THE POTENTIAL IMPACTS OF THE USE OF RECYCLED PACKAGING ON FOOD QUALITY

Authors **Patrick Silcock and Phil Bremer**

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New Zealand Food Safety Science & Research Centre
Hopkirk Institute, Massey University, Tennant Drive, Palmerston North 4442
Phone: +64 (0) 6 356 9099

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Scientific Executive Summary

Packaging serves many functions which can be grouped into four broad categories: containment, protection, convenience and communication. These functions relate not only to primary packaging (in contact with product) but also secondary (bundles and protect primary packaging) and tertiary packaging (bundles secondary packaging to allow mass transport). The modern food supply is dependent upon food packaging to maintain food safety and quality as well as minimise food waste and allow transportation around the globe. To ensure sustainable use of resources pressure exists to recycle packaging materials, including polymeric packaging.

Due to the lower overall energy use and lower emission of global warming related gases mechanical recycling is the most suitable and preferred recycling pathway for relatively clean and homogenous waste polymer streams. This review will focus on the potential effects of the mechanical recycling of polymers and paper/paper board on food quality.

Factors that may decrease the functionality of recycled packaging, including the quality (and safety) of its contents, include: the presence of non-intentionally added substances (NIAS); the occurrence of intentionally added substances (IAS), such as pigments used for printing, at concentrations higher than in virgin packaging; the presence of contaminating polymers and the extent of polymer degradation in the recycled material. The long-term stability of the food or beverage may be also affected by the presence of primary and secondary oxidation products.

For both polymers and paper/paperboard the impact the recycled content on product quality can be measured and the suitability of the packaging for a given application assessed.

Many analytical techniques are available to characterise the recycling-induced changes, however, attention should focus on properties that directly reflect product performance. This means focusing on the relevant mechanical properties, presence of odours and visual defects. When considering how recycled packaging may influence food quality key questions are: will the packaging protect and contain the enclosed product?; and will the packaging give rise to volatiles (off odours/flavours) which will adversely affect its contents? These questions suggest that technologists should focus on mechanical and sensory-based tests already established by standards associations (Tables 9 and 10).

Mechanical tests are required as the large variation in polymer sub-types that exist due to polymer synthesis-induced variation in polymer molecular weight, degree of branching, branch lengths and crosslinking gives rise to large variations in mechanical properties that make it difficult to draw general conclusions on the performance of recycled polymers compared to virgin polymers.

Sensory tests are recommended as they can be used to detect a wide range of odour/flavour defects (in a nonselective manner) in a product more easily than VOC analysis methods such as GC-MS. In addition, sensory based, visual tests, such as for colour, are well established QA tools.

It is important to note that quality concerns associated with the migration of substances from packaging into a food or beverage or from a food or beverage into packaging, are strongly influenced by the interactions of components in the food with the packaging material. Packaging factors that impact on the potential for and the rate of migration of substances include the concentration of the substance, and its polarity and size, with smaller molecules generally migrating faster than larger molecules. Inherent properties of the packaging material that impact on the migration of substances include its crystallinity and porosity. Properties of the finished packaging include its surface structure, thickness and the surface area of the product relative to the packaging. Environmental storage conditions such as temperature, humidity, and exposure time influence both the rate and extend of migration as can the composition of the product and interactions between the various components in the system.

Given the complexity of the interactions between recycled packaging and its contents and how this may impact on product quality (and safety), the risks associated with the use of recycled packaging are specific to the packaging material, the product and its storage conditions

This complexity also means that suitable mitigation process requires a good understanding of the recycled packaging / product “system” and the development of a quality framework that identifies critical packaging parameters and generates acceptable quality limits (taking the form of a product specification) that can be used to control the identified risks.

A quality framework that is suggested to be used is Safe-by-design, which is based upon a failure modes, effects and criticality analysis (FMECA) risk model combined with the recycling quality factor approach developed by Demets et al. (2021), which together allow the identification and quantification of risk and the generation of packaging quality limits that can be used as specifications. To assist the development of this framework resources are available (Tables 11 and 12).

In addition, food companies, need to confirm that their recycled packaging producers have suitable risk assessment-based controls in place through-out their recycling and production process which ensure that agreed recycled packaging specifications are met. If there is concern that, recycled packaging specifications may not be possible to be consistently met, or risks suitability mitigated, or as a sensible added level of assurance, testing regimes should be implemented to ensure that the recycled packaging is fit for purpose.

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1.0 INTRODUCTION

Food packaging is not a new phenomenon rather it has existed in different forms for millennia. The development of modern packaging systems which enhanced the preservation, quality maintenance and transport of food was integral to the development of the modern food system. The selection of an appropriate packaging system is complex and despite this still 30 to 50% of food waste is still believed to be due to inadequate storage (Sarker, 2020). The early industrial food supply relied on glass and tin cans to achieve a suitably packaged product. Since the 1940s, "plastic" packaging has become increasingly important and in 2019 the value of the global plastics market was estimated at USD568.9 billion (Debeaufort, Galić, Kurek, Benbettaieb, & Ščetar, 2021). This reliance on plastics is due to them being relatively inexpensive, lightweight, easily moulded (increases packaging efficiency) and flexible. However, plastic packaging does have the disadvantage of being susceptible to puncturing and it possesses relatively poor recyclability.

Terminology exists around plastics and packaging and some of the key terms are outlined below.

Polymers: long chains of repeating units forming a backbone, may contain chains of varying length off the backbone (branches) or crosslinks.

Polymeric packaging: polymers with the addition of low molecular weight processing aids.

Intentionally added substances (IAS): substances added for a technical reason to the packaging e.g., modify the polymer functionality or stabilise the polymeric formulation

Non intentionally added substances (NIAS): substances that have unintentionally made their way into food packaging.

Primary packaging: packaging in contact with food, typically for sale to consumer

Secondary packaging: this bundles the primary packs to protect the integrity of the primary packaging

Tertiary packaging: this holds together the secondary packaging to allow mass transport.

Recycling refers to a number of processes and a number of terminologies are used to classify the different recycling processes. Unfortunately, a universal agreement of terminology use does not exist though the most common appear to be:

Primary recycling is closed loop recycling, typically involving re-extrusion of polymer waste, usually by industries reprocessing waste from their production process;

Secondary recycling to describe mechanical recycling, where a sorted waste polymer stream is washed, stabilised and reused alone or with virgin polymer;

Tertiary recycling describes feedstock or chemical recycling where plastic waste is chemically cracked to monomers/petrochemical products and used to generate polymers; and

Quaternary recycling, where the waste polymer is incinerated to generate energy (Ncube, Ude, Ogunmuyiwa, Zulkifli, & Beas, 2021).

Primary recycling may also be associated with reuse in a product that is the same quality as the original materials, which is similar to above and secondary recycling defined as a process used to generate a lower value product than the original materials (Matthews, Moran, & Jaiswal, 2021).

For relatively clean and homogenous waste polymer streams mechanical recycling is the most suitable and preferred recycling pathway for polymers/packaging in waste streams. This due to its lower overall energy use and lower emission of global warming related gases. This review will focus on the potential effects of mechanical recycling of polymers and paper/paper board on food quality.

2.0 FUNCTIONS OF PACKAGING

Packaging serves many functions however these can be grouped into four broad categories: containment, protection, convenience and communication (Debeaufort et al., 2021; Sarker, 2020). These functions relate not only to primary packaging but also secondary and tertiary packaging.

Containment. Obviously, packaging must contain the food product to allow transport from the manufacturer to consumer, preventing losses and mixing, while maintaining the shape of the food product, e.g., cakes. Containment can also cover some social/cultural requirements e.g., halal/kosher.

Protection. Packaging must protect food from the environment. Most simply, it should provide physical protection from bruising for products like fruit and vegetables. It needs to provide protection from physical stresses like moisture loss which can cause product shrinkage, weight loss or texture changes like loss of crispness in lettuce. Conversely, insufficient protection can result in moisture gain resulting in loss of crunchiness in nuts or increases in water activity, which could allow microbial growth.

The barrier properties should be sufficient to prevent or limit oxygen transmission into oxygen sensitive foods or the transmission of flavour through the packaging. Flavour loss due to scalping by the packaging should be avoided and the packaging should not allow the transfer of substances that will promote degradative changes. It should also protect the contained product from light-induced degradation reactions. Packaging integrity must be maintained to prevent the ingress of microorganisms or other biological contamination, e.g., insects.

Convenience. Packaging contains features that allow consumers to see product and enable fast preparation while maintaining quality. It also may possess demographic specific features, e.g., easy opening features for elderly or child protective features.

Communication. Packaging, including secondary and tertiary packaging, enable a wide range of messages to be conveyed including product messages (marketing), product information (bar codes, storage and cooking instructions, price, etc), stock information, transport details. It communicates legal requirements, including shelf life, nutrient panel, product weight and ingredient list.

In addition to these functions packaging should be easily sourced, cost effective and meet environmental goals and/or restrictions.

The implementation of these functions does not preclude recycling however the impact of recycling on these functions needs to be considered.

