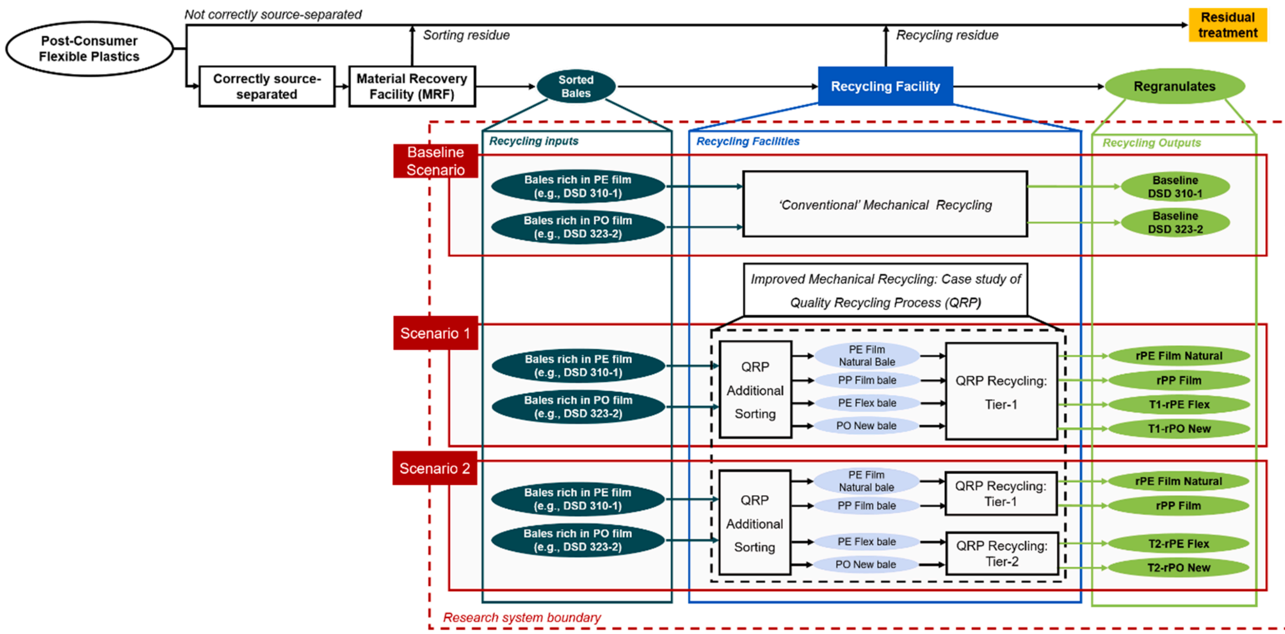


Fig. 1. A conceptual figure depicting PCFP waste treatment in Europe (adapted from Picuno et al., 2021; Antonopoulos et al., 2021; Kleinhans et al., 2021; CEFLEX, 2020; Horodytska et al., 2018; Brouwer et al., 2018).

a problem upon extrusion despite the structural similarities of PO (Ragaert et al., 2017; Van Belle et al., 2020). Next to that, a noticeable amount of odours remains even after washing and separation processes leading to recycling issues, which must be removed from the stream to allow more closed-loop recycling (Roosen et al., 2021; Demets et al., 2020; Chacon et al., 2020; Mumbach et al., 2019). These challenges result in the fact that the part of PCFP which is recycled often finds its way to applications such as park benches or garden furniture, and not to flexible plastics again. Alternatively it is mixed together with virgin or commercial and industrial (C&I) recycled plastics to produce products such as garbage bags (Faraca & Astrup, 2019; Brouwer et al., 2018; Ragaert et al., 2017). The above-mentioned challenges highlight the importance of improving current mechanical recycling process to enhance the quality and to allow more market applications of PCFP regranulates.

As a step to mitigate this status quo of PCFP waste recycling, an improved mechanical recycling process (Fig. 1) for PCFP waste is proposed by CEFLEX, called the *quality recycling process* (QRP), that consists of *additional sorting* and either *Tier 1* or *Tier 2 recycling* processes (Mosora, 2020). QRP can be perceived as a more elaborated route to the current conventional recycling process. As shown in Fig. 1, QRP could start from DSD 310-1 and DSD 323-2 bales created at MRFs, in which QRP adds additional sorting (called *QRP additional sorting* in this research) to these bales prior to the actual recycling process (either *Tier 1* or *Tier 2* recycling). The QRP additional sorting creates intermediate bales: PE Film Natural, PE Flex, PP Film, and PO New bales, which can be processed later either through Tier 1 or Tier 2 recycling of QRP, depending on the targeted market applications. More information on QRP can be found in Section 2.3.2.2.

To assess the performance of different recycling processes, material flow analysis (MFA) and performance indicators are often used. The outputs of MFA are compositional data and mass balances, which are often linked to define the performance of the studied systems based on quantity or quality indicators (Kleinhans et al., 2021). Quantity indicators refer to the amount of valuable products created from sorting or recycling facilities and the amount of recovered material (Roosen et al., 2022; Kleinhans et al., 2021). Quality indicators refer to the compositions and potentially technical processability (Demets et al., 2021), technical properties (Demets et al., 2021; Chacon et al., 2020; Grant et al., 2020b; Eriksen & Astrup, 2019), or functionality or circularity potential of the regranulates (Eriksen & Astrup, 2019; Eriksen et al., 2018; Vadenbo et al., 2016). These past studies also link the contamination level (i.e., non-polymer and undesired polymer content) to reflect regranulates quality. However, past studies are mainly done for rigid plastics waste recycling and their associated quantity and quality (Chacon et al., 2020; Eriksen & Astrup, 2019; Grant et al., 2020b), whilst research into PCFP waste recycling performance is scarce (Horodytska et al., 2018).

This research investigates the recycling performance of conventional and improved mechanical recycling (by using QRP as a case study) of PCFP waste. A mathematical model is developed and applied that is based on a modular material flow analysis (MFA) approach, which is expanded from the MFA sorting model developed and validated by Kleinhans et al. (2021). The first part of this paper focuses on describing the development of the MFA model. The inputs for the model are: experimental data (i.e., pilot trials and bales sampling at a sorting test facility), expert judgment, and literature. In the second part of this paper, the developed model is applied to trace the flow of wastes from the selected bales throughout QRP and compared to the conventional recycling. The third part of the paper assesses QRP and conventional recycling performance by applying selected performance indicators to the model outputs. Four performance indicators related to quantity (*process yield* and *net recovery*) and quality (*polymer grade* and *transparency grade*) are used to compare the results. Moreover, the compositional data produced by the MFA model (called 'modeled compositional data' hereafter) at the flakes and regranulates levels is compared with experimentally obtained compositional analyses (i.e., compositional analysis of flake and regranulate of the actual samples) for model validation. Lastly, evaluation of the technical properties of regranulates is out of scope of this study and is investigated by Bashirgonbadi et al. (2022).

2. Materials and methods

2.1. General modeling procedure

An overview of the modeling procedure of QRP and conventional recycling is presented in Fig. 2. The needed inputs for the MFA modeling

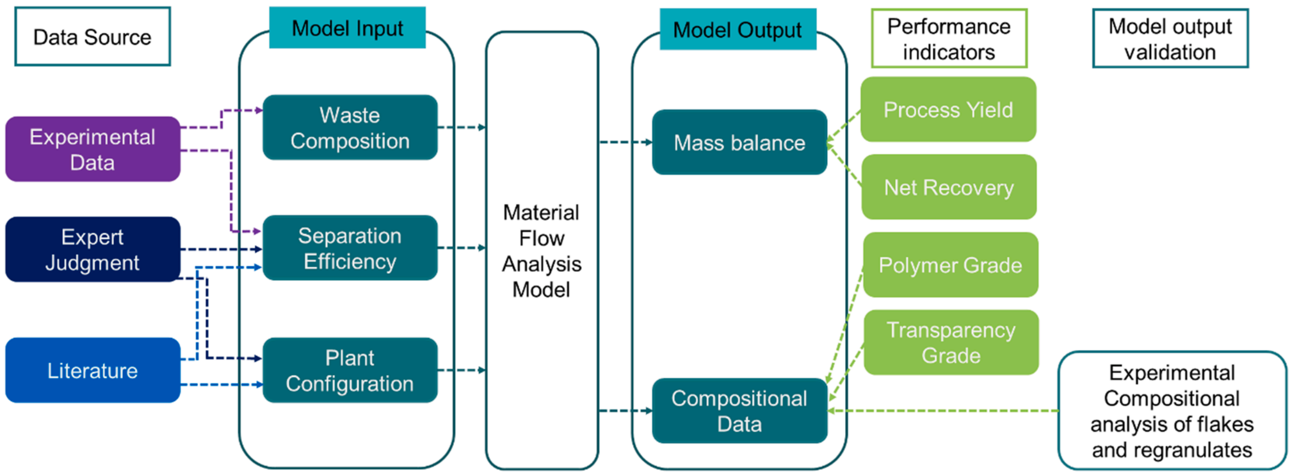


Fig. 2. A diagram that summarizes the MFA model and assessment procedure in this research, including the required model inputs and generated outputs.

are the waste composition of the bales (Section 2.3.1), a defined plant configuration of QRP and conventional recycling process at equipment level (Section 2.3.2), and the associated separation efficiency of these equipment (Section 2.3.3). To quantify these parameters, we have used three data source: experimental data, expert judgment, and literature sources.

