

# The function and properties of common food packaging materials and their suitability for reusable packaging: The transition from a linear to circular economy

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## ABSTRACT

For the last few decades, plastics have been the material of choice for food packaging applications. Combining mechanical performance with barrier properties and transparency, plastics have been a cost-effective solution for safely distributing food produce. Unfortunately, most plastic packaging is based on a linear model where packaging is designed for single use, resulting in vast amounts of post-consumer waste being generated annually. In response to this concern, many public and private bodies globally have set ambitious sustainable development targets with the goal of reducing plastic waste. To assist in meeting these targets, the implementation of reusable packaging schemes has been suggested. These schemes aim to prolong the lifespan and worth of plastic packaging and have the potential to reduce the environmental impact of single-use plastics, provided all aspects of their design are carefully considered. One design aspect often neglected is the influence of repeated use on the properties of the packaging material. Very little literature exists investigating the effects that repeated contamination and washing can have on the material's intrinsic properties. This review article aims to comprehensively review the functions and properties of various food packaging materials to assess their suitability for reusable food packaging applications.

## 1. Introduction

The plastic packaging industry is one of the largest growing sectors in the synthetic plastics market today [1]. Accounting for 44 % of global plastic production in 2021, plastics have remained a popular choice as a packaging material, playing an essential role in protecting and maintaining the quality of goods as they are distributed throughout the world's supply chains [2,3]. Plastic materials are desirable in packaging applications because of their lightweight, durability and relatively low cost when compared to traditionally used materials such as glass, metal and paper [4]. One specific application where plastic materials have excelled is food packaging. Plastics have established themselves as capable materials for this application by combining barrier properties and transparency with good mechanical performance and ease of

processability at a low cost [5]. Due to their material characteristics, plastics can fulfil the fundamental requirements of food packaging, whilst also providing an adaptable medium to display information for the consumer and create aesthetic solutions for commercial environments [6].

Despite the many functional and economic benefits plastic packaging materials have to offer, they still present some drawbacks. Their greatest disadvantage being the global environmental impacts associated with their manufacture, use and disposal; which have been an increasing matter of concern to producers, consumers and governments over the last five decades [7,8]. The current design of plastic packaging is predominantly based on a linear model, meaning it is designed for single use, and consequently, its value is lost immediately on disposal [9]. As a result of this design, vast amounts of post-consumer waste are produced

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annually. For example, in 2020, it was estimated that a total of 17.9 M tonnes of post-consumer plastic was collected throughout the EU, of which only 46 % was recycled, 37 % incinerated for energy recovery and 17 % disposed of in landfill sites [2]. In the U.S., the recycling rate is lower, with it being reported that 44 M tonnes of domestic plastic waste was generated during 2019, of which only 5 % was recycled while 86 % and 9 % were landfilled and sent for energy recovery, respectively [10]. China, who is the largest producer and consumer of plastic globally, reported that 63 M tonnes of post-consumer plastic waste was collected in 2019, 30 % of which was recycled, 32 % disposed of in landfill sites and 31 % incinerated for energy recovery [11,12]. If this waste management trend continues, it is estimated that approximately 12 B tonnes of plastic waste will have accumulated globally in landfills or the natural environment by 2050 [13].

In response to the alarming growth rate of plastic waste, several policy measures and voluntary actions have been launched globally by public and private bodies to address the problems caused by plastic packaging [14]. These actions have included policies and regulations to reduce or ban single-use plastics and voluntary measures such as collaborative commitments and pacts to foster the circular economy of plastics [14–17].

In the EU, perhaps the most ambitious endeavour to reduce plastic waste is the EU Commission's Circular Economy Action Plan proposed in 2015 and the European Strategy for Plastics adopted in 2018, which aim to see 55 % of plastic packaging recycled by 2025 and all plastic packaging available on the market recyclable or reusable in an economically viable way by 2030 [18,19]. In addition, on October 2023 the EU Commission voted to adopt the Proposal on Packaging and Packaging Waste Regulation (PPWR) looking establishing requirements for the entire packaging life cycle: make packaging easier to reuse and recycle, reduce unnecessary packaging and waste, and promote the use of recycled content [20]. Among the measures stand the set up specific waste reduction targets for plastic packaging (10 % by 2030, 15 % by 2035, 20 % by 2040), the ban single use packaging for on-spot consumption in the HORECA sector and the encouragement on the use of reusable packaging, identifying the need to define reusable packaging, including minimum number of times it should be reused [20].