3.0 PACKAGING SUSTAINABILITY

Packaging sustainability considerations are multifaceted, where carbon dioxide, energy inputs, resource inputs, transport and disposal and/or recyclability all need to be considered. During manufacture, glass requires 1.06 kg CO_2/kg bottle material with an energy consumption of 10.5 MJ/kg bottle material. In contrast the manufacture of PET only requires 0.49 kg CO_2/kg bottle material and an energy consumption of 0.6 MJ/kg bottle material to manufacture. The environment impact of transport (both empty and once packed for sale) per unit is much lower for PET than glass. Energy costs are substantially reduced in the recycling of both glass and PET though PET still requires less energy than glass (Sarker, 2020). However, due to difficulties with disposal of polymeric materials, in the near future packaging materials will need to have high recycled polymer contents (Antonopoulos, Faraca, & Tonini, 2021; Eriksen & Astrup, 2019; Eriksen, Christiansen, Daugaard, & Astrup, 2019; Matthews et al., 2021; Roosen et al., 2022).

The food industry has been applying the three Rs, reuse, reduce and recycle to food packaging. Packaging manufacturers successfully reduced bottle weights by reducing the wall thickness. Though due to functional requirements a minimum wall thickness exists and for PET bottles this limit has been reached (Sarker, 2020).

The recyclability of plastics varies considerable with Poly(ethylene terephthalate (PET), polyethylene (PE) and polypropylene (PP) considered readily recyclable, with polystyrene (PS), polyvinyl chloride (PVC) and polyurethane (PUR) being considered less recyclable and multiple layer films are also problematic. The current recycling rates vary widely around the World with Europe and in particular Germany leading efforts to recycle packaging.

Future trends and political pressure in recyclable polymeric packaging would appear to focus on design of packaging and separation of polymers. Looking to improving separation of polymers by ensuring polymer sorting operations are able to effectively remove lids and labels of unintended polymers. Taking this further, source separation of food and non-food packaging is being suggested.

An emerging trend is improving the recyclability of packaging through improved design, i.e., "design for recycling" (Antonopoulos et al., 2021; Eriksen & Astrup, 2019; Eriksen et al., 2019; Matthews et al., 2021; Roosen et al., 2022). Examples of the changes being promoted involves restrictions around PET, PE and PP so that no black or multipolymer packaging is allowed, restrictions around what polymers may be used in food packaging, a move towards the design of less complex polymer films containing only layers that can be easily differentiated during sorting and less complex polymeric formulations, e.g., restricting the addition of colours to aid the use of recycled polymers. Potentially, these changes could have a bigger impact on some packaging functionality than the recycling process, itself.

4.0 PACKAGING MATERIALS

4.1 Paper and paperboard

In 2018, 420 million tons of paper-based packaging was used across three product sub-categories: paper packaging, flat cardboard and corrugated cardboard. Most paper-based packaging is used as secondary packaging.

Paper and paperboard are typically produced from cotton plants or soft wood trees, e.g., pine. Softwood is favoured over hardwood as the resulting pulp possesses long cellulose fibres (about 3mm length), which confer high mechanical strength to the finished paper/paperboard (Debeaufort et al., 2021; Sarker, 2020). Wood may be pulped by mechanical, thermomechanical, chemi-mechanical pulping or chemical pulping. Most pulp is produced using chemical pulping and uses either Kraft process (alkaline) or Acid process (only soft wood) and accounts for nearly 90% of all paper produced. Most virgin pulp is derived from sawmill waste and recycled paper makes up 40 – 45% of pulp fibres, forming an important source of pulp fibres (Debeaufort et al., 2021; Sarker, 2020). The recycled paper pulping process is less intensive requiring only hydration and agitation to recover the secondary fibres though hot water and chemicals may be added to assist extraction. Wire filtration is used to remove debris and impurities. The majority of packaging is provided by Kraft pulp though some mechanical pulps are used as corrugating medium (Debeaufort et al., 2021; Sarker, 2020).

Pulps may then be bleached or thinned to remove lignan, where an important secondary goal is to limit cellulose degradation. Recycled pulp is also bleached but this is to remove ink. Pulp along with additives, whose functions include pH adjustment, water repellency, aiding binding, increasing mechanical strength and aiding processing, are converted into paper or paper board mostly using the Fourdrinier process. When the final grammage (or fibre density) is less than 250 $g.m^2$ the product is categorised as paper and when greater than 250 $g.m^2$ it is categorised as paperboard/cardboard. In addition to grammage, pulp fibre orientation is important and three-dimensional orientation desirable as this provides the best strength (Debeaufort et al., 2021; Sarker, 2020).

The physicochemical and mechanical properties of paper/paperboard are dependent upon the chemical composition of the paper pulp and physical properties of the dried paper fibres. These properties change with successive recycling (Debeaufort et al., 2021; Sarker, 2020) . Paper and paperboard can be recycled up to seven times before being required to be mixed with new fibres/virgin pulp and the recycled content is mostly directed to paper and cardboard packaging applications. Recycled fibres are used to produce white lined chip board, which are used for packaging dry products, breakfast cereals and frozen or chilled products however due to recycled fibre content it is generally not used in contact with food. The other major food related application is corrugated paperboard, which contains 89% recycled fibres and has the highest rate of recycling.

4.2 Polymers

The most important polymers used in food packaging are PE, PP and PET. PE and PP are both polyolefins that are derived from an alkene repeating unit that has a general formula of C_nH_{2n}.

4.2.1 Polyethylene

Based on value PE has the largest share of the plastics market, at 25.7% (Debeaufort et al., 2021; Sarker, 2020). PE is produced from ethylene and consist of about eight sub-types that vary in density due to differences in molecular weight, degree of branching and/or cross linking (Sarker, 2020). PE is popular as it is easily processed, low cost, resistant to degradation from to acids, bases, oxidants or reducing agents and possesses good barrier properties. The most popular forms are high density polyethylene (HDPE), low density polyethylene (LDPE), and linear low density polyethylene (LLDPE).

LDPE has many branches that may be short or long. The branching reduces the polymer density resulting in a polymer that is soft, flexible, stretchable, has good clarity, good heat sealability and low crystallinity (40 – 55%). Typical properties of LDPE suitable for moulding and films are shown Table 1.

Table 1. Variation in selected properties of LDPE that is suitable for either molded or film applications.

Properties	**LDPE Molded**	**LDPE Film Grade**
Density	0.910 - 0.980 g/cc	0.915 - 1.00 g/cc
Water Absorption	0.0001	0.0001
Water Vapor Transmission	18.6 g/m²/day	0.990 - 16.0 g/m²/day
Oxygen Transmission	197 - 200 cc-mm/m²-24hr-atm	2000 - 6820 cc/m²/day
Viscosity	21000 - 305000 cP (@ 190	
Melt Flow	0.250 - 2300 g/10 min	0.120 - 65.0 g/10 min
Tensile Strength, Ultimate	2.80 - 56.5 MPa	7.00 - 34.5 MPa
Tensile Strength, Yield	7.00 - 64.8 MPa	8.00 - 22.0 MPa
Modulus of Elasticity	0.0900 - 0.449 GPa	0.140 - 0.480 GPa
Flexural Yield Strength	9.03 - 932 MPa	160 - 290 MPa
Flexural Modulus	0.0248 - 1.45 GPa	0.124 - 0.690 GPa

Tensile Impact Strength	160 - 315 kJ/m²	
Torsional Stiffness	159 - 1030 MPa	
Melting Point	95.0 - 327 °C	97.8 - 218 °C
Crystallization Temperature		95.0 - 104 °C
Brittleness Temperature	-87.0 - 0.000 °C	-76.0 - -32.0 °C
Haze	3.30 - 20.0 %	1.10 - 55.0 %
Gloss	8.50 - 83.0 %	8.20 - 135 %
Transmission, Visible	50.0 - 95.0 %	55.0 - 90.0 %
Processing Temperature	82.2 - 260 °C	140 - 400 °C
Melt Temperature	105 - 329 °C	110 - 260 °C

HDPE is linear with few branches resulting in high crystallinity (70 – 80%) and a polymer that is hazy and strong. Compared to LDPE the crystals in HDPE are larger and more uniform. HDPE compared to LDPE typically has a higher melting point, greater tensile strength, less permeable and is harder. Typical properties of HDPE suitable for injection molding and blow molding are shown in Table 2.

