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# Design from recycling: Overcoming barriers in regranulate use in a circular economy

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ABSTRACT

Despite government and consumer attitudes, industry's use of recycled material remains low and narrowly scoped. Critical advances in recycling practices and technology depend on increased scope of application for regranulates, which can be achieved through design from recycling principles. We investigated regranulates and laboratory reprocessed material in the context of processing, ability to meet functional requirements, viability of closed loop recycling, design strategies and co-dependent industry reforms. Reprocessing results in polymer degradation, changes in melt flow rate (MFR) and tensile impact strength ($a_{tN}$) and restricts polymer processing options. Contamination and multilayer packaging cause changes in MFR, $a_{tN}$, elastic modulus ($E$) and elongation at break ($\varepsilon_b$) affecting ability to meet application-specific functional requirements. The problem is complex, whereby the preferences and requirements of recyclers, designers, industry, and consumers are contradictory. New high value regranulate applications using clever design practices are necessary to finance new sorting and processing technology in addition to industry and consumer tolerance and conservative product expectations to circumvent these competing interests.

## 1. Introduction

The importance of recycling and its relevance to achieving a sustainable future for humans on Earth has been indisputable for over 50 years (Jody et al., 2023). Recycling has an exceptionally positive image; It is often a focal point in new sustainability-related policies and is valued by consumers to the point that it has become highly marketable (Grębosz-Krawczyk and Siuda, 2019). However, despite all the hype surrounding recycling, which would seem to be ubiquitous, the reality is a lot bleaker than one might expect. Only 8.5% of new products are made using recycled polymers (Plastics Europe, 2022). Additionally, 86% of all use of recycled polymers are in just three applications: building and construction (45%), packaging (30%) and agriculture, farming and gardening (11%) (Plastics Europe, 2022).

Manufacturer design preference for virgin over recycled polymers is easy to understand; Recycled polymers often exhibit poorer mechanical properties, can be more difficult to process, less aesthetically and olfactorily appealing and cannot be used for food contact applications (Karaagac et al., 2021a, 2021b). Industry reluctance to work with regranulates, however, retards widespread adoption and implementation of recycled materials; It is not possible to justify investment in improving recycling technologies and infrastructure while regranulates remain useful for only selected low value products, such as bin liners. The growth of recycling in practice, as opposed to as a philosophy, is directly linked with the scope of application for which regranulates can be used (Raghuram et al., 2023).

'Design for recycling', which considers the impact of the design process on the recyclability of materials at their end of life, is a well-known research area (Roos et al., 2019; Sudheshwar et al., 2023; Thompson et al., 2020). Advances include cradle-to-cradle design, where products are designed with disassembly and recyclability in mind (Bjørn and Hauschild, 2018; Hansen and Schmitt, 2021), eco-informed material selection during design (Jones et al., 2022; Law and Narayan, 2022), extended producer responsibility, which holds the manufacturer responsible for the recyclability of their product (Leal Filho et al., 2019) and improved public awareness and education on recycling (Smol et al., 2018; Wang et al., 2020). Other eco-informed design strategies focus on resource pressure and circulation (Desing et al., 2021; Toxopeus et al., 2018) and life cycle assessment (LCA) (Broeren et al., 2016; Rigamonti et al., 2018). However, 'design from recycling', which focuses on the concept of circular economy and examines the extent to which a new product can be produced from existing recycled polymer

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streams and the design specifications required to do so (Ragaert et al., 2020) is highly underrepresented in the literature, yet arguably critical, timely and widely applicable.

Fundamentally, 'design from recycling' is limited by the 'quality' of regranulates, an important yet vague and undefined term pertaining to technical considerations linked but not directly correlated with issues, such as contamination and degradation of polymers (Tonini et al., 2022). Post-consumer polymer waste may be contaminated with inorganic material, such as glass or metal, and organic material, such as food residue or even other polymers, due to imperfect sorting practices (Gazzotti et al., 2022). Polymers also degrade into smaller molecules or fragments under oxidative, hydrolytic, thermal, photo or microbial stress (Hinsken et al., 1991). These processes result in changes in the molecular mass, morphology, and mechanical properties of regranulates, meaning that they no longer meet the design requirements of a given application. Contamination and polymer degradation effects in recycled material are well documented in the literature (Archodoulaki et al., 2022; Chamas et al., 2020; López et al., 2014) which typically focuses on characterizing property changes and their relevance within the context of polymer science and polymer processing, i.e., changes in melt mass-flow rate (MFR), increased stiffness and more brittle fracture behavior. How these changes affect the combination of abstract (e.g., aesthetics, user experience, etc.) and technical (e.g., material selection, manufacturing processes, etc.) aspects associated with design and ramifications for stakeholders along the value chain are, however, rarely considered.