The model outputs are mass balances and compositional data, which is converted to a selection of performance indicators adapted from previous studies (Roosen et al., 2022; Kleinhans et al., 2021), which are described in Section 2.4.1. To validate the model outputs, experimental compositional analyses of flakes and regranulate samples are compared with the modeled compositional data (Section 2.4.2).

2.2. Description of study area and scenarios

2.2.1. Study area

This research is conducted with an assumption that QRP would be installed (but not limited to) in Europe, thus assumptions and modeling parameters are linked to the European data. The starting point of the research is DSD 310-1 and DSD 323-2 bales created at MRFs, while the end point is regranulates (an '*r*' is added to the nomenclature, e.g., rPP Film refers to PP Film regranulate). In this research, the bales are products from a German MRF which is transported to a sorting test facility in The Netherlands for compositional analysis and pilot sorting trials (more in Section 2.3.1). Based on expert judgment, all created DSD 310-1 bale and approximately 30 % of DSD 323-2 bales are currently processed in Europe through the conventional recycling process. The remaining 70 % of DSD 323-2 bale is exported outside Europe. However, for the purpose of a fair comparison by the MFA, in this research it is assumed that all DSD 323-2 bale would be processed in Europe.

2.2.2. Scenarios

This research focuses on three mechanical recycling scenarios. First, *baseline scenario*: conventional recycling. In the baseline scenario, DSD 310-1 and DSD 323-2 bales are processed through conventional recycling process to produce regranulates. Second, *scenario 1*: QRP with Tier 1 recycling. In scenario 1, DSD 310-1 and DSD 323-2 bales are processed through QRP additional sorting. Thereafter, all created QRP bales are processed through Tier 1 recycling to produce regranulates. Third, *scenario 2*: QRP with Tier 1 and Tier 2 recycling. Based on expert judgment, and as demonstrated by Bashirgonbadi et al. (2022), Tier 1 and Tier 2 recycling produces regranulates for different market applications because of the differences in regranulates quality. Therefore, in scenario 2, the products of the QRP additional sorting of DSD 310-1 and DSD 323-2 bales, namely PE Film Natural and PP Film bales are processed through Tier 1 recycling, while PE Flex and PO New bales are processed through Tier 2 recycling. Detailed information on the plant configuration of QRP and conventional recycling can be found in Section 2.3.2.

2.3. MFA model

The following sub-sections explain: (*i*) waste composition, (*ii*) plant configuration, (*iii*) the separation efficiency.

2.3.1. Waste composition: DSD 310-1 and DSD 323-2 bales

The compositional analysis of DSD 310-1 and DSD 323-2 bales is conducted at the Nationaal Testcentrum Circulaire Plastics (NTCP) sorting test facility in Heerenveen – The Netherlands. Seven DSD 310-1 (approx. 3.6 tonnes) and six DSD 323-2 bales (approx. 3.5 tonnes) are transported from a German MRF in Autumn 2020. There are three different level of waste classification used in this research: *Main group*, *sub-group*, and *sub-category* levels, as shown in Table SI1 in the supporting information (SI).More detailed information on the sampling procedures can be found in SI 2.

2.3.2. Plant configurations

Experts from the industry are involved in the development of the conventional recycling and QRP configuration (Fig. 3), i.e., HTP GmbH & Co. KG develop the process flow diagram with subsequent consultation with waste management operators and equipment manufacturers such as Attero B.V., EREMA Group GmbH, and Herbold Meckesheim GmbH. Based on expert judgment and previous study by Larrain et al. (2021), plastics recycling plants can operate at 20,000 tonnes/year and 7,000 hour/year, equivalent to 3 tonnes/hour processing capacity. This capacity is used in our model: 20,000 tonnes/year of DSD 310-1 and 20,000 tonnes/year DSD 323-2 mass input for both QRP and conventional recycling.

2.3.2.1. Conventional recycling. The flow diagram of conventional recycling line of DSD 310-1 and DSD 323-2 bales can be found in Fig. 3a. The recycling process starts by shredding the materials into roughly 10 cm in size. For DSD 310-1, metals and non-PE are typically removed before washing using overbelt magnet and NIR sorters. For DSD 323-2, metals and non-PO materials are removed only during washing, density separation, and extrusion.

The cold washing consists of washing by water at 25–40 °C, wet granulation, and friction washer. In the cold washing, the materials will be further size-reduced into flakes sized roughly 1 cm. Contaminations, such as organic residues, paper and labels, are further removed by a friction washer, in which a high-speed screw is used to remove contaminants by centrifugal forces. Thereafter, the remaining heavy polymers and metals are removed in a density separation bath. Before

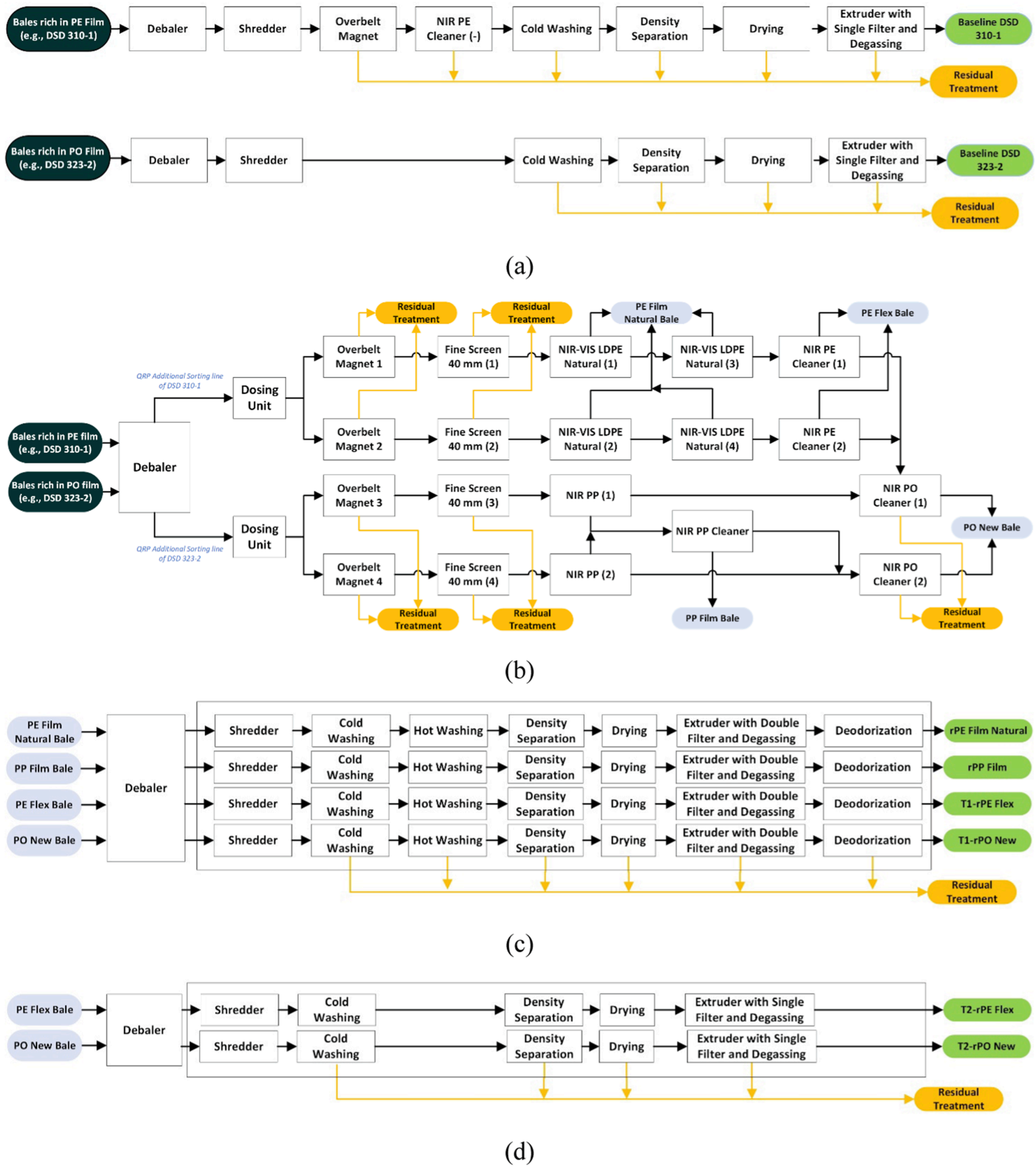


Fig. 3. Flow diagram of (a) conventional recycling, (b) QRP additional sorting, (c) QRP Tier 1 and (d) QRP Tier 2 recycling (adapted from CEFLEX, 2021).

extrusion, the materials are dried using mechanical and thermal drying to remove moisture. Lastly, a single melt filter extruder is used to remove some of the remaining contaminants (Larrain et al., 2021; Faraca & Astrup, 2019; Faraca et al., 2019; Horodytska et al., 2018; Brouwer et al., 2018; Ragaert et al., 2017). In this research, the regranulates produced from the conventional recycling DSD 310-1 and DSD 323-1 bales are referred as "*Baseline DSD 310-1*" and "*Baseline DSD 323-2*", respectively.