Table 2. Variation in selected properties of HDPE that is suitable for either injection molded or blow molded applications

Properties	**HDPE - Injection Molded**	**HDPE - Blow Molding**
Density	0.924 - 0.995 g/cc	0.938 - 1.06 g/cc
Water Absorption	0.000 - 0.0700 %	0.0001
Viscosity	32000 - 200000 cP (@ 190 °C)	
Viscosity Test	280 - 3800 cm³/g	
Melt Flow	0.0250 - 1610 g/10 min	0.0100 - 55.0 g/10 min
Tensile Strength, Ultimate	7.60 - 43.0 MPa	11.7 - 44.0 MPa
Tensile Strength, Yield	11.0 - 43.0 MPa	15.2 - 43.0 MPa
Modulus of Elasticity	0.565 - 1.50 GPa	0.650 - 4.30 GPa
Flexural Yield Strength	13.8 - 75.8 MPa	
Flexural Modulus	0.280 - 1.86 GPa	0.586 - 2.62 GPa
Tensile Impact		53.4 - 131 J/cm
Compressive Yield Strength	4.00 - 23.0 MPa	
Melting Point	118 - 137 °C	26.0 - 139 °C
Crystallization Temperature	108 - 120 °C	112 - 118 °C
Brittleness Temperature	-180 - 76.0 °C	-118 - 82.2 °C
Yellow Index	-1.04	
Processing Temperature	82.2 - 280 °C	171 - 249 °C
Melt Temperature	130 - 280 °C	130 - 280 °C

LLDPE is a copolymer, containing 1 – 10% alkene co-monomers. It is a long linear polymer with many short side chains. The side chains are shorter and more frequent than LDPE resulting in a higher degree of crystallinity. Like LDPE it has good clarity and good heat sealability but is strong and tough like HDPE (Piergiovanni & Limbo, 2016). It produces films that are thinner and have better stress crack resistance than HDPE and LDPE. Typical properties of LLDPE suitable for extrusion and film manufacture are shown in Table 3.

Table 3. Variation in selected properties of LLDPE that is suitable for either extrusion or film applications

Physical Properties	**LLDPE - Extrusion**	**LLDPE - Film**
Density	0.906 - 1.01 g/cc	0.900 - 1.50 g/cc
Water Vapor Transmission		4.70 - 14.0 g/m²/day
Water Vapor Transmission (38.0 - 38.0 °C)	15.0 - 15.0 g/m²/day	6.00 - 30.0 g/m²/day
Oxygen Transmission		0.720 - 236 cc-mm/m²-24hr-atm
Melt Flow	0.110 - 48.0 g/10 min	0.200 - 123 g/10 min
Tensile Strength, Ultimate	9.00 - 28.0 MPa	7.45 - 43.0 MPa
Tensile Strength, Yield	7.58 - 20.0 MPa	9.00 - 22.1 MPa
Modulus of Elasticity		0.0110 - 0.413 GPa
Flexural Modulus	0.248 - 0.750 GPa	0.140 - 0.920 GPa
Melting Point	119 - 127 °C	87.0 - 130 °C
Crystallization Temperature		104 - 115 °C
Brittleness Temperature	-76.0 - -42.0 °C	-90.0 - -60.0 °C
Haze	1.30 - 43.0 %	0.500 - 80.0 %
Gloss	19.0 - 102 %	3.20 - 155 %
Transmission, Visible		2.00 - 90.0 %
Melt Temperature	149 - 325 °C	123 - 450 °C

4.2.2 Polypropylene

PP has a high crystallinity that is between LDPE and HDPE, very low density (0.9g/cm^3) and good clarity. It can either be orientated (axially or biaxially) or non-orientated, with orientated pp having increased strength, stiffness and better gas barrier properties but poorer heat sealability (Piergiovanni & Limbo, 2016). It has a higher melting temperature compared to PE and as such is more frequently used for higher temperature food packaging applications, like retort packaging. Typical properties of PP suitable for extrusion and film manufacture are shown in Table 4.

Table 4. Variation in selected properties of PP that is suitable for either extrusion or film applications

Properties	Polypropylene - Extrusion	Polypropylene - Film
Density	0.886 - 1.84 g/cc	0.886 - 1.46 g/cc
Water Absorption	0.000 - 0.0300 %	
Water Vapor Transmission	14.0 - 14.0 g/m²/day (37.8 °C)	0.0497 - 1.55 g/m²/day
Oxygen Transmission Rate		0.0931 - 2100 cc/m²/day
Melt Flow	0.250 - 1850 g/10 min	
Tensile Strength, Ultimate	5.78 - 460 MPa	18.8 - 152 MPa
Tensile Strength, Yield	19.0 - 45.0 MPa	3.38 - 42.1 MPa
Flexural Yield Strength	25.0 - 58.8 MPa	0.700 - 7.51 GPa
Flexural Modulus	0.586 - 3.20 GPa	0.450 - 2.28 GPa
Compressive Yield Strength	4.00 - 14.0 MPa	
Melting Point	130 - 174 °C	119 - 170 °C
Haze	2.00 - 46.0 %	0.100 - 90.0 %
Gloss	38.0 - 113 %	3.00 - 145 %
Transmission, Visible	18.5 - 90.0 %	0.200 - 90.0 %
Processing Temperature	120 - 268 °C	
Melt Temperature	160 - 330 °C	182 - 274 °C

4.2.3 Poly(ethylene terephthalate) (PET)

PET is the important polyester in food packaging where it is used mainly for films and blow molded bottles. It is a semi-crystalline polymer though in packaging can be either amorphous (very transparent) or crystalline (opaque and more heat resistant) (Piergiovanni & Limbo, 2016). Typical properties of PET are shown in Table 5.

Table 5. Variation in selected properties of PET

Properties	Range of values
Density	0.0700 - 1.45 g/cc
Water Absorption	0.0500 - 0.800 %
Water Vapor Transmission	0.490 - 6.00 g/m²/day
Oxygen Transmission	5.10 - 23.0 cc-mm/m²-24hr-atm
Viscosity Test	62.0 - 86.0 cm³/g
Melt Flow	3.50 - 65.0 g/10 min
Acetaldehyde	0.100 - 3.00 ppm
Tensile Strength, Ultimate	22.0 - 95.0 MPa
Tensile Strength, Yield	5.52 - 90.0 MPa
Modulus of Elasticity	1.57 - 5.20 GPa
Flexural Yield Strength	55.3 - 135 MPa
Flexural Modulus	0.138 - 3.50 GPa
Compressive Yield Strength	20.0 - 109 MPa
Melting Point	200 - 260 °C
Glass Transition Temp, Tg	70.0 - 78.0 °C
Haze	0.300 - 40.0 %
Gloss	108 - 166 %
Transmission, Visible	67.0 - 99.0 %
Processing Temperature	90.0 - 300 °C
Melt Temperature	120 - 295 °C

5.0 EFFECT ON RECYCLING PROCESS ON PACKAGING QUALITY

Polymer quality has largely been ignored and investigations around recycled polymer quality has largely focused on the possible presence of contaminants, with a safety perspective more so than a quality/performance in-use perspective (Demets et al., 2021).

The development of ambitious recycled plastic content targets has ignored the technical substitutability of virgin polymers with recycled polymers, i.e., does the functionality of the recycled polymer allow it to replace virgin polymer in a desired application and how much virgin polymer can be replaced. In essence the substitutability can be interpreted as a proxy for quality. However, the quality question has focused on the polymer rather than having a food focus and the substitutability is largely focused on life cycle analyses (LCA). The focus on LCA makes the results less relevant when assessing their impact on packaging function in-use.

A number of studies (Demets et al., 2021; Eriksen et al., 2019; Huysman, De Schaepmeester, Ragaert, Dewulf, & De Meester, 2017; Rigamonti, Niero, Haupt, Grosso, & Judl, 2018) have developed differing approaches to the addressing the impact of recycling on polymer quality. Only

Rigamonti et al. (2018) and Demets et al. 2021) considered technical requirements of the polymers from an application perspective. The approach of (Rigamonti et al. (2018) based quality on a single main technical property, whereas Demets et al. (2021) used a number of processing and technical parameters. The approach of Demets et al. (2021) was also broader considering quality impact on product design as well as LCA, making it more relevant to packaging end users. However, this approach ignored the impact of VOCs on technical functionality. Considering the safety and quality of reused PET bottles Bovee, deKruijf and Barendsz (1997) took a different approach proposing the use of Hazard Analysis Critical Control Point plans (HCAAP) to identify and control safety and quality hazards. Using a similar approach, the Safe-by-design packaging development used Failure Modes, Effects and Criticality Analysis (FMECA) as the basis for ensuring safety Nguyen, Goujon, Sauvegrain and Vitrac (2013). Though the Safe-by-design packaging development version of FMECA is concerned primarily with migration of toxic compounds it is designed to predict migration of VOC, which could include taints.

To understand the effect of recycling on polymer quality it is important to recognise that the polymer synthesis process results in different subtypes of the same polymer that vary in polymer chain length, degrees of branching and degrees of crosslinking. These different subtypes, typically referred to as grades, possess different processing and mechanical properties which are defined in their technical data sheets (TDS). For an example of the types of data held in TDS see two examples of LLDPE in appendix 1.

Unlike virgin polymers or polymer blends recycled polymers do not come with technical data sheets (Demets et al., 2021). Even if during recycling perfect separation into single polymer types occur, separation of the different grades is not feasible, e.g., recycled PE may be a blend of LLDPE, LDPE and/or HDPE with different degrees of branching and crosslinking. This means the technical properties will not be the same as the virgin polymer for most recycled polymers. Though the mechanical properties of virgin polymer for most recycled polymers may be in the same range the mean elastic modulus may be up to 14% lower for HDPE and the minimum elastic modulus and tensile strength may be as much 91% and 57% lower than the virgin polymer types, respectively (table 6) (Demets et al., 2021). This broad range in values mean that it is not possible to make general conclusions on how recycled polymers will perform compared to virgin polymers.