Even moderate changes in polymer processing and mechanical properties result in downcycling (or cascading) i.e., conversion into products of lower quality or value, rather than recycling of the material i.e., conversion into products of equal or higher quality or value for the same (closed-loop recycling) or a different (open-loop recycling) application to the original application of the polymer (Jehanno et al., 2022). The relationship between material 'quality', recycling process and destined application can be modelled in the context of economics (Nelen et al., 2014), LCA (JRC, 2018) and technical metrics (Hummen and Sudheshwar, 2023). However, while these studies do attempt to join their corresponding parameters with sector and process analysis, their scopes are often very narrow, and they offer little big picture perspective on recycling reform or the roles of and interactions between the key stakeholders.

We investigated the processing and mechanical properties of common commercial regranulates in Austria, laboratory reprocessed material and corresponding virgin polymers as a reference. Results were interpreted within the context of design from recycling and used to assess design from recycling considerations, such as processing restrictions, issues with polymer degradation and contamination, polymer ability to meet functional requirements, the viability of closed loop recycling, design strategies and co-dependent industry reforms to promote increased use of recycled polymers. With a technical focus on the recycler and designer, the polymer processing issues they encounter, their individual and shared property preferences and requirements, while considering ramifications down the supply chain for the manufacturing industry and consumers, we achieve a diverse technical perspective that is holistic and broad scoped yet well linked with the roles of key stakeholders and critical polymer science and processing fundamentals.

## 2. Experimental section

### 2.1. Materials

LD 310 E low density polyethylene (PE-LD) was purchased from Dow Chemical Company, (Michigan, U.S.A), while MB6561 high density polyethylene (PE-HD) and BC918CF polypropylene (PP) copolymer were kindly provided by Borealis (Vienna, Austria). H7058–25R PP was kindly provided by Braskem (Rotterdam, Netherlands). PE-LD and Dipolen S PE/PP regranulates were purchased from Rissland (Katzhütte, Germany) and MTM Plastic (Niedergebra, Germany) while Systalen 7002 PE-HD regranulate and RPPC03GR PP regranulate were kindly provided by Duales System Holding (Cologne, Germany) and Total (Paris, France), respectively. All regranulates had an ash content < 2 wt.% and no other known impurities. These materials were used as received. PE-LD snack packaging and shrink film contaminated with PE-LLD, PE-HD cosmetic bottles and PP film (modified atmosphere packaging), yogurt cups and buckets were also purchased or collected from post-consumer waste bins in eastern Austria. All laboratory recycled materials had an ash content < 5 wt.% and contained no polymeric contamination, except for PP films which contained < 5 wt.% PE. Collected materials were washed and milled prior to use.

### 2.2. Reprocessing of virgin PE-LD, -HD and PP

Virgin PE-LD, -HD and PP were reprocessed to simulate the recycling cycle. Virgin granulates were extruded using a single screw extruder (EX-18–26–1.5, Extron Engineering Oy, Finland) with a screw diameter of 18 mm and length to diameter ratio of 25:1 at 240 °C and 70 rpm screw speed. The extruded material was then ground into flakes using a mill (Fritsch Pulverisette 19, FRITSCH GmbH, Germany) to obtain the reprocessed samples. Recent standards, such as DIN SPEC 91,446 focus on the classification and trading of recycled plastics, indirectly relating to the recycling process by standardizing the classification of recycled plastics based on Data Quality Levels (DQLs) and promoting better understanding of the quality and characteristics of the materials being traded and used (Deutsches Institut für Normung, 2021). However, no standards currently exist directly governing the reprocessing of material by recyclers. The described process is nonetheless analogous to typical industry practices (Shamsuyeva and Endres, 2021). The reprocessing and grinding process was repeated ten times to simulate ten recycling cycles with samples collected and tested after 1, 3, 5, 7 and 10 cycles. 10 × reprocessing of a material is an extreme case and represents the upper limit or an unlikely scenario based on currently available infrastructure.

### 2.3. Compression moulding of PE-LD, -HD and PP virgin material and regranulate and preparation of the mechanical test specimens

PE-LD, -HD and PP virgin material and regranulates were compression moulded (Collin P 200 P, Germany) at 180 °C and 50 bar with a cooling rate of 20 K/min to prepare mechanical test specimens for all materials. At least ten dog-bone tensile (thickness 1.8–1.9 mm) and tensile impact test specimens (thickness 1.1–1.2 mm) were cut from each compression moulded sheet in accordance with ISO 527–2-A5 (The International Organization for Standardization, 2012) and ISO 8256/1A (The International Organization for Standardization, 2004), respectively. Tensile impact test specimens were notched with a Notch-Vis tool (Ceast, Germany).

The MFR was measured for at least ten replicates of each sample according to ISO 1133–1 (The International Organization for Standardization, 2011) at 230 °C under 2.16 kg load on the MeltFloW basic (Karg Industrietechnik, Germany). These conditions were selected to enable comparison of PE and PP at the same temperature.