In the U.S., currently, no federal law exists concerning plastic waste reduction and packaging reuse. However, five U.S. states, California, Colorado, Maine, Minnesota, and Oregon, have introduced extended producer responsibility (EPR) packaging legislation into state law [21]. EPR laws are legislative tools that assign producers responsibility for the end-of-life of their products. These laws set out requirements to reduce the use of plastic packaging and the production of plastic waste to meet the state's recycling and climate targets. For example, California's Plastic Pollution Prevention and Packaging Producer Responsibility Act (S.B. 54) aims to see 100 % of packaging in the state recyclable or compostable, 65 % of all single-use plastic to be recycled and a 25 % reduction in the use of plastic packaging by 2032 [22]. Additionally, to encourage packaging reuse, the law offers the incentive of making reusable packaging exempt from EPR programme fees. More recently, in the U.S., as of July 2024, the Biden-Harris Administration has released its first Plastic Strategy to tackle plastic pollution. The White House's Plastic Strategy presents ongoing and proposed federal actions to reduce plastic waste, focusing on eliminating single-use plastics across the federal government and national supply chain. The Plastic Strategy aims to phase out federal procurement of single-use plastics from food service operations, and events by 2027 and all federal operations by 2035 [23].

In the eastern hemisphere, China has also implemented necessary policies and legislation to guide plastic packaging waste management. In 2017, the General Office of the State Council issued the Implementation Plan for Prohibiting the Entry of Foreign Garbage and Advancing the Reform of the Solid Waste Administration System. This legislation banned 24 different foreign waste imports, including plastic packaging waste, from domestic sources immediately from the end of 2017 and from industrial sources by 2019 [24]. In 2021, the National

Development and Reform Commission and the Ministry of Ecology and the Environment jointly issued China's "14th Five-year Plan" Plastic Pollution Control Action Plan, which details measures to reduce the production and use of plastic, develop alternatives for plastics, and substantially reduce the amount of plastic waste in landfills from 2021 through 2025 [12,24]. Other countries who have also introduced policies and legislation to tackle plastic waste include Japan, who introduced the Resource Circulating Strategy for Plastics in 2019, which aims to achieve a 25 % reduction in the generation of single-use plastic waste per year and have a total of 60 % of plastic materials from packaging be recyclable by 2030, and Australia who launched their National Plastics Plan in 2021 which aims to see 70 % of plastic packaging recyclable, reusable or compostable by 2025 [12,25].

A potential solution to reduce the production of plastic packaging waste and assist in meeting sustainable development targets that has received considerable interest is the implementation of reusable packaging schemes [26]. According to Greenwood et al. identifying routes to prolong the use and maintain the value of plastic packaging is key to reducing plastic waste [26]. Reusable packaging schemes aim to do precisely this by extending the lifespan and worth of plastic packaging through circular systems wherein the packaging is returned at the end of its use, cleaned and used for the same purpose once more [26]. Based on the findings of various life cycle analyses (LCA's), reusable packaging systems can potentially reduce plastic waste and its overall environmental impact; however, numerous elements must be considered to ensure their viability [26–29].

When considering the viability of reusable packaging models, the properties of the packaging material are an aspect that is often neglected. As mentioned, most plastic packaging available today is designed for single use and may not be suitable for repeated use [9]. To our knowledge, limited research is dedicated to investigating the influence of repeated use or prolonged exposure to the harsh conditions of the commercial/industrial cleaning process on the material properties of packaging. Additionally, there is minimal research available towards the suitability and enhancement of plastic packaging for reusable models. For reusable packaging schemes to be a viable solution for the future, maintaining the integrity of the packaging and retaining the packaging material's properties is essential to ensuring that it can effectively contain, protect and preserve its contents throughout its lifetime. The purpose of this article is to comprehensively review the function and properties of common food packaging materials to assess their suitability for reusable food packaging applications.

## 2. The functions of food packaging

Food packaging plays an essential role in the modern food industry as it aims to preserve product quality and guarantee food safety throughout its distribution and shelf life [30]. Its main objective is to facilitate food transportation, protect food from environmental factors and provide consumers with ingredient and nutritional information [31]. Without food packaging, product distribution would be a messy, inefficient and costly exercise, and modern mass consumer marketing would be virtually impossible [32].