Table 6. Mechanical properties of recycled polymers expressed as percentage of virgin polymer*

Polymer type	**Minimum elastic modulus**	**Mean elastic modulus**	**Minimum tensile strength**
L(L)DPE	81%	NA	NA
HDPE	91%	14%	NA
PP	59%	3%	15%
MPO**	67% (cf HDPE)	NA	57% (cf HDPE)
PET	64%	9%	30%

* Values extracted from a combined 96 studies on the effect of recycling on polymer technical properties by (Demets et al., 2021)

** MPO - Mixed polyolefin: this is a recycled polymer mixture containing differing proportions of LLDPE, LDPE, HDPE and PP based on the composition of polymer mixture being recycled

Both IAS and NIAS may contribute VOC that impact on the quality of food packaging. When considering the potential of VOC to contribute to off-odours it is the combination of odour threshold, their concentration and their ability to be transferred into the food that are important. Though a number of studies have been carried out on the VOC present in recycled polymers (Chen et al., 2020; Groening, Hakkarainen, & Albertsson, 2008; Marc & Zabiegala, 2017; Roosen et al., 2022; Q.-Z. Su, Vera, Nerín, Lin, & Zhong, 2021; Vilaplana, Martinez-Sanz, Ribes-Greus, & Karlsson, 2010), few studies have investigated the odour activity of the compounds present. In recycled PP, nine compounds consisting of branched alkanes, 2-chlorophenyloxiarane, diethyl phthlate, benzophenone and glycerol were found by gas chromatography mass spectrometry/ olfactometry (GC-MS/O) to be in present at a sufficient concentration as to be odour active, with benzophenone the most intense odour (Paiva et al., 2021). Using a grouping technique based on the compound odour description the odour of the recycled PPs were described as plastic-like. Benzophenone is widely present in packaging as it is used as a photo-initiator and in inks and coatings as well and its presence in paper and polymers has been reported by a number of other studies (Blanco-Zubiaguirre et al., 2021; Elizalde, Aparicio, & Rincón, 2020; Mariani, Giannetti, Mannino, & Ceccarelli, 2015). Odour active compounds that may be derived from food have also been detected in recycled polymers (Strangl, Fell, Schlummer, Maeurer, & Buettner, 2017; Strangl, Ortner, & Buettner, 2019; Strangl, Ortner, Fell, Ginzinger, & Buettner, 2020; Strangl, Schlummer, Maeurer, & Buettner, 2018). Odour active compounds present in packaging are not limited to recycled polymers, in a small study comparing 4 PP and 2 PE bags the major odour-active compounds were found to be acetic acid, propanoic acid, butanoic acid, xylene, octanol, octanal and nonanal (Vera, Canellas, & Nerin, 2020). The importance of each of these compounds varied in a manner consistent with the sensory odour descriptions, which were either plastic-like and rancid/green; plastic-like and fat/soap; or plastic-like and vinegar. These compounds were found to be transferred to tennax (as a model simulant) in sufficient concentrations to remain odour active. This data suggests that all packaging poses risks of inducing a product taint not just recycled packaging.

The VOCs in paper and cardboard have been more extensively studied. The major compounds emitted by recycled paper and paperboard have been reported as 1-octen-3ol, 1-octen-3-one, 2-nonenal, butanoic acid and 3-methyl butanoic acid (Czerny, 2017; Czerny & Buettner, 2009; Ziegleder, 2001). The aldehydes, ketones and alcohols have been attributed to lipid oxidation of unsaturated fatty acids from wood rosin and short chain fatty acids owing to microbial growth. Both of these reactions are not limited to the recycling process and can occur in virgin cardboard (Ziegleder, 2001). As Czerny (2017) notes even fresh cardboard has an odour. In addition, the discrimination by multivariate data (MVD) models of different paper mills producing virgin and recycled cardboard based on the cardboards' VOCs was dependent upon subtle differences in VOC concentrations (Langford, Du Bruyn, & Padayachee, 2021). Suggesting that all compounds were present in most samples though the VOC concentrations differed between samples. The implication of this is that a threshold concentration of VOC(s) is required for an off-odour to occur. Based on results from an instrumental analysis this threshold concentration is difficult to define. This also holds true for polymeric packaging and in addition it is how the compounds affect the food that is important.

6.0 MEASURING QUALITY CHANGES IN RECYCLED POLYMERS

Overall, when considering the effect of mechanical recycling on recycled polymer quality three quality parameters or effects need to be considered.

1. Presence of contaminating polymers in the recycled polymer composition

The presence of different polymer types usually gives rise to incompatibilities (Roosen et al., 2022). The incompatibility results in non-homogeneity within the polymer and at the interface between the incompatible polymers poor adhesion between the different polymers can lead to inferior visual and mechanical properties. Though it is not only the mixing of different polymer types that can give rise to problems as the same polymer used for different packaging applications e.g., injection moulding and extrusion blow moulding have different rheological requirements and cannot be used interchangeably (Demets et al., 2021; Eriksen et al., 2019). Both these effects can lead to visual and mechanical defects.

2. Degree of polymer degradation

Thermomechanical degradation occurring during mechanical recycling and reprocessing of recycled polymers leads to chemical and morphological alterations that can lead to mechanical and rheological defects.

3. The presence of low molecular weight compounds

Low molecular weight compounds can be present due to contamination, addition of additives and/or production of degradation products. Beyond safety, the likely impact of low molecular weight compounds is an adverse sensory impact, most likely a flavour or odour impact.

Together these three factors lead to modified mechanical properties and stability. Long term stability is further compromised by the increased concentration of oxidised components in the recycled polymeric packaging.

In paper and paperboard, recycling results in reductions in the packaging's apparent density, tensile and bursting strengths, which are dependent upon inter-fibre bonding strength and individual fibre strength (Wistara & Young, 1999). These reductions can be mitigated by beating and refining, chemical treatment, blending with virgin fibres and fibre fractionation. Recycled paper and paperboard may also contain volatile low molecular weight compounds.

6.1 Polymer contamination and degradation

A wide range of techniques have been used to detect polymer contamination in recycled packaging (table 7), with the most common being differential scanning calorimetry (DSC), thermal gravimetric analysis (TGA), Fourier-transform infrared spectroscopy (FTIR), NIR spectroscopy or Raman spectroscopy.

The limit of detection for the presence of contaminating polymers ranges from 0.01 to 3% depending upon the polymers present and the analytical technique used (Vilaplana & Karlsson, 2008).

Non-polymer contaminants like soil, metal particles, adhesives, etc can be detected using TGA. TGA can also provide information on the amount of moisture, VOCs, additive and fillers that are present. Though TGA will not allow identification of any components present, just the proportion.

A combination of microscopic and macroscopic techniques can be used to determine the extent of degradation, with the method used depending upon the type of degradation that needs to be characterised (table 7).

Table 7. Analytical techniques suitable to characterise polymers composition and properties.

Parameter	**Analytical technique**
Chemical functional groups	vibrational spectroscopy, NMR
Crystallinity, thermal properties	thermal analyses, x-ray diffraction
Morphology	SEM, TEM
Mechanical properties	mechanical testing
Molecular weight distribution	size exclusion chromatography, mass spectrometry
Degradation products and	Chromatography techniques

Ultimately when considering both contaminating polymers and thermo-degradative changes rheological or mechanical properties are most important and useful to know as these are a direct measure of product performance. From a virgin packaging manufacturing perspective, the melt flow index (MFI) is of particular importance as the values vary depending upon the polymer processing technique being used (table 8) (Eriksen et al., 2019). However, for recycled materials MFI use is limited as it cannot be measured in line. In the case of rPET intrinsic viscosity (IV) is the key parameter (Brouwer, Alvarado Chacon, & Thoden van Velzen, 2020; Eriksen et al., 2019). PET bottles in which high intrinsic viscosity (IV) values were measured showed lower chances of environmental stress cracking (ESC) than PET bottles with low IV values (Chacon, Brouwer, & van Velzen, 2020).

However, from a finished packaging performance perspective the mechanical parameters are of greater importance and of interest are tensile strength, impact strength, flexibility modulus and percent elongation (Demets et al., 2021). Clarity and the extent of inclusions are also good indicators of the performance of rPET.

Table 8. Melt flow index requirements for different processes.

Processing technique	Melt flow index (MFI)
Extrusion	0 – 1
Blow moulding	0.3 – 5
Injection moulding	5 – 50
Injection moulding thin-walled products	> 50

Source: (Eriksen et al., 2019)

From this perspective, mechanical properties should be clearly specified based on the application requirements and where necessary other techniques can be used to understand the degree of degradation and mechanism of degradation. Measures may include impact stability and drop height tests and will vary depending upon the packaging material and application. For example, in high impact polystyrene elongation at breaking is more important than modulus, which does not change or slightly increases upon recycling (Vilaplana, Ribes-Greus, & Karlsson, 2006)

6.2 Oxidative stability

The thermo-oxidative stability of recycled polymers is important to know as it affects package stability in-use. TGA can be used to measure thermal stability and using dynamic and isothermal methods information on the degradation mechanism can be obtained.