2.3.2.2. Quality recycling process (QRP). QRP consists of *QRP additional sorting* and *Tier 1* or *Tier 2* recycling depending on the targeted regranulate quality.

2.3.2.3. QRP additional sorting. It is assumed that QRP additional sorting sorts 20,000 tonnes/year DSD 310-1 and 20,000 tonnes/year DSD 323-2 bales. Both bales are processed separately in two different additional sorting lines (per bale) working in parallel after debaling (see Fig. 3b). The QRP additional sorting starts by overbelt magnets and fine screens separation, removing magnetic material and fine residue, respectively. Thereafter, NIR-based optical sorters are used: i) NIR-VIS

LDPE Natural, positively sorts PE film transparent clear, ii) NIR PE Cleaner, negatively sorts non PE materials, iii) NIR PP Film, positively sorts PP films, iv) NIR PP Cleaner, negatively sorts non PP materials, and v) NIR PO Cleaner, negatively sorts non PO materials.

From DSD 310-1, the QRP additional sorting aims to sort PE film transparent clear, as indicated in Table SI1. Next to this, a second bale is created consisting of the colored/printed PE films that are present in the DSD 310-1 bale. For these purpose, the QRP additional sorting uses optical NIR-VIS LDPE Natural sorters to 'positively' targeting PE film transparent clear and next cleaning the stream by 'negatively' removing all non-PE items using NIR LDPE Cleaner. The bale rich in PE film transparent clear is called "*PE Film Natural*" and bales rich in all colors PE films is called "*PE Flex*".

From DSD 323-2 bale, the QRP additional sorting 'positively' sorts PP films (transparent and coloured) by NIR PP Film sorters. Thereafter, the stream is cleaned by 'negatively' removing non-PP items using NIR PP Cleaner sorter, creating a bale rich in PP called "*PP Film*". The non-PP fraction of the DSD 323-2 bale is cleaned from the non-PO materials using NIR PO Cleaner sorters, creating a bale called "*PO New*".

2.3.2.4. QRP Tier 1 and Tier 2 recycling. The four bales of the QRP additional sorting are sent to the QRP recycling, in which the bales will be shredded, washed, and extruded. Two recycling lines can be used in QRP: Tier 1 (Fig. 3c) and Tier 2 recycling lines (Fig. 3d). The Tier 1 and Tier 2 recycling both start with shredding, followed by cold washing (i.e. identical to cold washing process in the conventional recycling, Section 2.3.2.1). In the case of Tier 1 recycling, an additional hot washing step is applied to remove more odours, papers, and adhesives from the waste stream. The recycling process ends with an extrusion process including a two steps filter with degassing and deodorization (hot air-based treatments) for Tier 1 and a single step filter with degassing (without deodorization) for Tier 2 recycling. In this research, the regranulates produced from QRP Tier 1 is referred as "*rPE Film Natural*", "*T1-rPE Flex*", "*rPP Film*", and "*T1-rPO New*", while the regranulates produced from QRP Tier 2 is referred as "*T2-rPE Flex*" and "*T2-rPO New*".

2.3.3. *Separation efficiency*

The modular MFA approach is based on separation efficiencies to predict material flows throughout the described plant configurations. The separation efficiency (expressed in %) represents the separation of the waste items (categories) at each sorting or recycling unit, which is called transfer coefficient or split factors in other studies (Kleinhans et al., 2021; Brouwer et al., 2018; Cimpan et al., 2016, Mastellone et al., 2017). This includes positive and negative separations as well as potential missorting.

Data on separation efficiencies is collected from relevant literature from plastic waste treatment in Europe (Kleinhans et al., 2021; Brouwer et al. 2018; Cimpan et al. 2016) combined with pilot trials performed in the frame of the CEFLEX activities. Experts from industry are interviewed to further validate the separation efficiencies used in the MFA model. The separation efficiency for every waste category (Table SI1) at every optical NIR sorter is determined by performing a mass balance analysis before and after sorting. During the trials, a few sampling points are defined in which the outputs of optical sorting are collected into three bags. Two out of three bags are chosen and the materials are mixed on the floor. Later, approximately 7.5 kg of sample is randomly collected for material composition characterization and used as the basis for the separation efficiency determination. Detailed procedures of material sampling protocol can be found in SI 2.

The separation efficiencies of sorting equipment used in MFA modeling can be found in SI 3, Table SI3.1. Further information regarding the quantification of separation efficiency based on mass balances and detailed values per waste category at different NIRs can be found in the SI 2. Additionally, the separation efficiency of the overbelt magnet is obtained from the study of Kleinhans et al., 2021, while the fines fraction (<40 mm in size) can be removed effectively (60 %) in the fine screen.

The aggregated separation efficiency for recycling equipment used in the conventional recycling, QRP Tier 1 and Tier recycling can also be found in Table SI 3.2 in the SI 3. It is assumed that up to 95 % of the organic residue, papers, and fine fraction remnants can be removed after the cold and hot washing. Under elevated temperature of > 80 °C and by adding washing agents such as caustic soda and detergents, the hot washing step can effectively remove adhesive and organic waste residues as well as partially remove some of the inks. More than 95 % of low-density monolayer PO floats and most of the heavier materials (70 %) such as non-PO based (other) laminated films, metallic materials, fibers, and other rigid polymers are assumed to sink in the density separation. As for the metalized PE / PP and other films listed in Table SI1, it is assumed that 70 % floats and 30 % sinks. After water-based washing process, the materials are dried using thermal and mechanical drying, removing more than 97 % of the moisture content. Later, in the extrusion process, materials and polymers with higher melting points (higher than 200 °C) are assumed to be retained at the extrusion filter with the sieve size of 90–110 μm (plus an additional 125 μm for two steps filtration technology). The efficiency of the melt filter extrusion process is relatively high (95 %) towards non-PO flexible materials. Lastly, the level of odors are reduced by 55 % – 90 % in the deodorization process (Roosen et al., 2021; Larrain et al., 2021; Picuno et al., 2021; Demets et al., 2020; Strangl et al., 2020; Faraca & Astrup, 2019; Strangl et al., 2021; Brouwer et al., 2018).

2.4. *Assessment of the recycling performance*

To facilitate interpretation and allow proper comparison of different scenarios, two indicators related to quantity: (i) *process yield* (ii) *net recovery* and two indicators related to quality: (iii) *polymer grade* (iv) *transparency grade* are used, adapted from previous studies (Roosen et al., 2022; Kleinhans et al., 2021). Afterwards, the modeled composition at flakes and regranulate levels produced by the MFA model is compared with the experimental compositional analyses from the flake and regranulate samples.

2.4.1. *Performance indicators*

The summary of the selected quantity and quality indicators can be found in Table 1 and is illustrated in Fig. 4. The *process yield* (Y) measures the share of total waste entering a recycling facility (μ^{I}) that is finally converted into regranulates (μ^{r}). The *net recovery* (R) indicates the fraction of waste T entering a recycling facility (μ_{I}^{T}) that is found in the correct regranulates. In the Table SI4, the targeted regranulates ($f_{regranulate}^{T}$) for all listed waste categories (in Table SI1) can be found.

The *polymer grade* at bales (G_b), flakes (G_f), and regranulates (G_r) level is a simple proxy to measure the quality of the products as it reflects the *concentration of the PE and/or PP* (films and/or rigid) at QRP bales, flakes and regranulates level over the total mass of all materials in the respective product, i.e., total mass of all materials in bale (f_{bale}^{m}), flakes (f_{flakes}^{m}) and regranulates ($f_{regranulate}^{m}$) level. The targeted materials at bales (f_{bale}^{T}), flakes (f_{flakes}^{T}), and regranulates ($f_{regranulate}^{T}$) level for PE Film Natural, PE Flex and Baseline DSD 310-1 (from conventional recycling) are all PE from the DSD 310-1 bale. The PP Film targets all PP, while PO New and Baseline DSD 323-2 (from conventional recycling) target all PO materials from DSD 323-2. Moreover, an indicator as a proxy to measure the quality of the color of the regranulates is added, called *transparency grade* indicator (t_r), which indicates the *concentration of transparent film* in the regranulates ($f_{regranulate}^{t_{film}}$), i.e., concentration of *PE film transparent clear* or *PP film transparent* (t_{film}). The value of these indicators ranges between 0 and 100 %.