### 2.4. Tensile (impact) testing of PE-LD, -HD and PP virgin material and recycled samples

A universal testing system comprising a Zwick 050 frame, 1 kN load cell and extensometer (Zwick Roell, Germany) was used to perform tensile tests on the prepared specimens at a constant velocity of 10 mm/min. The elastic modulus $E$, tensile strength $\sigma_{UTS}$ and elongation at break $\varepsilon_b$ were calculated using the ZwickRoell testXpert II software (v. 3.6) across five replicate tests. An Instron 9050 impact pendulum (Ceast, Germany) was used to establish the tensile impact strength $a_{tN}$ of the notched samples across at least ten replicates.

## 3. Results and discussion

### 3.1. Fundamental technical problems with recycling and recycled materials

#### 3.1.1. Restricted processing options based on polymer degradation and contamination

The high temperatures and shear forces associated with re-extruding polymers during recycling results in increased crosslinking and branching (primary mechanism for PE) and chain scission (primary mechanism for PP) associated with changes in molecular mass and weight distribution (Hinsken et al., 1991). These changes in chain length affect polymer crystallinity and shrinkage in turn, necessitating tool changes by the manufacturer. They also affect the MFR and melt strength making undesired changes to machine parameters e.g., injection speed and pressure in injection moulding necessary for processing or worse, restrict polymer processing options and subsequently the products and applications for which the polymer mixture can be used (Demets et al., 2021). Pipe extrusion and extrusion blow moulding, which is used to produce hollow vessels such as bottles, require viscous blends with low MFRs (Table 1). Conversely, film extrusion often used to produce packaging requires a considerably higher MFR (1.5–5 g/10 min) and injection moulding, which is used to produce parts with more intricate geometries such as screw on caps, requires an even higher MFR (6–16 g/10 min). These polymer processing options are also restricted to use with polymers exhibiting a property profile in line with the requirements of the end product e.g., PE-LD or -LLD for film extrusion and PE-HD for pipe extrusion, extrusion blow moulding and injection moulding.

Extrusion-associated crosslinking and branching typically results in a reduced MFR in PE while chain scission results in the opposite effect in PP (Yin et al., 2015). The processing time associated with extrusion is the most influential factor associated with this change in MFR, with longer processing times associated with greater reductions in the MFR of PE and increases in the MFR of PP (Martey et al., 2021; Schall and Schöppner, 2022). Temperature and shear rate (screw speed) also promote changes in MFR but to a lesser extent. Contamination of PE with PP and vice versa, a common problem in recycled polyolefins due to their similar densities and hence more challenging sortability, also affects MFR in all applications detailed in Table 1 but especially in injection moulding (Karaagac et al., 2021b). Multilayered structures, which are used in ~30% of polymer packaging, by definition also comprise multiple polymers, such as PE (PE-LD, PE-LLD) and PP (homopolymer, random and block copolymer), and are not easily separated using common sorting technologies (Schmidt et al., 2022). A single processing step can see the MFR of PP contaminated PE increase by as much as 10% (Karaagac et al., 2021a). With up to 10 wt.% PP contamination common in PE recycled mixtures this can cause an otherwise reducing MFR to remain constant or increase slightly (Juan et al., 2021). While the MFR of virgin polymers is very easily modified using highly reactive additives e.g., peroxides or cross-linking agents accurately dosed based on the virgin polymer type it is much more challenging in recycled polymers due to organic and inorganic contaminants which might either act as reaction accelerators or inhibitors making the effects of additives unpredictable (Maris et al., 2018). Polymer degradation during re-extrusion affects the recycling yield since crosslinked or branched gel is typically removed by the recycler and discarded at an early stage in the recycling process (Schyns and Shaver, 2021).

**Table 1**
MFR measured at 230 °C for 2.16 kg of granulate.

| Process | Polymer | MFR (g/10 min) | Products Virgin | Recycled |
|---|---|---|---|---|
| Pipe extrusion | PE-HD | 0.2–0.6 | Pipes | Pipes |
| Extrusion blow moulding | PE-HD | 0.6–2.7 | Hollow vessels | Hollow vessels (coloured) |
| Film extrusion | PE-LD/LLD | 2.7–9 | Films, packaging | Bin liners (coloured) |
| Injection moulding | PE-HD | 10–20 | Complex geometries | PE/PP injection moulded parts |

#### 3.1.2. Closed-loop recycling: ambitions and paradoxes in a post-consumer world

Closed loop recycling can be seen as a best-case scenario in recycling terms, i.e., a separately collected waste stream of known polymers with little contamination sourced from e.g., battery housings, car bumpers (Kozderka et al., 2017) or beverage bottles. It represents a tiny fraction of the recycling industry and practical realizations remain limited to PET bottle-to-bottle recycling and some examples utilising PE-HD milk containers (Gaduan et al., 2023).