The oxidation induction time (OIT) and oxidation temperature (T_{ox}) offer information on the long term stability of the packaging material or packaging and whether further stabilisation of the recycled packaging is required (Vilaplana & Karlsson, 2008). These are usually determined by DSC or sometimes TGA. However, both TGA and DSC can only use very small samples sizes, which can make representative sampling difficult. In addition, sample shape and heating rate may also introduce significant variability (Rosa, Sarti, Mei, Filho, & Silveira, 2000). Given these disadvantages the carbonyl index, which is a measure of secondary oxidation and oxidation history can provide more reproducible data especially if given a challenge test (Strandberg, Burman, & Albertsson, 2006). The carbonyl index can be measured using FTIR spectroscopy, which can enable a larger, more representative sample to be used.

6.3 Low molecular weight compounds

Low molecular weight compounds present in recycled polymers may be volatile or non-volatile, typically consisting of monomeric oligomeric polymer residues, solvent residues, initiators, catalysts, additives (including antioxidants, stabilisers, plasticisers, flame retardants), degradation products from polymer and additives, and environmental impurities and contamination from in-use and during recycling process.

To analyse these compounds gas and liquid chromatography have been most widely used. For volatile organic compounds (VOCs), gas chromatography (GC) paired with solid phase microextraction (SPME) and stir bar sorptive extraction (SBSE) are emerging as popular techniques (Vilaplana & Karlsson, 2008). Though VOC-extraction techniques have also included purge and trap, Likens-Nickerson distillations and solvent assisted flavour evaporation (SAFE). SPME is widely available, fast and solvent free. Though care is required not to saturate the fibre and because the binding of the VOC to the fibre is based upon a specific interaction the VOC detected with the highest intensity is not necessarily the VOC present in the highest amount. SBSE also relies upon a specific interaction between the adsorbent material on the stir bar and the VOC, however because of the much greater volume of adsorbent overloading by VOCs of the SBSE is much less of a problem.

It is difficult to develop a quantitative analytical method when knowledge on which VOCs will be present is unknown. Again, it is not the presence of small molecular weight compounds in particular that is a problem it is the specific effect that their presence has on product quality. Further, without knowledge on what the VOC will be present selecting the correct analytical conditions is fraught as all VOC extraction methods have a blind spot, i.e., compound(s) that will not be extracted or will be lost during sample preparation. In light of this techniques that closely mimic the impaired function and allow broad detection of any defects are practically the most useful. Sensory-based techniques would appear to best fit these requirements.

7.0 EFFECT OF PACKAGING CONTAINING RECYCLED POLYMERS ON FOOD QUALITY

Though the effect of the use of packaging with recycled content on food safety has been well documented the effect on food quality has been widely ignored. Recycling may result in either food product carryover, chemical contamination, contamination with other packaging/polymers or packaging degradation. Numerous publications make reference to the effect of recycling on polymer quality (for example, Eriksen & Astrup, 2019; Matthews et al., 2021) but few studies quantify this (Eriksen et al., 2019) and none place the changes in the context of food quality. Simply reporting that the recycling process results in polymer hydrolysis is not helpful. It could be assumed that a reduction in molecular weight would result in increased mass transfer rates and reduction in physical strength. However, in semi-crystalline polymers, hydrolysis during recycling may result in an increased degree of crystallisation (Vilaplana & Karlsson, 2008), which would reduce mass transfer rates and increase impact resistance though result in a decrease in percent elongation (Teck Kim, Min, & Won Kim, 2014).

Based on the effects of recycling on polymer quality the potential effect on food quality can be considered under a number of possible mechanisms.

7.1 Mechanical stability

For food quality to be assured the key packaging functions of protection and containment need to be met (see section 2). To achieve this the packaging requires sufficient strength to resist reasonable external physical stresses and allow containment of the contents. However, the literature has largely investigated the packaging material directly rather than a food facing approach. In this light it is most useful to consider section 5 to understand how quality changes in packaging materials will impact on the quality of food. For example, depending upon the recycling process, PET may suffer from environmental stress cracking, which can result in catastrophic failure, i.e., a complete loss of the bottle contents (Chacon, Brouwer, & van Velzen, 2020). Some effects may not directly impact on food quality but lead to a perceived loss of quality, e.g., haze formation in clear polymers due to presence of contaminating polymers or polymer crystallisation, as in PET (Chacon et al., 2020; Pinter et al., 2021).

7.2 Oxidation

The recycling process generates peroxides, which means that depending on the peroxide and packaging composition that the packaging could act as a prooxidant. Prooxidant ability would be affected by the peroxide molecular weight as migration rates increase with decreasing molecular weight and compound $k_{o/w}$ (or polarity) (Cai et al., 2017) and whether the recycled content is in direct contact with the food. Cruz & Zanin (2003) report the presence of peroxides in HDPE but not their fate. Kassouf et al. (2014) report the migration of antioxidants from PP into olive oil and sorption of olive oil by PP, which increased migration rates. In this context transfer of low MW peroxides is not unreasonable. Though the transfer of peroxides does not appear to have been reported, the likelihood of transfer to food could be assessed using modelling approaches (Nguyen et al., 2013).

Also, increased mass transfer rates could lead to increased oxygen transfer however this effect has not been reported. Dombre, Rigou, Wirth, & Chalier (2015) reported that recycled PET (rPET) bottles and virgin PET bottles had oxygen transmission rates of 1.63 and 1.97 x 10^{-3} $cm^3m^{-2}day^{-1}$ at 23°C and 65% humidity. This suggests that oxygen transmission rates need not be higher in recycled polymers and a similar result between PET and rPET bottles was found by (Toussaint, Vidal, & Salmon, 2014). Dombre et al. (2015) also found no significant differences in oxidation related VOC between wines stored in the two bottle types. This is supported by the findings of Revi, Badeka, Kontakos, & Kontominas (2014) where differences of 1.6 and 1.8 mL O_2/(package day atm) did not result in differences in oxidation in bag-in-box wine. In studies using virgin films with different oxygen transmission rates a similar lack of difference in oxidation parameters have been found. Frozen par-baked bread packaged in one of two films with large differences in oxygen transfer rates had no difference to the extent of lipid oxidation, rather film translucence was believed to be more important than oxygen transfer rates (Novotni et al., 2011). This finding highlights the importance of identifying the correct packaging parameter that influences shelf life. Based on these results possibly oxygen transfer is not a critical parameter or it is a product specific parameter to consider. It should also be noted that simply poor selection of virgin LDPE could result in oxygen transmission rates that vary from 104 to 275 cm^3 μm/m^2 day atm (Teck Kim et al., 2014).

7.3 VOC

The role of recycled packaging in giving rise to taints and off-odours in foods, especially in recycled plastics has been poorly characterised. Though phthalates and bisphenols have been detected in fruit, ice cream, rice, eggs and pasta after direct contact with paperboard (Blanco-Zubiaguirre et al., 2021; Xue, Chai, Li, & Chen, 2019; Zülch & Piringer, 2010), illustrating the breadth of food products that may be contaminated with low molecular weight compounds. The migration of substances from packaging into a food or beverage or from a food or beverage into packaging, is strongly influenced by the interactions of components in the food with the packaging material. The migration rates of VOCs have been found to increase as the volatility increases and in paperboard as the polarity increases the migration rate of VOCs slows. Environmental storage conditions such as temperature, humidity, and exposure time influence both the rate and extent of migration as can the composition of the product and interactions between the various components in the system (Hahladakis et al., 2018; Muncke et al., 2020). For example, transfer rates increase as the storage temperature increases and the contact time with the food increases (Han et al., 2016). The characteristics of the food are also important with the migration rate of substances from packaging into its contents generally increasing as the food's lipid content increases and if the lipid is present as free fat, i.e., non-emulsified rather than emulsified lipid, the migration rate is higher (Elizalde et al., 2020). Further, if some of the fat present migrates into the packaging material it can further increase the mobility of substances within the packaging material,

Interestingly, some evidence for the transfer of VOC from packaging exists in the antimicrobial packaging literature where compounds like thymol, and cinnamaldehyde have been encapsulated in food packaging and their effect on food determined (Haghighi-Manesh & Azizi, 2017). Extrusion of the polymer mixture containing these compounds did not substantially reduce their concentrations in the polymer mixture, with only reductions of about 25% to 40% observed, suggesting that odour compounds present after recycling will be present in the finished packaging. Having said that, the incorporation of 0.5% cinnamaldehyde in a LDPE/LLDPE layer sandwiched between LDPE/LLDPE/EVOH and LDPE/LLDPE (contact layer) films (30 µm) did not significantly reduce overall sensory quality of the milk though it did reduce taste quality slightly (Haghighi-Manesh & Azizi, 2017). The relatively minor effect on the sensory properties of the milk may reflect the contact time and associated storage temperature, which are important aspects influencing the extent of transmission from packaging to food (Nguyen et al., 2013). Food composition will also affect migration rates.