2.4.2. *Compositional analysis at the flakes and regranulates level*

The modeled compositional data is compared against experimental

Table 1
The summary of the selected indicators, their corresponding definitions and formulas applied to evaluate the performance of the recycling process, adapted from Roosen et al. (2022) and Kleinhans et al. (2021).

Performance indicator	Definition	Equation
Quantity indicator		
Process yield	The share of mass waste input I (in tonne/year) that is being converted into regranulates r (in tonne/year)	$Y = \frac{\mu^r}{\mu^I}$
Net Recovery	Fraction of waste T entering recycling plant that is found in the desired regranulate r	$R = \frac{f^T_{regranulate}}{\mu^T_I}$
Quality indicator		
Polymer Grade		
QRP Bale grade	The concentration of the targeted waste categories T in the QRP bales	$G_b = \frac{f^T_{bales}}{\sum_{m=1}^{M} f^m_{Bales}}$
Flakes grade	The concentration of the targeted waste categories T in the flakes	$G_f = \frac{f^T_{flakes}}{\sum_{m=1}^{M} f^m_{flakes}}$
Regranulate grade	The concentration of the targeted waste categories T in the regranulates	$G_r = \frac{f^T_{regranulate}}{\sum_{m=1}^{M} f^m_{regranulate}}$
Transparency Grade	The concentration of transparent films (i.e., PE film natural and PP film transparent) t_{film} in the regranulates	$t_r = \frac{f^{t_{film}}_{regranulate}}{\sum_{m=1}^{M} f^m_{regranulate}}$

compositional analyses of the flakes and regranulates samples to validate the model. The samples were shredded, washed, and extruded according to QRP chains in the test centers, as such creating flakes and regranulates of PE Film Natural, PE Flex, PP Film, and PO New.

The composition of hot-washed flakes of PE Film Natural, PE Flex, PP Film, and PO New, is determined by Fourier-Transform Infrared Spectroscopy (FTIR). A representative sample of flakes was isolated from each fraction following a standardized mass reduction and sampling procedure CEN/TS 16010. Each sample contained 120–130 flakes. Thereafter, the polymeric composition at both sides of flakes was characterized. After weighting the flakes of a similar polymer, the overall composition could be obtained. Bruker Tensor 27 device, with OPUS 6.5 software, equipped with Attenuated Total Reflection on ZnSe-crystal, is used for the FTIR study at a resolution of 4 cm^{-1} in 16 sample scans and frequency range from 4000 to 600 cm^{-1}.

The composition of the materials at regranulate level is determined by Differential Scanning Calorimetry (DSC). In this research, six different regranulates are characterized:

- rPE Film Natural
- rPP Film
- T1-rPE Flex and T2-rPE Flex
- T1-rPO New and T2-rPO New

To estimate the compositions of the regranulates, the melting enthalpies of PE and PP of the second heating cycle in these materials are compared with master curves as described by Kisiel et al. (2019). For DSC measurements 10 mg per sample is prepared and Polyma 214 device is used in two runs of 25 °C to 290 °C to 25 °C (10 K/min) in a nitrogen atmosphere. The average crystallinity of the PE and PP phases is considered to be 38 % and 50 %, respectively (Kisiel et al., 2019).

2.5. Sensitivity analysis

A sensitivity analysis is carried out to assess the impact of potential variations of the selected modeling parameters towards the performance indicators of QRP (i.e., process yield, net recovery, polymer grade, and transparency grade). Nine modeling parameters are varied in the sensitivity analysis such as the bale compositions, five separation efficiencies of the optical sorters, and four separation efficiencies of the recycling equipment. This approach is applied to gain insights into the most sensitive parameters. In this study, the sensitivity analysis is done by changing each individual modeling parameter by ± 25 % one by one while maintaining the other parameters at a constant value. More information on the new bale compositions and separation efficiencies (±25 %) can be found in the SI 7.

3. Results and discussion

3.1. Material flow and process yield

Fig. 5 shows the material flows of the baseline scenario (Fig. 5a), scenario 1 (Fig. 5b), and scenario 2 (Fig. 5c). From Fig. 5, it can observed that of the total 20,000 tonnes/year of DSD 310-1 bales, 14,643 tonnes/year is converted into Baseline DSD 310-1 regranulate, while 11,708 tonnes/year Baseline DSD 323-2 regranulate is produced from 20,000 tonnes/year DSD 323-2 bales through the conventional recycling. Less regranulates are thus produced from recycling DSD 323-2 bale because of a higher degree of contamination in the input bales that accounts for more than 35 % of the total mass (i.e., residue and non-PO materials). The process yield of PCFP waste recycling through conventional recycling of DSD 310-1 and DSD 323-2 bales is 66 %, equal to 26,351 tonnes/year regranulate production. Previous studies suggest that Baseline DSD 310-1 regranulate would typically end-up in open-loop recycling such as garbage bags or agriculture pipes. On the other hand, the Baseline DSD 323-2 regranulate is mainly used in robust applications such as garden furniture or benches (Faraca & Astrup, 2019; Horodytska et al., 2018; Bashirgonbadi et al., 2022).

In scenario 1 and 2 of QRP, first the QRP additional sorting creates 5,219 tonnes/year PE Film Natural bales, 12,783 tonnes/year PE Flex bales, 3,781 tonnes/year PP Film bales, and 13,780 tonnes/year PO New bales. Relative to the 20,000 tonnes input of DSD 310-1, the QRP additional sorting sorts 26 % of the input into PE Film Natural bales, 64 % into the PE Flex bale, and 5 % into the PO New bale. Furthermore, from the 20,000 tonnes of DSD 323-2, 19 % is sorted into the PP Film

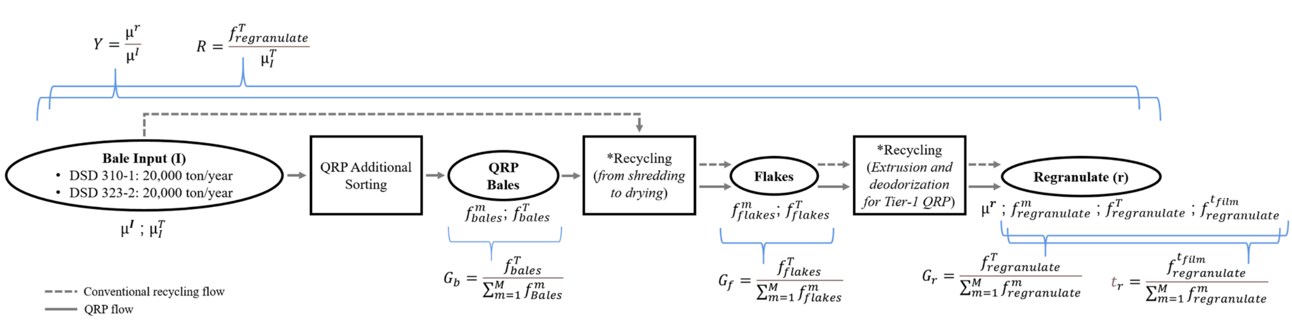
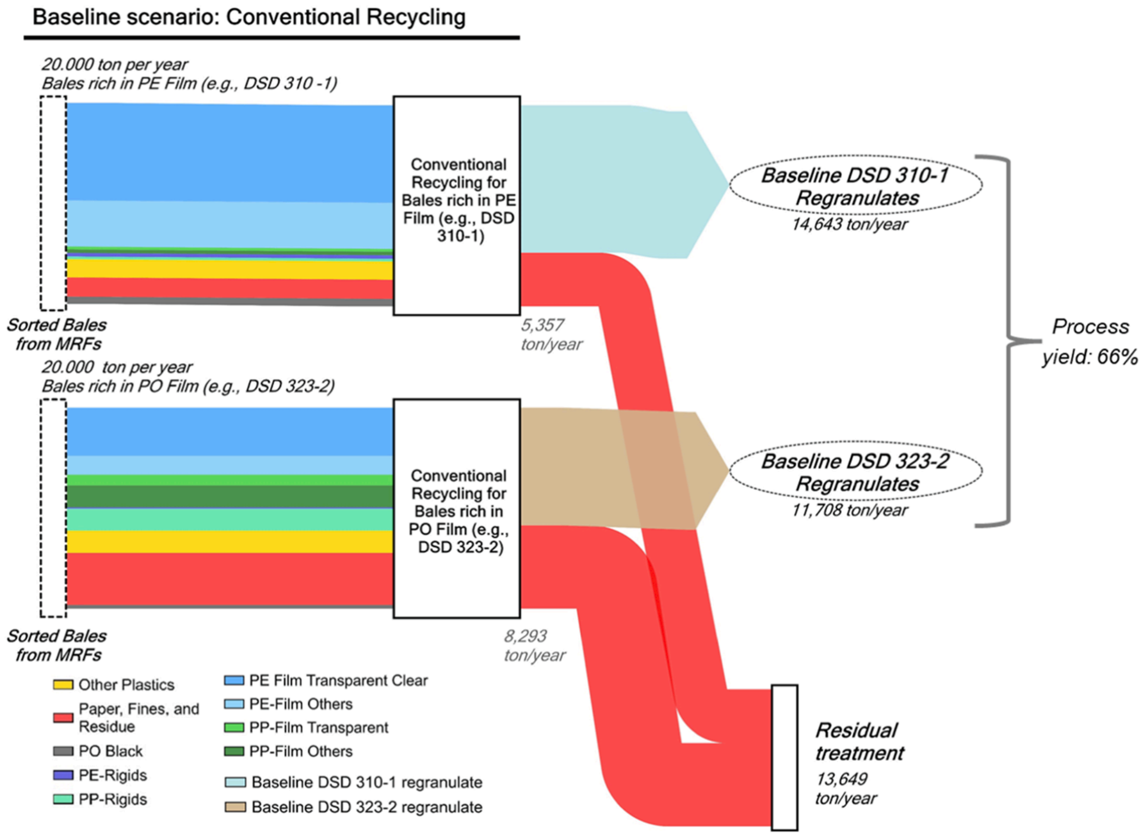