The main reason for the stunted adoption of closed-loop recycling is a lack of suitable input material. ~90% of recycled material is post-consumer waste, which is typically dirty, mechanically deformed and derived from widely used packaging materials with short service lives (Archodoulaki and Jones, 2021; Soares et al., 2022; Tukker, 2012). Colour and odour problems in recycled polyolefins coupled with legal requirements associated with food packaging and reductions in their mechanical properties often make closed-loop packaging-to-packaging recycling impossible. Volatile organic compounds migrating into the polymer matrix (Cabanes and Fullana, 2021) downgrade the use of this material to products that do not use white or natural colours (Golkaram et al., 2022). (Hot and cold) washing procedures help to target unpleasant odours but do not improve mechanical properties, which makes their inclusion less economically and ecologically viable (Bashirgonbadi et al., 2022).

Closed-loop recycling also has limitations in terms of long-term viability, due to the limitations on the number of times the material can be recycled before it degrades e.g., 2–3 times for PET (La Mantia and Vinci, 1994). Most PE regranulates also have a lower MFR than virgin polymers due to the predominance of crosslinking mechanisms and finding a regranulate that is suitable for injection moulding is subsequently very challenging (Mendes et al., 2011). This restricts the design options for recycled PE-HD to pipe extrusion and extrusion blow moulding, effectively downgrading injection moulding grade PE-HD for use in these more restricted applications as its MFR reduces (Oblak et al., 2015; Yin et al., 2015).

Mixing 'cleaner' waste streams with virgin polymers can help to combat the effects of polymer degradation and dilute contamination but often relies on large quantities of virgin material to do so, consequently failing to promote dominant use of recycled material in products. A mixture comprising 30% regranulate and 70% virgin material statistically contains only 0.8% material that has be processed ≥ 5 times, which may yield satisfactory properties for many applications (Niessner, 2022). However, mixtures comprising 70% regranulate and 30% virgin material contain ~5% material that has been processed ≥ 5 times, which will limit the applications for which the material can be used.

In addition to most post-consumer waste and consequently most recycled material not being suitable for closed-loop recycling, it is very challenging to repurpose it for another application. This is because the dominance of packaging in this stream results in the presence of a narrow range of polymers used for packaging e.g., PE-LD, PE-HD, PP, PET designed with a property profile to meet this single application and not others (Horodytska et al., 2018). For example, the mechanical properties of PE-LD- and -LLD are most suitable for production of films and there are limited options other than to use them for their original application – packaging (Franz and Welle, 2022).

Despite these limitations of mechanical recycling, the aim should be to retain and maintain quality within the primary recycling loop and integrate secondary materials as a design standard prior to chemical recycling or energy recovery.

*3.1.3. Impaired ability to meet functional requirements due to polymer degradation and contamination*

Processing limitations aside, the other fundamental technical challenge when designing with recycled polymers is 'material functionality', i.e., the specific properties and characteristics of a material that determine its suitability for a particular application or purpose. Important mechanical properties of recycled polymers, such as $E$, $\sigma_{UTS}$, $a_{tN}$ and $\varepsilon_b$, are inferior to virgin polymers (Golkaram et al., 2022; Thoden van Velzen et al., 2021). They also can't be modified using additives such as plasticizers (as is possible in virgin polymers) due to the risk that substances within the degraded polymer matrix will leak (Shi et al., 2022). This makes design from recycling more challenging since the restricted property profiles of recycled polymers may not match the functional requirements of an application or product.

Contamination in recycled mixtures has arguably the greatest effect on their mechanical properties. Post-consumer waste streams may contain a wide range of different materials, both inorganic and organic. Inorganic matter, such as glass, metal and even organic contaminants, such as food and beverage residues or paperboard can often be easily separated from polymers using a range of different sorting and processing technologies, including hot wash, air classifier systems, magnetic separation and sink-float sorting (Lange, 2021). But the inability to accurately sort polymers from each other results in polymer-based contamination of one polymer within a mixture with another (Qu et al., 2022). Since these polymers all have different properties, including MFR, $E$, $\varepsilon_b$ and $a_{tN}$ even a small quantity of polymer contamination in a mixture predominantly comprising another polymer can result in considerably altered mechanical properties. PP contamination in PE is an especially good example of this with the presence of $<10$ wt.% PP in a PE mixture resulting in a considerably higher $E$ and much lower $\varepsilon_b$ and $a_{tN}$ in the mixture than would be present in virgin PE (Karaagac et al., 2021a). This can affect the suitability of a mixture in both cases where it is intended for use as a film and in cases where it is intended for use as a rigid vessel (Fig. 1**a, b**).