A comparison of VOC changes in rose wine packaged in virgin and recycled PET after 12 months found that storage time had a larger effect on the concentration of VOCs in the wine than package type (Dombre et al., 2015). Having said that expert tasters found that the rose packaged in recycled PET had more red fruit character and the rose packaged in virgin PET had a more amylic character, which can be described as bubble gum, candy, apple, banana (https://www.aeb-group.com/en/rose-wine-a-world-with-a-wealth-of-nuances-and-scents-to-discover). It was thought that this may have been due to the recycled PET scalping lower concentrations of VOCs. This difference would suggest differences could occur in concentration of flavour compounds that do not necessarily result from taints or off flavours but none the less result in a perceivable difference. It also highlights the risk of only relying on VOC instrumental methods.

8.0 MEASURES OF PACKAGING DEFECTS ON SUBSEQUENT FOOD QUALITY

Regardless of whether the packaging defects are due the presence of contaminating polymers, thermomechanical degradation, presence of polymer-derived peroxides or VOCs, the likely impact on the food is largely reduced to mechanical properties and changes to flavour (though potentially some packaging appearance issues may arise).

8.1 Odour or flavour changes

It is not necessarily what odour-active compound(s) are present in the packaging but whether they are present in sufficient quantity to give rise to an odour in the food. As such it is insufficient to show a compound is present, rather it is necessary to show that the compound is transferred in sufficient amounts to result in a sensory change and preferably the description of the sensory change (Cai et al., 2017). Ideally, the consumer impact of any sensory change should be considered, i.e., are the changes in sensory properties sufficient to result in acceptability changes.

These sensory changes can be linked back to VOC compositions so that sensory analysis does not need to be routinely carried out. MVD and neural network models have been used to predict off odour based upon a relationship between VOC concentration and sensory properties (Corollaro et al., 2014; Gasperi et al., 2001; Granitto, Gasperi, Biasioli, Trainotti, & Furlanello, 2007; Phillips et al., 2010; Su, Vera, Salafranca, & Nerin, 2021; Ting et al., 2015). However, these models are only as good as the test set used to develop the model, especially when non-typical odours appear and generally do not account for interactions between VOCs. The perceived off odour from any packaging is unlikely to be due to one compound, rather it is most frequently the perception of a number of VOC. Given these difficulties simple sensory tests have an ability to detected a wide range of odour/flavour defects (in a nonselective manner) more easily than VOC analysis methods such as GC-MS.

In addition to off-odours generally being due to more than one VOC, detection by sensory methods is generally non-selective, allowing a broader range of odour-active compounds to be detected and in particular unexpected odour-active VOC. Standard methodology already exists that can be used to detect off-odours from packaging (Table 9).

Table 9. Sensory test standards applicable to the evaluation of packaging

Standard	Title
DIN EN 1230-1:2010	Paper and board intended to come into contact with foodstuffs –
DIN EN 1230-2:2010	Paper and board intended to come into contact with foodstuffs –

ISO 13302:2003	Sensory analysis – Methods for assessing modifications to the flavors of foodstuffs due to packaging
ASTM E619-09	Standard practice for evaluating foreign odors in paper packaging
DIN 10955:2004-06	Sensory Analysis—Testing of Packaging Materials and Packages for Foodstuffs.
ISO 13302:2003	Sensory Analysis—Methods for Assessing Modifications to the Flavour of Foodstuffs Due to Packaging.
DIN EN ISO 8586:2012	Sensory analysis – General guidelines for the selection, training, and monitoring of selected assessors and expert sensory assessors
ISO 8589:2007	Sensory analysis – General guidance for the design of test rooms
DIN EN ISO 4120:2007	Sensory analysis – Methodology – Triangle test
DIN EN ISO 5495:2007	Sensory analysis – Methodology – Paired comparison test
DIN EN ISO 10399:2010	Sensory analysis – Methodology – Duo-trio test
DIN ISO 8587:2010	Sensory analysis – Methodology – Ranking
DIN EN ISO 13299:2010	Sensory analysis – Methodology – General guidance for establishing a sensory profile

(Czerny, 2017; Siegmund, Wrana, & Leitner, 2022)

Sensory analysis methods can generally be split into direct and indirect methods. Direct methods involve incubating a packaging sample of standardised weight and dimensions in an inert vessel and assessing the odour. Indirect methods involve incubating the packaging sample of standardised weight and dimensions in an inert vessel with a food sample and assessing the food sample. The food sample is selected based on its sensitivity to flavour changes. The advantage of the indirect tests is that they can detect changes due to packaging taints, chemically-induced reactions and scalping. Milk chocolate is commonly used as the food sample due to its sensitivity to taints and oxidation, and resistance to microbial spoilage. Though other foods like butter, margarine, mild cheddar cheese, biscuits, milk, other beverages and even standardised concentrations of ethanol in water have been used (Czerny, 2017; Siegmund et al., 2022). Ideally two food types are selected that may favour VOC of different polarities though this may depend upon the characteristics of the food the packaging being examined is used with. Appendix 2a and 2b provide an example of a direct and indirect method used by the author for quality determinations of cardboard. If the packaging fails the sensory tests, then VOC analysis, normally GC-MS or GC-MS/O can be used to understand the cause of failure. If carrying out GC-MS/O it is important to ensure the extract being presented to the GC-MS/O is representative of the off flavour (Delahunty, Eyres, & Dufour, 2006).

8.2 Mechanical properties of food packaging.

For mechanical testing a large number of standard methods exist (Table 10) and it is important to understand which test is most applicable to the mechanical requirements that the food product requires to maintain integrity. This will differ between manufacturers, packaging types and food products.

When implementing mechanical tests, it is important to remember the temperature and humidity the packaging will be exposed to. For example, the impact strength of an ice cream container at 25 °C is likely not relevant to what happens at -20 °C. For cardboard other mechanical functions may be important, e.g., wet tensile strength or folding endurance.

Table 10. Standard methods available to assess the mechanical properties of polymers

Mechanical characteristic	Description	Property [unit]	Standards
Strength	The material's ability to withstand an applied load without failure (tensile strength) or plastic deformation (yield stress).	Tensile strength σ_m [MPa] Flexural strength σ_f [MPa] Yield strength σ_y [MPa]	ISO 527 ISO 178 ISO 527
Stiffness	The material's resistance to elastic deformation.	Elastic modulus E [MPa] Tensile modulus E_t [MPa] Flexural modulus E_f [MPa]	 ISO 527 ISO 178
Toughness	The total energy a material can absorb/dissipate before failure.	Surface under tensile curve [J/ m^3]	ISO 527
Ductility	The total plastic deformation a material can withstand under	Tensile strain at break ε_b [%]	ISO 527
Impact strength	The material's ability to withstand a sudden load at a high	Charpy (un) notched impact strength a_c [kJ/ m^2] Izod un(notched) impact strength a_i [kJ/m^2] Dart drop impact m_f [g]	ISO 179 ISO 180 ISO 7765

Source: Demets et al. (2021)

9.0 POTENTIAL STRATEGIES TO REDUCE IMPACT OF PACKAGING QUALITY LOSS ON FOOD QUALITY

MITIGATION – HOW TO REDUCE THE RISK?

9.1 Quality framework

The first part of any mitigation strategy is what framework to use. A challenge in this space is that the majority of quality frameworks used for polymer-based packaging are not suitable for assessing their quality or safety as they are tied to LCA calculations. Rather, to ensure safety and quality a HACCP based approach is recommended (Bovee et al., 1997). A HACCP or Good Manufacturing Practice (GMP) approach provides a standard methodology for to ensure quality that is well understood in the food industry. Importantly, a vital component of HACCP is a risk management system, where quality and safety are assured by specifying packaging requirements and having in place critical control points to monitor and verify their effectiveness. For example, with rPET bottles packaging requirements included acetaldehyde limits, stress cracking, burst pressure and gas barrier properties (Bovee et al. 1997). However, what the authors did not address within their framework was how to develop the specifications or determine the critical limits.

An alternative design model, that can incorporate quality / safety was used by Nguyen et al. (2013), as a key part of a Safe-by-design packaging development adapted from a version of Failure Modes, Effects and Criticality Analysis (FMECA). The FMECA approach was initially developed for the aeronautics industry and like HACCP, as implemented in the food industry, it takes a preventative approach (Nguyen et al., 2017). For packaging the FMECA approach is suggested to have some advantages over HACCP. Limitations of HACCP for packaging have been stated to include: that it does not incorporate early product/process design rather it targets control and corrective action at the production or distribution stage; risk is not quantified as in FMECA; and relationships between parts are not considered rather each part is considered independently before being joined together (Nguyen et al., 2013).

The advantage of the updated FMECA approach is that uncertainty, consequences of linked causes, risk of failure along a complex flow chart with many materials, and many substances are all taken into account (Nguyen et al., 2013). As an example, of why relationships between parts need to be considered a computer modelling case study showed that the migration of benzophenone into a microwavable soup was dependent upon storage time only if the packaging was offset printed (Nguyen et al., 2013)[*]. Though the Safe-by-design packaging version of FMECA is concerned primarily with migration of toxic compounds it can readily be modified to consider taints and the approach can be applied to manage mechanical failures. Compared to Bovee et al. (1997), Safe-by-design is likely to allow better management of risk. In addition, as Safe-by-design was specifically designed to address compound migration into food it should allow more reliable calculations of

[*] Offset printing: where printing present on the outside of the packaging is stored in contact with an internal packaging layer, e.g., roll of printed film or stack of printed cups.

acceptable limits for common contaminating VOCs that could give rise to taints. In addition, the resources for this are available on-line and key resources are available as freeware or free access (Table 11). However, how Safe-by-design can manage unknown/unexpected odours is not clear and for mechanical properties a specification and how to determine the quality limits is still required.