Fig. 4. A diagram with indicated symbols used to define the selected performance indicators applied in this research.



(a)

Fig. 5. The material flow of aggregated waste category from bales rich in PE film (e.g., DSD 310-1) and PO film (e.g., DSD 323-2) through (a) conventional recycling (b) QRP where all four regranulates are produced from Tier 1 recycling (c) QRP where rPE Film Natural and rPP Film are produced from Tier 1 whilst rPE Flex and rPO New are produced from Tier 2 recycling.

bale whilst 64 % is sorted into the PO New bale. The QRP additional sorting removes a fraction of the residue (incl. papers and fine fractions) and non-PO materials, which accounts for 11 % (equal to 4,438 tonnes/year) of the total mass input.

After the QRP additional sorting, these bales go to the recycling process. Four regranulates are created in scenario 1: rPE Film Natural (4,676 tonnes/year), T1-rPE Flex (9,558 tonnes/year), rPP Film (2,874 tonnes/year), and T1-rPO New (8,646 tonnes/year). Thus, from DSD 310-1 and DSD 323-2 bales up to four regranulate types through sencario 1, the process yield is 64 % (in total 25,754 tonnes/year regranulates). In scenario 2, PE Flex and PO New bales are processed through Tier 2 recycling and a slight difference can be observed. The amount of rPE Film Natural and rPP Film remain, while the production of T2-rPE Flex and T2-rPO New increases to 9,878 tonnes/year and 8,953 tonnes/year respectively. The 3 % increase of regranulates production in scenario 2 can be explained by the fact that Tier 2 recycling employs less recycling equipment and consequently generates less residue. The process yield of recycling PCFP waste through scenario 2 slightly increases to 66 % (in total 26,381 tonnes/year regranulate). Concluding, the process yields of recycling PCFP waste via conventional recycling and QRP are relatively similar, which is in line with the typical reported process yield in previous studies of 60 %–80 % (Picuno et al., 2021; Brouwer et al., 2018; Faraca & Astrup, 2019). Potential differences in composition of the regranulates will be investigated in Section 3.3.

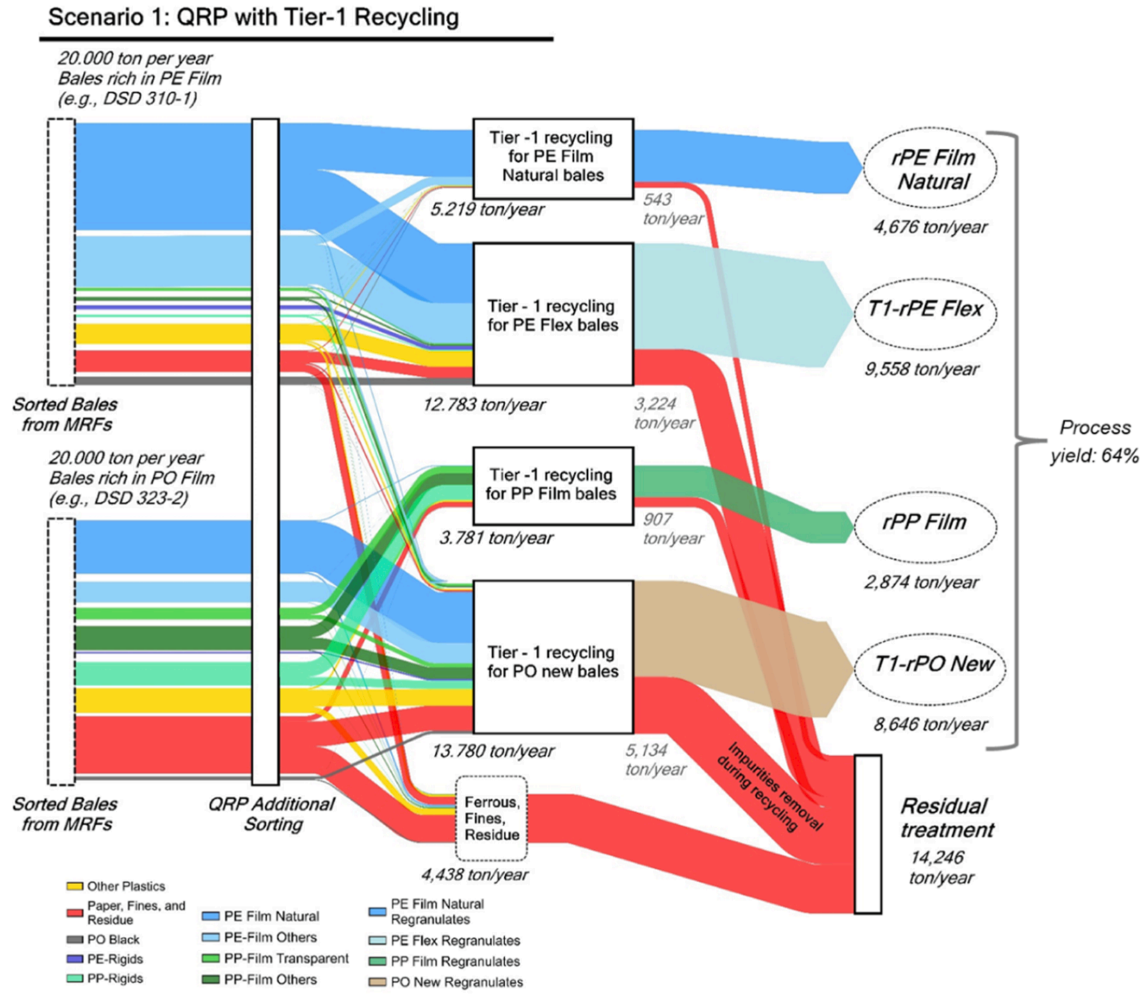
3.2. Net recovery

The estimated net recovery of PE film transparent clear, PE film others (i.e., colored/printed PE films), PP film transparent, PP film others (i.e., colored/printed PP films), PE rigid and PP rigid waste (aggregated in the *sub-group* level, see Table SI1) from DSD 310-1 and DSD 323-2 through conventional recycling and two QRP scenarios can be found in the SI 5, Fig. SI5.

It can be observed that the net recovery of all presented waste categories (shown in aggregated *sub-group* level, see Table SI1) is always higher in scenario 2 compared to scenario 1 of QRP, because the scenario 2 processes PE Flex and PO New bales through Tier 2. This finding is expected because it is unavoidable that hot washing and extrusion with extra filtration also remove a small fraction of PE and PP.

However, when we compare QRP with the conventional recycling, the differences in net recovery range between 1 and 10 %. Little difference can be observed on the recovery rate of PE film transparent clear in QRP (91 % – 93 %) compared to the conventional recycling (94 %). As for the PE film others, we can observe a drop of net recovery from the conventional recycling (92 %) to QRP (79 % – 81 %). For, PP film transparent the net recovery increases from 79 % in the conventional recycling to 82 % – 85 % in QRP. While, the net recovery of PP film others slightly drops from 57 % in the conventional recycling to 51 % – 52 % in QRP. However, PP film transparent and PP film others end up in a separate PP regranulate type, whereas in the conventional recycling these materials end up in Baseline DSD 323–2, which is a mixed PO regranulate type. As for the two other fractions, we can note little differences (by a margin of 1 % – 4%) between the conventional recycling and QRP.

Amongst PCFP waste, a relatively higher net recovery rates can be observed for PE film transparent clear (>90 %) and PP film transparent



(b)

Fig. 5. (*continued*).