PE-LD and -HD regranulates exhibit lower MFRs and PP regranulates higher MFRs than virgin material (Fig. 1**c**). PE-LD regranulate exhibits considerably lower MFR and $a_{tN}$ than virgin material but little difference in $E$ and $\varepsilon_b$. PE-HD and PP regranulates exhibit considerably lower $E$, $a_{tN}$ and $\varepsilon_b$ than virgin material. Laboratory processed samples typically exhibit greater differences in properties compared to virgin material than commercial regranulates (Fig. 1**d**). This is likely due to the absence of technologies used in industry, such as degassing, melt filtration and stabilizing processing aids e.g., additives. Re-extrusion based polymer degradation (crosslinking and chain scission) with respect to processing time—the most influential factor affecting crosslinking—also greatly affects the MFR and mechanical properties of regranulates (Fig. 1**e**). The MFR of PE-LD and -HD regranulates decreases with increasing reprocessing cycles, while that of PP homo- and copolymers increase. $a_{tN}$ decreases before stabilizing with increasing reprocessing cycles in PE-LD and PP copolymer and $a_{tN}$ is largely unaffected by reprocessing cycles in PE-HD. However, PP copolymers are far more susceptible to $a_{tN}$ losses with increasing reprocessing cycles. It should be noted that these effects are only the result of material damage due to mechanical stress and heat (processing) and neglect the influences of contamination and degradation that occur during the service life of a product, such as irradiation and oxidation (weathering).

The concept of material functionality is critical to design from recycling, since the properties of regranulates will always diverge from what would be considered optimal or desirable for design purposes. Achieving the property profile of virgin material isn't possible, and even if it was, it would be prohibitively expensive to do so. Consequently, the economic and successful use of regranulates can only be considered within the context of suitability for a given application. Expression of the material functionality of regranulates using a single aggregate metric alongside LCA or environmental impact assessment (EIA) data would enable designers to maximise environmental benefit in products. The establishment of simple yet insightful and accurate metrics to aid design decisions must be a priority.

*3.2. A necessary compromise: designing with recycled materials*

One of the biggest problems currently hindering the expanded use of recycled materials is consumer perception (Polyportis et al., 2022). Or at least the lack of willingness from companies to risk consumers rejecting their products if they were to be made from recycled material due to issues associated with reduced material properties, less desirable colours or odours (Park and Lin, 2020). This is perhaps a baseless fear given the exceptionally positive image that environmentally friendly and recycled products currently enjoy in society (Ketelsen et al., 2020). These factors are in fact typically considered highly marketable selling points these days (Gelderman et al., 2021).

While marketing is obviously important in shaping consumer perceptions, designers play the most active and fundamental role in product image and function (Michelini and Razzoli, 2004). Whether a product is successful or not largely depends on how it looks and how well it works (Kumar and Noble, 2016). Whether a product is perceived as 'cool' also largely depends on these factors (Tiwari et al., 2021). Designers will play a pivotal role in reinventing the norm – setting new unwritten standards on acceptable colour deviations, odours and material properties (Mugge, 2018). Less than perfect needs to be okay with the redeeming factor that the product is more environmentally friendly (Ehrenfeld, 2008). Expanding the range of accepted applications for recycled materials will be the key factor in increasing recycling rates and improving the utilisation of recycled streams (Perry et al., 2012). Recycled materials must be associated with cool products, not just bin liners and similar.

Of course, that is easier said than done. Issues with extrusion- and contamination-based mechanical property degradation in recycled polymers do make their property profiles very different from virgin polymers – more limited and much less easily modified **(**Fig. 1**)**. This causes issues in both processing, where the MFR plays a considerable role in how the recycled material can be processed, in addition to the ability of the recycled material's mechanical properties to service product function (Hopewell et al., 2009). Managers and designers must manage their expectations and tolerance for the time and human resources required to achieve optimal processing conditions, profit margins and product quality when working with recycled polymers (Kumar et al., 2021). Optimisation of extrusion processes to minimise processing time (and less importantly shear rate and temperature) and reduce crosslinking and improving sorting capabilities to reduce contamination without affecting production viability will constitute a considerable investment of time and money (De Weerdt et al., 2022). These compromises are perhaps more palatable when considered in the knowledge that they will play an important role in creating a more sustainable society and that since climate change affects us all, they will ultimately be marketable.

Designing with recycled polymers is more challenging, but possible (Preka et al., 2022). MFR is a strong and useful indicator of polymer degradation for designers and can be used to gauge when special attention must be afforded to the design process. To ensure products meet safety standards and expected minimum service life using degraded material that is less durable than virgin polymers and exhibits varied and unpredictable material properties, designers must over-engineer e.g., thicker walls and avoid notches, sharp curves and edges and filigree details e.g., flap hinge closures (Martínez Leal et al., 2020). There is massive potential for improved design practices across many products and industries (Dokter et al., 2021; Rauch et al., 2022). Minimising the time required to achieve a design (often prioritised) comes at the expense of any real investigation or understanding as to how well a design really fulfills its requirements (Stechert and Franke, 2009). Many designs using virgin polymers considerably outperform their baseline requirements (Hauschild et al., 2020). Finite element analysis and other