Table 11. Details of resources available for Safe-by-design

Classification	Description	Links	License
Stand-alone compliance testing programs	Migratest EXP commercial AKTS-SML version 6	https://www.fabes-online.de/en/software-en/migratest-exp/ https://www.akts.com/sml-diffusion-migration-multilayer-packaging/download-diffusionprediction-software.html	(demo available)
Compliance testing client/server	Client-server SFPP3* application (SafeFoodPackaging portal version 3) to be used by one to 25 simultaneous users. SFPP3 includes all public data of the European task force TF-MATHMOD. *Interactive training on SFPP3 tools with case studies (French):	http://sfpp3.agroparistech.fr:443/cgi-bin/login.cgi http://rmt-propackfood.actia-asso.eu/	freeware, partly opensource, online access or standalone installation.
Expandable preventive and safe-by-design tools	FMECAengine** and key2key() language enabling simulation from one to thousands food packaging systems, an entire supply chain, etc.open-source (written in Matlab, Octave **FMECAengine includes and expands all features implemented in SFPP3.	https://github.com/ovitrac/FMECAengine	
Online databases	Thermophysical properties of polymers free access Diffusion and partition coefficients of the European task force TF-MATHMOD	http://polymerdatabase.com/ http://modmol.agroparistech.fr/Database/	free access freely accessible
Guidance	EU rules: US rules: Generic:	http://publications.jrc.ec.europa.eu/repository/handle/JRC98028 https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey_P100BCMB.TXT http://modmol.agroparistech.fr/home/	freely accessible freely accessible freely accessible

	Generic:	https://www.foodpackagingforum.org/food-packaging-health/migration-modeling	freely accessible

Demets et al. (2021) do however provide a framework that could be used to develop suitable specifications. The methodology was proposed for use to quantify the substitutability of recycled packaging for virgin packaging and involves two quality aspects, a processability function and technical functionality of the packaging. In this instance the processability is less important, unless blowing your own bottles. Though the only technical properties considered are mechanical (Table 10), with sensory properties not being considered. The relevant mechanical characteristics are selected and specification limits applied. Each mechanical characteristic was assigned an optimum value and quality limits which were either an upper and lower limit or for some characteristics only a lower limit was appropriate. A scoring function was then applied where 1 was the range of optimal values and as the value moved outside the optimum different scoring functions were applied that best reflected the rate of change in quality. Five types of scoring functions were used, trapezoidal (double), bell shaped, gaussian, trapezoidal (single) and sigmoidal. The different scoring functions allow quality to decrease at the most appropriate rate. Mechanical characteristics were then scored based on the mechanical properties and summed to give an RQ (recycling quality) factor. It is suggested that sensory changes could be scored the same way. Though it is important to ensure the scoring is set up in a manner that means if a critical parameter fails the weighting is such that the packaging is rejected and not accepted for use. A potential advantage or disadvantage of this approach is that a packaging material that scored poorly on a number of characteristics could return a recommendation to reject even though it exceeded the minimum values (albeit only just) stated for each characteristic. Whether this is an advantage or disadvantage depends on whether combined poor performance over a number of characteristics suggests this could collectively cause a problem or a disadvantage in that acceptable packaging is being rejected. Mechanical properties specifications and identified critical parameters can be drawn from web resources (Table 12). An example of the details available from Matweb is shown in appendix 1.

Table 12. Resources available that provide information on paper and polymer mechanical and thermal properties.

Description	**Web link**
Polymer thermal and mechanical	http://polymerdatabase.com/main.html
Polymer thermal, optical and	http://www.matweb.com/index.aspx
Polymer properties; Supplier	https://omnexus.specialchem.com/
Paper properties	https://paperonweb.com/paperpro.htm
Pulp properties	https://paperonweb.com/pulppro.htm

9.2 Apply model and minimise identified risks

Using a combination of Safe-by-design and Recycling Quality values would appear to provide a robust methodology to identify and quantify risks as well as generate packaging quality specifications. Mitigation then becomes a matter of reducing the identified risks. If there is concern that recycled packaging specifications may not be possible to be consistently met or as a sensible added level of assurance, testing regimes should be implemented to ensure that the recycled packaging is fit for purpose. The quality risks will be specific to each packaging material and function, i.e., is the packaging primary, secondary or tertiary packaging and are confounding factors like offset printing or even offset stacking used.

To reduce the risk of taints, where possible a barrier of some form between the food and recycled content should be implemented. For example, this could take the form of liner to separate paper/cardboard from food or virgin polymer layer in recycled polymers. If for example, a liner can be used to slow the migration of VOC greater than 220 g mol^{-1} by manipulating film thickness and barrier properties. Changing the film from HDPE to PP would reduce the extent of transfer by a factor of 10. Other factors that can be manipulated include polymer process temperature (lower temperature has lower diffusion) and choosing a glassy polymer (Dole et al., 2006). If the VOC has a molecular weight of less than 220 g mol^{-1} equilibrium is reached very quickly regardless of any practical design. In this instance, transfer of these small VOCs from the packaging to the food is best reduced by examining the complete packaging process from packaging receipt until packaging of the food, where the objective is to minimise VOC concentrations in the packaging. Examples of steps that could be taken are forced air circulation during storage of packaging and reducing packaging confinement during storage (Nguyen et al., 2017). The same approaches as outlined above can be used with polymeric packaging to reduce VOC transfer through the use of a functional barrier, which may be the same polymer as the recycled polymer.

Processors are recommended to generate specifications for each packaging component based on risk of failure and impact of failure on product quality then test sufficiently robustly to have confidence failure is not occurring and failed packaging can be rejected on delivery. When assessing risk remember that a layer separating the recycled content from the food will be of limited use if for example the container arrives as a stack of containers where the internal virgin layer is in contact with an external recycled polymer layer (set off / offset packed). The specification should include mechanical aspects and odour/flavour. As off-flavours will be most likely be from unknown or unexpected compounds, a sensory test will in all likelihood be the most effective means of detecting an issue.

When selecting participants for a sensory panel a process is needed to assure that participants have the required acuity (they can detect differences at an appropriate level of sensitivity), aptitude (interested and possess the required level of diligence), received appropriate training and have sufficient time available to sit on a panel. In addition, suitable space should be set up for the testing. This does not need to be to the ISO standard (ISO-8589, 2007) but should be free from odours that may conceal a problem and free from distractions though space may also be used for other functions when not being used for sensory testing. The tests should be prepared by someone who is not also assessing the samples, samples blind coded and prepared in a reproducible manner. Assistance and training could be provided to help establish suitable facilities and panels along with appropriate training protocols.

10. CONCLUSIONS

Factors that may decrease the functionality of recycled packaging, including the quality (and safety) of its contents, include: the presence of non-intentionally added substances (NIAS); the occurrence of intentionally added substances (IAS), such as pigments used for printing, at concentrations higher than in virgin packaging; the presence of contaminating polymers and the extent of polymer degradation in the recycled material. The long-term stability of the food or beverage may be also affected by the presence of primary and secondary oxidation products.

When considering how recycled packaging may influence food quality key questions are: will the packaging protect and contain the enclosed food / beverage?; and will the packaging give rise to volatiles (off odours/flavours) which will adversely affect its contents? These questions suggest that technologists should focus on mechanical and sensory-based tests already established by standards associations.

Mechanical tests are required as the large variation in polymer sub-types that exist due to polymer synthesis-induced variation in polymer molecular weight, degree of branching, branch lengths and crosslinking give rise to large variations in mechanical properties that make it difficult to draw general conclusions on the performance of recycled polymers compared to virgin polymers.

Sensory tests are recommended as they can be used to detect a wide range of odour/flavour defects (in a nonselective manner) in a product more easily than VOC analysis methods such as GC-MS and visual tests (colour) are well established important QA tools.

It is important to note that quality concerns associated with the migration of substances from packaging into a food or beverage or from a food or beverage into packaging, are strongly influenced by the interactions of components in the food with the packaging material.

Given the complexity of the interactions between recycled packaging and its contents and how this may impact on product quality and safety, the risks associated with the use of recycled packaging are specific to the packaging material, the product and its storage conditions

This complexity also means that suitable mitigation process requires a good understanding of the recycled packaging / product “system” and the development of a quality framework that identifies critical packaging parameters and generates acceptable quality limits (taking the form of a product specification) that can be used to control the identified risks.

The Safe-by-design, quality framework combined with the recycling quality factor approach is suggested as an appropriate way to identify and quantify of risk and to generate recycled packaging quality limits that can be used as packaging specifications.