(>80 %). One of the reasons for a relatively higher values for the two PCFP waste items is the fact that these waste items fall under these waste categories are usually found as monolayer films. One of the additional advantages of such mono PE or PP flexible packaging types in recycling, next to the potential compatibility issues later in the regranulate, is that they also float more effectively in the density separation tank compared to multilayer films (Mumbach et al., 2019; Eriksen et al., 2020). Furthermore a monolayer structure is often regarded as one of the reasons for a more efficient sorting, as monolayer waste items are more correctly detected by optical NIR sorter (Kleinhans et al., 2021). And finally, during extrusion, parts of multilayer films can be retained on the extrusion filter and thus removed into the residual stream (Chacon et al., 2020).

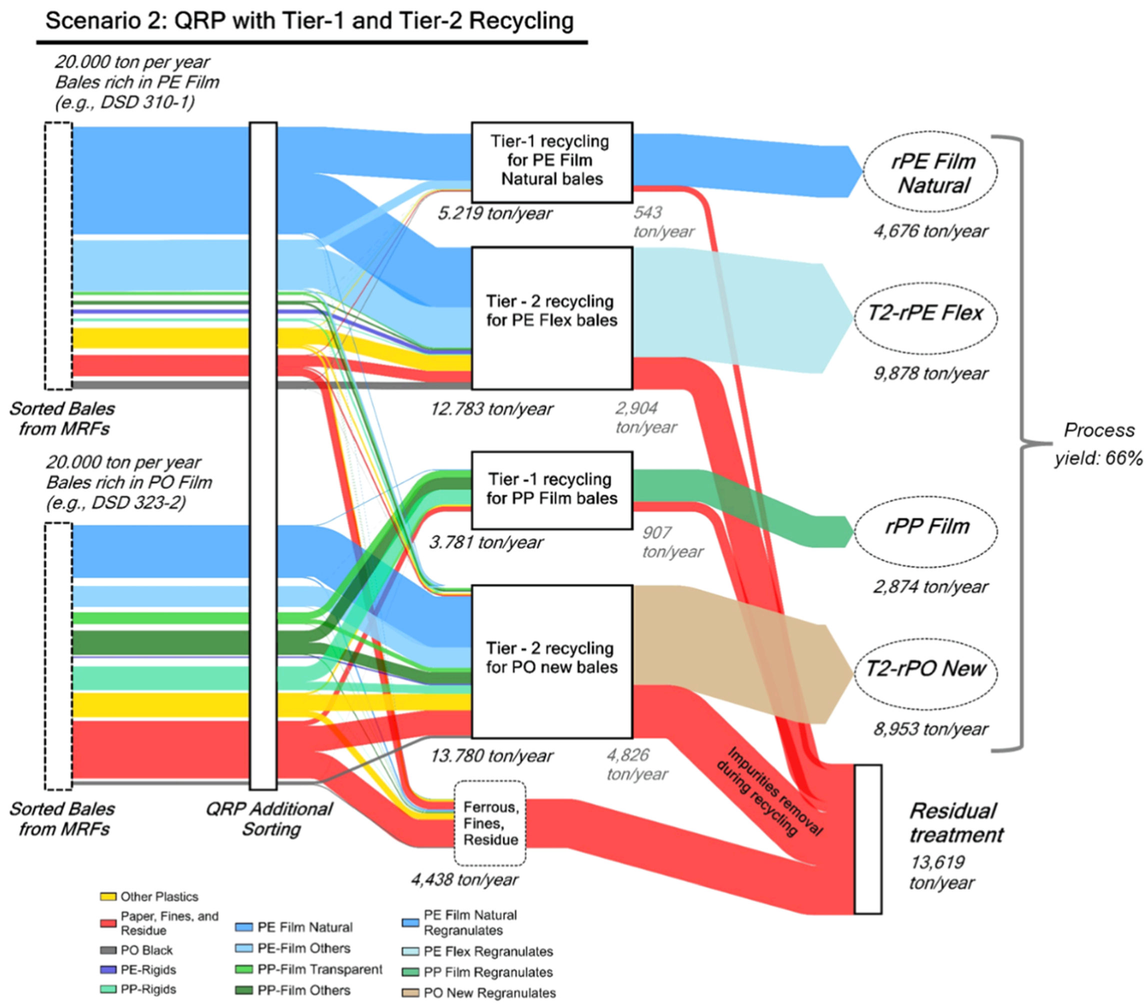
On the contrary, PE film others and PP film others have a relatively lower net recovery, e.g., roughly 80 % and 50 % in QRP respectively. The presence of multilayer films and black plastic items in these waste categories can be regarded as one of the reason for a relatively lower net recovery. A considerable amount of PE film others is missorted during the QRP additional sorting, in which up to 13 % of PE film others is forwarded into PE Film Natural bale that only targets PE film transparent clear waste. Detailed information can be found in the SI 5.

3.3. Polymer grade and transparency grade

The modeled compositional data of the Baseline DSD 310-1 and Baseline DSD 323-2 flakes and regranulates from the conventional recycling can be found in Fig. 6, which also demonstrates the evolution of waste composition from the original bales (i.e., DSD 310-1 and DSD 323-2 bales) to the respective flakes and regranulates. The summary of the evolution of polymer grade (and process yield) of the conventional recycling and QRP can also be found in the SI 5, which indicates that the polymer grade is improved, while the process yields of conventional recycling and QRP are similar.

In Fig. 6, the S1 and S2 refers to the scenario 1 and scenario 2, respectively, while *other plastics* are all non-PO plastics and *other residues* are non-polymer materials. From Fig. 6 it can be observed that other residues (including paper and fine fractions) as well as other plastics (i.e., all non-PO plastics) from the original bales to Baseline DSD 310-1 and Baseline DSD 323-2 flakes and regranulates are removed after washing, density separation, and extrusion by > 90 %. The polymer grade of Baseline DSD 310-1 flake and regranulate is 93 % and 97 % respectively, because PP can still be present after washing and extrusion process. Similarly, 7 % of non PO can still be expected at Baseline DSD 323-2 flakes, making the grade of this flake to be 93 %. However, the polymer grade of Baseline DSD 323-2 can reach up to 100 % as it consists of a mixed PO materials, i.e., 57 % PE and 43 % PP, after extrusion process (Fig. 6).

In the case of QRP scenarios, the modeled compositional data of QRP bales, flakes, and regranulates is also presented Fig. 6. The polymer grade of PE Film Natural bale, PE Flex bale, PE Film bale, and PO New bale is 97 %, 78 %, 81 %, 72 % respectively. In fact, the QRP PE Flex bale is bale rich in PE films (75 % transparent and colored PE films) and PO



(c)

Fig. 5. (*continued*).

New bale are bales rich in a mixed PO films (63 % transparent and colored PE/PP films). After washing, density separation, and drying, the polymer grade of PE Film Natural and PP Film flakes is 99 % and 95 % respectively. Further extrusion does improve the grade of rPP Film as the polymer grade increases to 96 %, while the grade of rPE Film Natural remain at 99 %, because most of the residue and non-PO have already been removed during washing and density separation. Within the PP Film flakes and regranulates, a small percentage of PE (3 %) can still be found, because the density and melting point of PE and PP are close, thus cannot be removed in the density separation and extrusion with melt filter. For Tier 1 and Tier 2 PE Flex flakes and regranulates, the polymer grades are 90 % and 95 % respectively, while the polymer grade of Tier 1 and Tier 2 PO New flake and regranulate is 93 % and 100 % respectively. The T1- and T2-rPO New is expected to be composed of mixed PE (73 %) and PP (27 %).

The transparency grade indicator is added at the regranulates level. From Fig. 6, it can be observed that the Baseline DSD 310-1 and Baseline DSD 323-2 regranulates have transparency grades of 62 % and 57 % respectively. For the QRP regranulates, the transparency grade of rPE Film Natural and rPP Film is 83 % and 39 % respectively. The transparency grade of T1- and T2-rPE Flex is 54 %, while the transparency grade of T1- and T2-rPO New is 61 %. The transparency grade shows that highest value is achieved by rPE Film Natural (83 %) as a result of NIR-VIS sorting in QRP. The value for rPE Flex (54 %) is slightly lower than Baseline DSD 310-1 (62 %) whilst the value for rPO New (61 %) is slightly higher than Baseline DSD 323-2 (57 %), however this is in the same range when concerning the potential market applications. As for the rPP Film, the transparency grade is considerably lower than the other regranulates (39 %), yet the polymer grade is high, thus many applications can still be made from rPP Film (Bashirgonbadi et al. 2022).