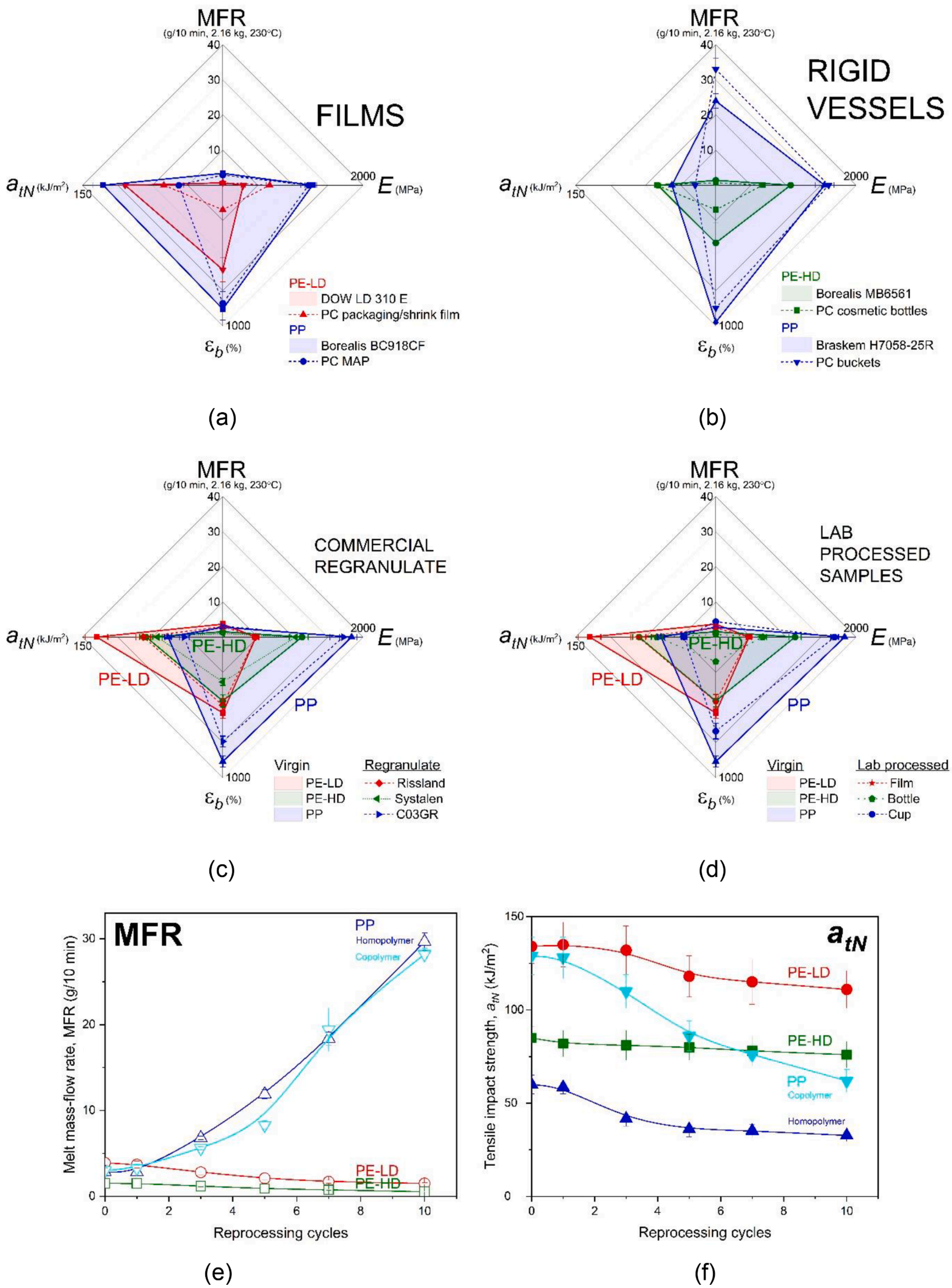


**Fig. 1.** Melt mass-flow rate MFR, elastic modulus $E$, elongation at break $\varepsilon_b$ and tensile impact strength $a_{tN}$ property profiles of virgin and post-consumer (PC) low (PE-LD) and high (PE-HD) density polyethylene and polypropylene (PP) based (a) films and (b) rigid vessels; differences between (c) commercial regranulates and (d) lab processed samples compared to virgin material; and the effect of reprocessing cycles on polymer (e) MFR and (f) $a_{tN}$.

simulation and modeling is readily available to assist in design and could be used to generate designs suitable for recycled polymers (Mulakkal et al., 2021). Reduced mechanical properties and other recycling-derived polymer degradation effects, such as altered degree of crystallinity (Vilaplana and Karlsson, 2008) can also be offset by over-engineering, which is as described an already common practice – increasing product thickness to fulfill function (Maris et al., 2014). Ironically, the concept of overengineering using recycled material does, however, necessitate the use of far more plastic than would be needed to fulfill the same function if virgin polymers were used. Notably, not all properties are affected equally by degradation and subsequently the suitability of recycled material for a product does depend on how it will be loaded e.g., flexural modulus is most important in plastic sheets (Golkaram et al., 2022). Smarter design practices could also include the separation of products into parts (supporting design for disassembly practices), each with unique functional requirements and the use of material combinations and synergies to produce multi-material structures (Abuzied et al., 2020). Suitable parts could be produced using recycled polymers while parts with more demanding functional requirements could be produced using other more suitable materials (Martínez Leal et al., 2020). Similarly, crosslinking-derived gels in films that affect their esthetic can be used as the middle layer in three layered structures to offset use of virgin material (Radusin et al., 2020).