In addition, food companies, need to confirm that their recycled packaging producers have suitable risk assessment-based controls in place through-out their recycling and production process which ensure that agreed recycled packaging specifications are met. If there is concern that, recycled packaging specifications may not be possible to be consistently met, or risks suitability mitigated, or as a sensible added level of assurance, testing regimes should be implemented to ensure that the recycled packaging is fit for purpose.

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APPENDICES

Appendix 1. Range in values for the properties of two classes of linear low density polyethylene obtained from matweb.com

Physical	LLDPE-film	LLDPE – injection molded
Density **(g/cc)**	0.900 - 1.50	0.870 - 0.963
Moisture Vapor Transmission **(cc-mm/m²-24hr-atm)**	0.240 - 0.470	--
Water Vapor Transmission **(g/m²/day)**	4.70 - 14.0	--
Oxygen Transmission **(cc-mm/m²-24hr-atm)**	0.720 - 236	--
Oxygen Transmission Rate **(cc/m²/day)**	3500 - 5000	--
Viscosity **(cP)**	--	42.0 - 300000
Environmental Stress Crack Resistance **(hour)**	1.00 - 1000	1.00 - 1000 4.00 - 4.00
Thickness **(microns)**	8.00 - 150	25.4 - 38.1
Melt Flow **(g/10 min)**	0.200 - 123	0.800 - 150
Base Resin Melt Index **(g/10 min)**	0.700 - 3.50	--
Spiral Flow **(cm)**	--	32.0 - 67.8
Mechanical		
Hardness, Shore D **()**	44.0 - 67.0	44.0 - 70.0
Tensile Strength, Ultimate **(MPa)**	7.45 - 43.0	7.93 - 45.5
Film Tensile Strength at Yield, MD **(MPa)**	5.00 - 50.0	1.31 - 12.5
Film Tensile Strength at Yield, TD **(MPa)**	4.48 - 46.0	10.3 - 13.0
Tensile Strength, Yield **(MPa)**	9.00 - 22.1	7.30 - 42.0
Film Elongation at Break, MD **(%)**	80.0 - 1400	460 - 1000
Film Elongation at Break, TD **(%)**	460 - 6500	540 - 1100
Film Elongation at Yield, MD **(%)**	19.0 - 550	--
Film Elongation at Yield, TD **(%)**	12.0 - 780	--

Appendix 1. (continued)

Mechanical	LLDPE-film	LLDPE – injection
Elongation at Break **(%)**	0.800 - 1000	8.00 - 1100
Elongation at Yield **(%)**	--	8.20 - 30.0
Modulus of Elasticity **(GPa)**	0.0110 - 0.413	0.140 - 1.57
Flexural Modulus **(GPa)**	0.140 - 0.920	0.0165 - 0.800
Secant Modulus **(GPa)**	0.0800 - 0.625	0.294 - 0.593
Secant Modulus, MD **(GPa)**	0.0103 - 0.717	0.179 - 0.207
Secant Modulus, TD **(GPa)**	0.00145 - 0.869	0.221 - 0.238
Izod Impact, Notched (ISO) **(kJ/m^2)**	10.0 - 100000	18.0 - 100000
Dart Drop, Total Energy **(J)**	--	2.44
Puncture Energy **(J)**	0.452 - 10.5	--
Coefficient of Friction **()**	0.100 - 2.00	0.120 - 0.500
Coefficient of Friction, Static **()**	0.170 - 1.00	0.200 - 0.580
Tear Strength Test **()**	16.0 - 22.0	--
Elmendorf Tear Strength MD **(g)**	10.0 - 1210	260 - 600
Elmendorf Tear Strength TD **(g)**	25.0 - 1470	490 - 900
Elmendorf Tear Strength, MD **(g/micron)**	0.0750 - 35.0	2.00 - 15.0
Elmendorf Tear Strength, TD **(g/micron)**	0.275 - 135	7.30 - 27.6
Dart Drop **(g/micron)**	1.57 - 70.9	3.00 - 19.7
Dart Drop Test **(g)**	30.0 - 1350	290 - 1000
Seal Strength **(g/25 mm)**	1800 - 2400	--
Film Tensile Strength at Break, MD **(MPa)**	9.65 - 82.7	21.0 - 56.5
Film Tensile Strength at Break, TD **(MPa)**	7.24 - 284	16.0 - 47.0
Heat Seal Strength Initiation Temperature **(°C)**	92.0 - 180	--

Appendix 1. (continued)

Thermal		
Melting Point **(°C)**	87.0 - 130	75.0 - 128
Crystallization Temperature **(°C)**	104 - 115	106 - 111
Deflection Temperature at 0.46 MPa (66 **(°C)**	--	42.0 - 57.2
Deflection Temperature at 1.8 MPa (264 **(°C)**	--	35.0 - 35.6
Vicat Softening Point **(°C)**	65.0 - 123	41.1 - 130
Brittleness Temperature **(°C)**	-30	-49.1
Optical	**LLDPE-film**	**LLDPE – injection**
Haze **(%)**	0.500 - 80.0	1.50 - 55.0
Gloss **(%)**	3.20 - 155	45.0 - 94.0
Transmission, Visible **(%)**	2.00 - 90.0	--
Processing		
Processing Temperature **(°C)**	90.0 - 274	88.9 - 230
Nozzle Temperature **(°C)**	--	149 - 205
Melt Temperature **(°C)**	123 - 450	95.0 - 302
Mold Temperature **(°C)**	--	10.0 - 60.0
Die Opening **(cm)**	0.0640 - 0.280	0.0810 - 0.254
Injection Pressure **(MPa)**	--	2.76 - 14.0

Appendix 2. Methods for sensory testing of cardboard.
Appendix 2A. Protocol for odour testing of cardboard

Odour Testing

The test protocol below may be followed, or alternatively that detailed within EN 1230-1:2001. When reporting results, reference MUST be made to the test protocol followed.

MQM 1.1 (Sept 02)

Equipment

Kilner jar (clean & odour free)
Distilled water (odour free)
Oven

Frequency

As required

Method

1. Rinse out jar with distilled water and leave to air-dry.

2. Remove an A4 sample of the material under test from its foil wrapping and cut into 10mm strips.

3. Add 0.5ml of distilled water to the Kilner jar.

4. Place the strips of material into the jar and seal the jar using the lid.

5. Place the sealed jar in the oven, preheated to 38°C (± 1°C), for a minimum of 4 hours.

6. When the 4 hours have elapsed, remove the jar from the oven and leave it to cool at room temperature for a minimum of 30 minutes.

7. Remove the lid and smell the contents of jar.

8. The results are assessed as follows:

0	=	No perceptible off-odour
1	=	Off-odour just perceptible (but still difficult to define)
2	=	Slight off-odour
3	=	Distinct off-odour
4	=	Strong off-odour

Part points (+ or -, ½) can be used. The panel taster may also describe any off-flavour in words.

9. A specially selected panel, of preferably 5 people, should carry out the test. However, a minimum of 3 people is permissible.

10. An average of the panel's results is taken. The figure is recorded, along with any comments, against the production batch reference.

Acceptable Limits

An average of up to 1.7 is considered acceptable as a pass. If the average is greater than 1.7 the material will be re-sampled and re-tested.

If the material again scores above 1.7, then the material will be quarantined and samples sent to customer for assessment. If customer does not accept the quarantined material, it will be rejected.

Remarks

Stages 2, 3 and 4 must be carried out with the minimum of delay.

Appendix 2A. Protocol for taint testing induced by cardboard

Taint Test

The test protocol below may be followed, or alternatively that detailed within EN 1230-2:2001. When reporting results, reference MUST be made to the test protocol followed.

MQM 1.2 (Sept 02)

Equipment

Kilner jar
Milk chocolate
Aluminium foil

Frequency

As required

Method

1. Rinse out jar with distilled water and leave to air-dry.
2. Cut A4 sample of material under test into 10 mm strips.
3. Place 10 mm strips into the jar along with a foil cup containing 5 or 6 pieces of chocolate and replace the lid.
4. Wrap another 5 or 6 pieces of chocolate in foil and place in an empty, **taint free** jar. This is the control sample.
5. Leave the test and control jar at room temperature for a minimum of 24 hours.
6. When the 24 hours has elapsed, eat a piece of chocolate from control sample. Rinse out mouth with water.
7. Eat a piece of chocolate from the test jar and compare its taint with the one from the control sample.
8. Results are assessed as follows:

0	No taint
1	Barely perceptible taint
2	Perceptible taint
3	Moderate taint
4	Strong taint
5	Very strong taint

9. The test must be carried out by a panel of preferably 5 people. However, a minimum of 3 people is permissible.

10. An average of the panels' results is taken. The figure is recorded, along with any comments, against the production batch reference.

Acceptable Limit

An average of 1.0 is considered acceptable as a pass.
(PLEASE NOTE WHAT IS CONSIDERED A PASS WILL BE PRODUCT SPECIFIC)

If any of the panels' results are recorded as being greater than 1.0, the material will be re-sampled and re-tested. If the material again scores greater than 1.0, then the material will be quarantined and samples will be sent to customer for assessment. If the customer does not accept the quarantined material, it will be rejected.

Remarks

Stages 2, 3 and 4 must be carried out with the minimum of delay.