When comparing the modeled compositional data of conventional recycling and QRP in Fig. 6, it can be observed that the rPE Film Natural and rPP Film produced in the QRP scenarios have high modeled PE and PP contents. These are regranulates produced from higher quality bales (i.e., PE Film Natural and PP Film) that are not produced from the conventional recycling. Moreover, the polymer grade of T1- and T2-rPE Flex (95 %), which is basically the PE fraction from DSD 310-1 bale with the natural films ‘picked out’, is just slightly below the polymer grade of Baseline DSD 310-1 regranulate (97 %). This finding indicates that rPE Flex would still allow to make similar applications to the conventional recycling with this bale, whereas the new bales with transparent film (i.e., PE Film Natural bale) can be used in higher-valued applications, as also shown in Bashirgonbadi et al. (2022). Similarly, the modeled compositional data of the T1- and T2-rPO New and Baseline DSD 323-2 regranulate is similar. Moreover, there is very little difference (<1%) between the rPE Flex and rPO New composition in QRP Tier 1 and Tier 2 recycling. However, previous studies have suggested that high odour and ink contamination levels limit the potential use of regranulates (Bashirgonbadi et al. 2022; Horodytska et al., 2018; Hou et al., 2018). Moreover, a study by Grant et al. (2020b) shows that high transparency level correlates to high quality regranulates and leads to higher market value as color may cause aesthetic issues and might not be suitable for

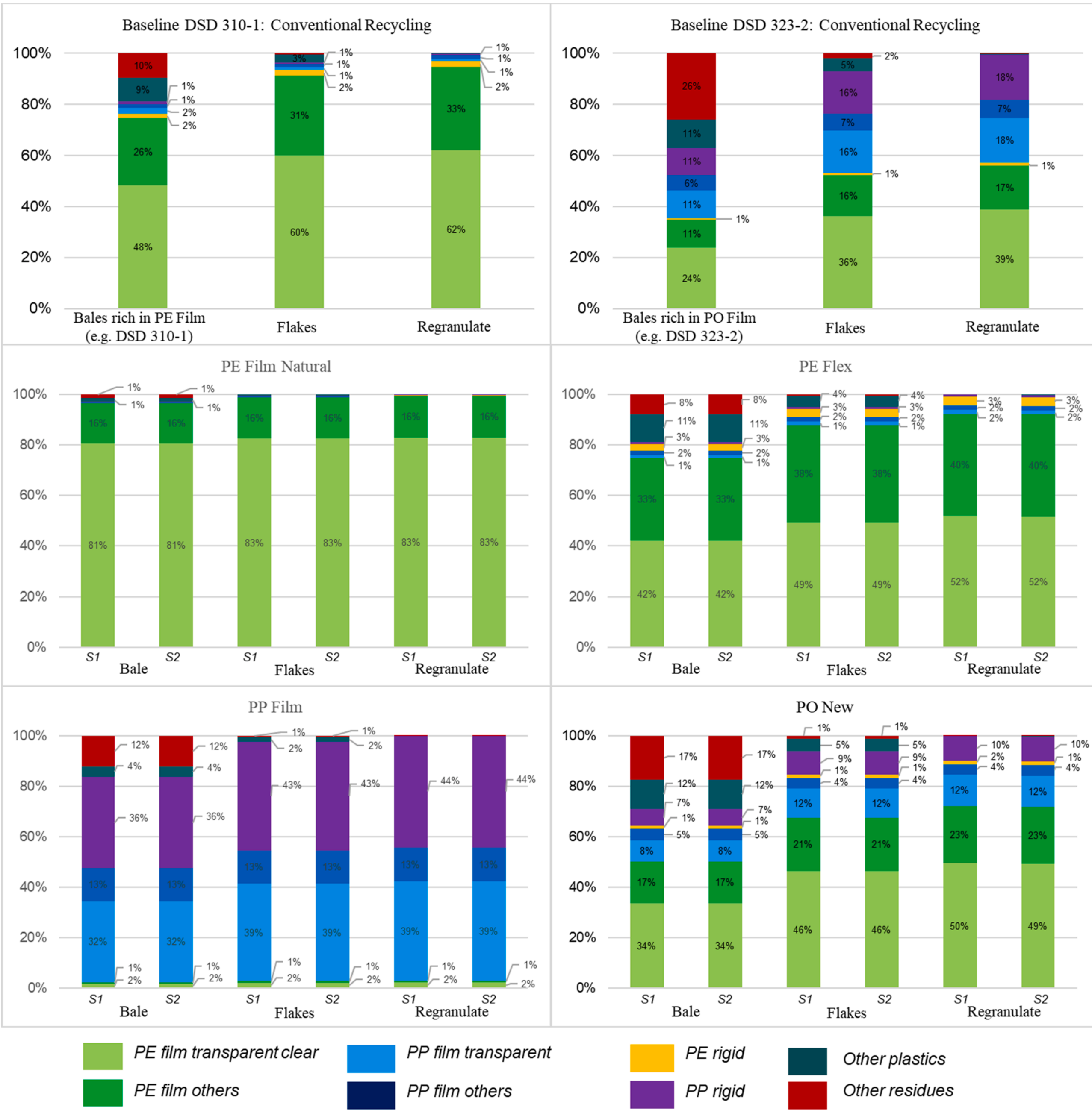


Fig. 6. Modeled compositional data of flakes and regranulates from the conventional recycling and QRP, including the four QRP bales. S1 and S2 in the figure refers to the scenario 1 and scenario 2 respectively (see Section 2.2.2).

certain applications (e.g., food packaging) (Schyns and Shaver, 2021; Radusin et al. 2020).

Furthermore, investigation of the technical properties of QRP regranulates by Bashirgonbadi et al. (2022) demonstrates that Tier 1 recycling enables rPE Film Natural and rPP Film to be reprocessed into more demanding applications such as shrink film, sealable pouches, and standing pouches. From the mechanical properties analysis of rPE Flex and rPO New, it is found that rPE Flex can be considered for film blowing but still requires measures (like blending with virgin or C&I) to increase dart drop resistance in a final product, while rPO New is unfit for film blowing. Other potential market for rPE Flex and rPO New is injection molding applications. Bashirgonbadi et al. (2022) also shows that processing PE Flex and PO New bales through Tier 2 recycling might be economically more attractive.

3.4. Comparison of the modeled compositional data and experimental compositional analyses

The modeled compositional data of QRP flakes and regranulates is compared with the experimental composition analyses. Main results can be found in the SI 6, including detailed information on the compositional analysis of the samples. It should be noted that certain disparities between the modeled compositional and experimental data occur. The model overestimates the experimentally found composition of PE content in the QRP PE Film Natural flakes and regranulates by a margin of 7–9 %. Similarly, the modeled compositional data overestimate the PE Flex flakes and regranulates composition by 1–9 %. The model overestimates the composition of PE and PP by 4–18 % in PP Film and PO New flakes and regranulates, in which the biggest difference can be observed in the composition of rPP Film (i.e., overestimation of PP by

18 %). The deviation is expected because the PE Film Natural flakes and regranulates contain up to 16 % of PE film others waste category, which is potentially multilayer PE films. Similarly, it can be observed that PE Flex contain up to 40 % PE film others (Fig. 6), which can be multilayer films. The detailed composition of potentially multilayer films is not characterized in the MFA model but it might be detected in the experimental analysis, which can be composed of, amongst other, PET, EVOH, Aluminum, or paper (Roosen et al., 2022; Roosen et al., 2020).

The FTIR and DSC also have limitations in determining the composition of multilayer samples. FTIR can only detect the surface of flakes as the infrared beam does not penetrate more than 5 μm (Roosen et al., 2021; Chen et al., 2021). Flakes of one side PE and the other side PP are also assumed to be 50 % PP and 50 % PE, which is not necessarily the case. The DSC method for composition analysis of blends (Kisiel et al., 2019) is derivative method which significantly decreases the error margin of DSC-based compositional analysis, but remain an estimate at best due to the assumptions it requires (like the averaged out crystallinity of the constituting polymers). Additionally, the heats of fusion for each constituent relative to their content deviate from the linear regression. Deviations are caused by phase morphology transition from sea-island structure to co-continuous structure and a non-linear correction curve. Furthermore, crystallization interactions between the phases in a blend can contribute to faulty characterization (Jose et al., 2004; Madi, 2013; Kisiel et al., 2019; Larsen et al., 2021). This may explain some discrepancies (in Table SI6.1) where a decrease of PO content can be seen between the PE Flex and PP Film flakes to the point of their respective regranulates (e.g., from 83 % to 79 % in PP Film). After regranulation we should normally expect an increase of PO concentration because more residue and non-PO materials should be further removed by the melt filter.