The final important consideration for designers is the cyclic nature of the material stream and design when it comes to recycling (Cândido et al., 2011). Design from recycling is rather unsurprisingly closely linked with design for recycling. If products are designed to be more easily sorted and recycled (design for recycling) then designers will also see these benefits carry through to the design from recycling stage in the form of higher quality recycled mixtures with less contamination and superior mechanical properties, making the design from recycling process easier (Svanes et al., 2010). The same is true of diversification of the material stream. If designers want to work with certain polymers at the design from recycling stage then they obviously need to introduce those polymers into circulation during the design stage (Venkatachalam et al., 2022).

### 3.3. Co-dependent strategies for recycling industry reform

Contamination is the main problem in recycling streams (Fig. 1). Design from recycling, while critical, relies on 'fully compatible' regranulates, with $<$ 5–10% contamination. Even clever technology assisted design practices have their limits with 'limited compatibility' regranulates ($\geq$ 30% contamination) currently effectively useless for design from recycling. Achieving better quality (or even useable) recycled polymer mixtures for designers is going to depend heavily on improved sorting and recycling practices that achieve lower levels of mixture contamination (Zelenika et al., 2018). Current sorting technology typically relies on ballistic and density separation methods and near infrared (NIR) technologies, which are limited in precision and can be disrupted by product designs that utilise multiple layers or coatings that confuse infrared sensors. More sophisticated technologies utilising precision object identification, intelligent adaptive systems and machine learning algorithms are under development but again the interlinked nature of design and recycling must be emphasised: the viability of more complicated and expensive sorting and recycling technologies relies on greater market demand for recycled polymers and more applications with higher product values to compensate for the additional costs associated with generating superior recycled polymer mixtures (Fig. 2). Designers drive these changes but are reluctant to do so due to the inferior quality of recycled compared to virgin polymers (Demets et al., 2021).

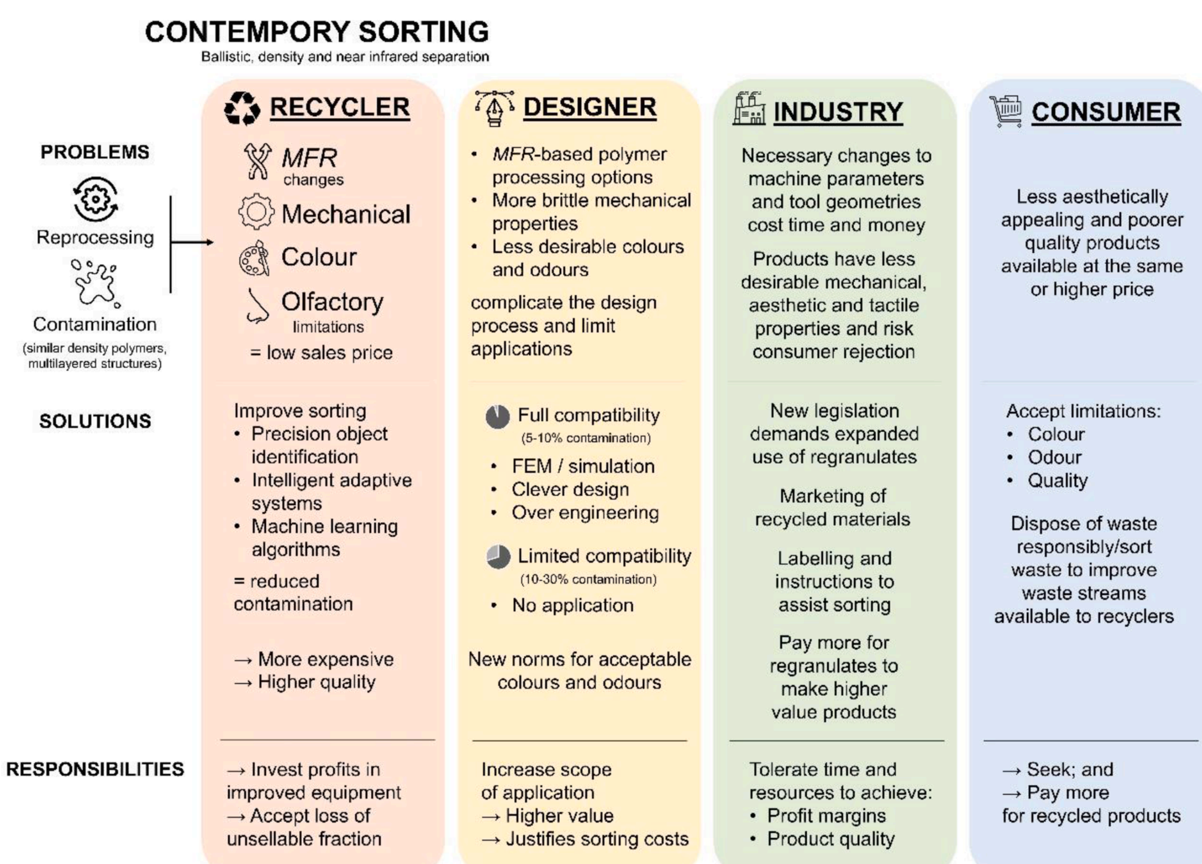


**Fig. 2.** Interlinked and co-dependent problems, solutions and responsibilities of recyclers, designers, manufacturers (industry) and consumers currently hindering design from recycling practices with opportunities for improvement through collaboration.

Future policy and legislation must focus on establishing and adopting new protocols and standards, improving operational feasibility, minimising associated administrative burdens and enforcing compliance with new legal frameworks. Recycling industry reforms targeting contamination levels $< 5\%$ can be achieved through more accurate sorting based on the tagging of products with detailed recycling information that can then be scanned on collection. This is demonstrated in the European Union-funded initiative 'Holy Grail', which is aimed at improving the efficiency of plastic waste sorting and recycling using digital watermarks and artificial intelligence, to create a "digital twin" of plastic packaging that can be read by sorting machines to identify the composition and recyclability of the packaging (Taneepanichskul et al., 2022). Other more generic options include the sorting of flakes using near infrared technologies to identify PP contamination or better, deliberate avoidance of the use of similar density polymers, such as PE and PP for the same application (design for recycling) (Martin De et al., 2010). That said, superior recycling would almost certainly change the type of recycled products available and their distribution (Tonini et al., 2022). Rather than a wide range of fairly uniformly mediocre recycled mixtures there would be a stark divide between high-quality, purer and obviously more expensive recycled mixtures and very low quality, highly contaminated mixtures of polyolefins that would potentially be without use (Jacobs et al., 2022).

On a final note, it is important to remember that design from recycling can help when dealing with contaminated and degraded materials but that we should be attempting to eliminate the root cause of the problem rather than the consequence. Our priority should be to design systems which avoid losses in quality in the first place. This is more representative of system change than product design as evidenced by PET bottle-to-bottle recycling, which largely owes its success to a clean, separate collection system in combination with appropriate product design. That said, the interconnected nature of the recycling sector and all its stakeholders, as discussed in this article, does mean that system change is reliant on a common goal and strategy acted upon by all stakeholders based on careful consideration of mutual and mutually exclusive priorities, requirements, and limitations.

## 4. Conclusion

While virgin polymers provide consistent, desirable, and customisable processing, mechanical properties and esthetic that make them popular with designers, regranulates are undisputedly more difficult to work with. High temperatures and shear forces used during recycling result in polymer degradation and subsequent change in MFR and $a_{tN}$. Polymer-based contamination in recycling streams and deliberate use of multilayer packaging affect MFR, $E$, $a_{tN}$ and $\varepsilon_b$, meaning regranulates may fail to meet the functional requirements of many applications. PE-LD regranulates exhibit considerable differences in MFR and $a_{tN}$ to virgin material. PE-HD and PP regranulates also notably differ from virgin material in MFR $E$, $a_{tN}$ and $\varepsilon_b$. Current sorting technologies cannot effectively combat these issues and in many cases the use of additives may not be desired due to risk of leakage. More advanced technologies are being developed; however, the future of recycling lies in the hands of designers, industry and consumers: the key players in a vicious circle. Regranulate value must be high enough to warrant investment in new sorting and processing technology, which is only the case if designers actually use regranulates. Better quality regranulates depend on reduced contamination, which can be aided by designing products to be more easily disassembled and sorted in the first place. Polymers that designers want to work with need to be introduced into circulation during design if they are to reappear later in the material life cycle. Industry must be willing to manage expectations and tolerance for time and human resources required to achieve optimal processing conditions, profit margins and product quality when working with recycled materials. Consumers must be willing to trade product esthetic for sustainability. The scope of application, value and interest in recycled material must increase for investment and advances in recycling. This can be achieved by clever design practices, finite element analysis, simulation, and modeling to use regranulates for interesting new products, not bin liners.

## CRediT authorship contribution statement

M.P.J. and V-M.A. conceptualised the manuscript. J.R and M.S. completed the experimental work. M.P.J visualised the data. All authors contributed to formal analysis, writing of the original draft and review and editing.

## 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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