These abovementioned findings highlight the current limitation of the MFA model on one hand, but also show the way forward to improve MFA model to assess the performance of plastic recycling. This includes the need for more detailed compositional characterization of the waste categories as well as more experimental work to get reliable quantification of the respective separation efficiencies. For example, a study from Brouwer et al. (2018) suggests that multi-material objects are usually being categorized based on their main material, whereas for the purpose of detailed compositional modeling, the full polymetric composition of the input waste would be more appropriate. Following the more detailed compositional analysis, the quantification of the separation efficiency based on the input–output experimental work

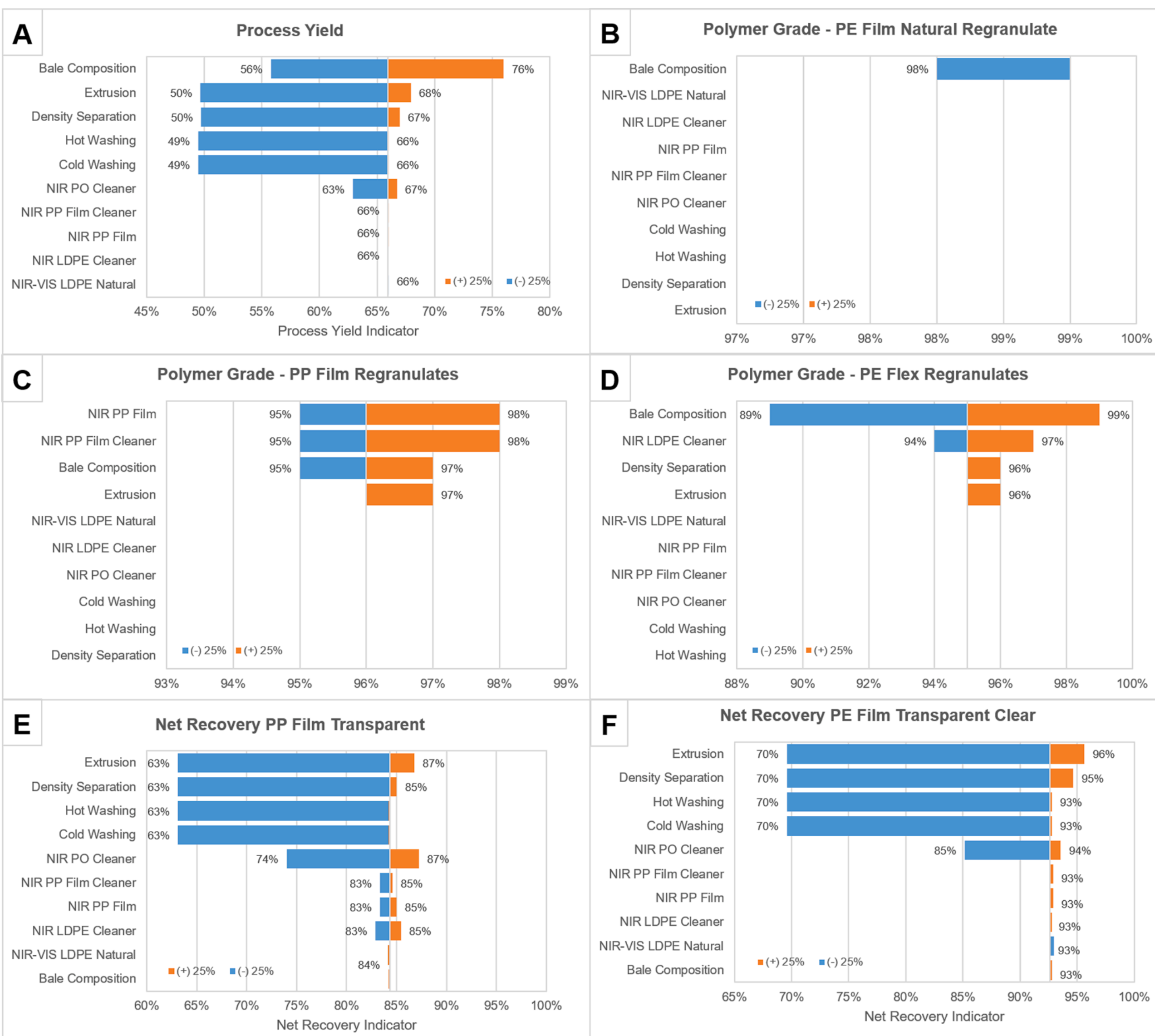


Fig. 7. Key results of the sensitivity analysis towards the performance indicators. More results can be found in the SI 7. The x-axis shows the effect on each performance indicator while the y-axis shows the respective modeling parameters that are varied by ± 25 %.

should be carried out to get more reliable results.

3.5. Sensitivity analysis discussion

Fig. 7 shows the key outputs of the sensitivity analysis towards the performance indicators. More detailed results of the sensitivity analysis can be found in the SI 7 (Fig. SI7 – SI11). Fig. 7 also indicates the relative importance of different modeling parameters by examining the relative changes of the performance indicators.

Fig. 7A shows that bale composition can greatly influence the process yield of QRP, which indicates the importance of maintaining (or even improving) the input bales quality. This result also suggests that if the bales quality is improved by 25 %, the process yield can increase from 64 % up to 76 %. Bale composition is also an important factor towards the polymer grade (Fig. 7C and 7D). Moreover, it can be observed that bale composition influences the transparency grade indicator (in the SI 7). The influence of bale composition is relatively smaller on the net recovery indicator (Fig. 7E and 7F).

The sensitivity analysis shows that separation efficiencies of the optical sorters are important towards the polymer grade of the respective bales, flakes, and regranulates (Fig. 7C and 7D). For example, the separation efficiencies of NIR PP Film and PP Film Cleaner are most important towards the polymer grade of PP Film bales, flakes, and regranulates (Fig. 7C). The same findings can also be found for the NIR-VIS LDPE Natural, NIR LDPE Cleaner and NIR PO Cleaner towards the polymer grade of PE Film Natural, PE Flex, and PO New bales, flakes and regranulates (in the SI 7). As for the PE Film Natural, the optical sorters' efficiencies affect the polymer grade of the bales but have relative small influence towards the flakes and regranulates (Fig. 7B, and the SI 7). This can be explained by the fact that NIR-VIS LDPE Natural has already high efficiency to sort transparent PE Film, creating a relatively high polymer grade at bale level. These findings suggest that the efficiency of the optical sorters determine not only the quality of the bales created, but also the subsequent products after washing and regranulation, i.e., flakes and regranulates.

In Fig. 7, the relative importance of achieving high efficiencies in the recycling equipment, i.e., cold and hot washing, density separation, and extruder, can be observed. The process yield of QRP (Fig. 7A) and net recovery of the waste can drop considerably if the separation efficiency of the recycling equipment decrease by 25 % (Fig. 7E and 7F). As the recycling equipment typically already shows a relatively high separation efficiency, it does not create much improvement on the process yield or net recovery indicators.

4. Conclusion

In this research, an MFA model is developed and applied to evaluate the performance of an improved mechanical recycling process, called the *quality recycling process* (QRP), which goes beyond conventional mechanical recycling process by employing additional sorting, hot washing with detergent, improved extrusion (with two-step filtration and degassing), and deodorization. The MFA shows that the process yield of QRP (i.e., 64 % – 66 %) is similar to the conventional recycling (i.e., 66 %). However, higher polymer grades can be obtained for certain regranulates, e.g., 99 % for the rPE Film Natural and 96 % for rPP Film. Moreover, rPE Film Natural has the highest transparency grade (i.e., 83 %), which correlates to high quality regranulates and potentially leads to higher market value. QRP also produces (T1- and T2-) rPE Flex and rPO New with polymer grades around 95 %, which is comparable to the current regranulates produced by conventional mechanical recycling. These findings suggest that rPE Flex and rPO New have similar qualities compared to the regranulates from conventional recycling, allowing the same applications. Moreover, through granular MFA modelling based on process knowledge it can be observed that monolayer transparent films (both PE- and PP-based) have better net recovery compared to multilayer (incl. black and heavily printed) films. Missorting is more likely to happen for multilayer films and a considerable amount of these materials is more likely to sink at the density separation or be retained at the extrusion filter.

Concluding, the QRP has the potential to produce regranulates that have a better quality compared to conventional mechanical recycling, which is key to fulfill a larger market segment of recycled plastic. Hence, the implementation of QRP by recyclers can be an important step to improve flexible packaging recycling rates and, finally, towards a more circular economy for flexible packaging.

CRediT authorship contribution statement

Irdanto Saputra Lase: Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Software, Data curation, Formal analysis, Visualization. **Amir Bashirgonbadi:** Writing – review & editing, Conceptualization, Methodology, Software, Data curation, Formal analysis, Visualization. **Freek van Rhijn:** Writing – review & editing, Validation, Resources, Conceptualization, Methodology. **Jo Dewulf:** Writing – review & editing, Validation, Resources, Supervision. **Kim Ragaert:** Conceptualization, Writing – review & editing, Validation, Resources, Supervision. **Laurens Delva:** Writing – review & editing, Validation, Supervision. **Martijn Roosen:** Writing – review & editing, Methodology, Validation. **Martine Brandsma:** Writing – review & editing, Methodology, Validation. **Michael Langen:** Writing – review & editing, Conceptualization, Methodology, Validation, Resources. **Steven De Meester:** Conceptualization, Methodology, Writing – original draft, Resources, Supervision, Project administration.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2022.09.002.

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