In today's market, multiple types of food packaging are available, manufactured from many different materials for various applications [33]. For example, paper bags are used for baked goods, plastic trays for fresh meat and aluminium cans for beverages. For the most part, these packaging types have been successful in their respective applications, and the reason behind this success is that they effectively serve several basic functions. Depending on the source of literature, these functions can vary. Jacob states that the three P's, i.e., preservation, protection and presentation, are the three essential functions of food packaging [34]. Although these determinations are logical, they may be too simple and do not consider other aspects, such as consumer usability, compared to Robertson's four functions: containment, protection, convenience and communication [32,33]. Many reviews refer to Robertson's four

functions or a variation of them when discussing the role of food packaging. They also include secondary functions such as traceability and tamper indication as illustrated in Fig. 1 [35–38].

### 2.1. Containment

According to Robertson, containment is a function often overlooked. All products, despite their nature, must be contained throughout their distribution and shelf life. If a package cannot contain a product during this period, then it is not a successful design. Without adequate containment, produce is more likely to be contaminated or lost to the environment. Robertson suggests that food packaging is still available today that does not serve this function, as evidenced by the numerous accounts of packages that have leaked their contents, particularly around closures and seals [32]. Therefore, containment is an essential and primary function that significantly contributes to the protection and preservation of produce during distribution [35].

### 2.2. Protection and preservation

Before the definition of containment, protection was regarded as the primary function of food packaging. The protection offered by a package is an essential element of the food preservation process. If a package's integrity is compromised, its contents are no longer considered preserved [33]. The damage a food package and its contents may sustain during distribution and shelf life can be categorised into three classes. The first class is physical damage exerted by impact, vibrations, compressive forces etc. The second class is compositional change as a result of exposure to environmental factors such as moisture, gases, odours, UV light, etc. The final class is biological damage (spoilage) due to attack by insects, rodents and microorganisms [39]. An effective packaging design should be capable of protecting its contents from these outside influences.

### 2.3. Convenience

Convenience refers to packaging design features that facilitate the product's ease of use. This includes features such as the ability to reseal, safely stack/store and place the package directly in a microwave. In addition, it includes design elements such as designing the packaging size to provide adequately sized portions of the product [33]. In this age, consumers may work longer hours, spend more time commuting and desire to maximise their limited leisure time; as a result, demand has been created for convenience in meal preparation and packaging solutions that support their hectic lifestyles [40]. Convenience features can

add value and give a competitive advantage to products but can also influence the amount of post-consumer waste requiring disposal [39].

### 2.4. Communication and marketing

Packaging can be considered the face of a product, providing the consumer with their initial impression of the product [39]. Food packaging is often designed using various shapes, colours and symbols to enhance the product's image and to promote the product over its competitors. These features allow consumers to recognize products instantly and for supermarkets to operate on the self-service model [32]. Food packaging also serves to convey information about the product to the consumer. According to Regulation (EU) 1169/2011, food packaging must state the product's name, the net weight of the packaged product, the date of minimum durability, the names and addresses of manufacturers/packagers, ingredient lists and nutritional facts [41]. In the U. S. the Food and Drug Administration (FDA) and Federal Food, Drug, and Cosmetic Act (21 USC 343) specify similar labelling requirements [42]. Packaging is often designed to provide additional features such as cooking instructions and brand information; however, these features can influence waste production [39].

### 2.5. Tamper indication

Tamper-evident packaging is a particular type of food packaging that features a mechanism that makes it apparent if a package has been previously opened [43]. These mechanisms typically include seals/labels, special membranes, breakaway closures and printed text/graphics that irreversibly change upon opening as shown in Fig. 2. Although these design features can potentially reduce or eliminate the risk of tampering and promote consumer assurance that the products they are purchasing are unopened, fresh and safe, they do require additional packaging materials, which can make the disposal process more complex [39].

### 2.6. Traceability

The FDA defines traceability as the ability to track the movement of produce and its ingredients throughout all stages of the distribution chain [44]. Traceability systems typically have three main objectives: to improve supply chain management, facilitate trace-back for food safety/quality and differentiate/market products with subtle or undetectable quality attributes [45]. Traceability mechanisms incorporated into food packaging typically take the form of a unique code. Nowadays, these codes are available in various formats, such as printed barcodes,

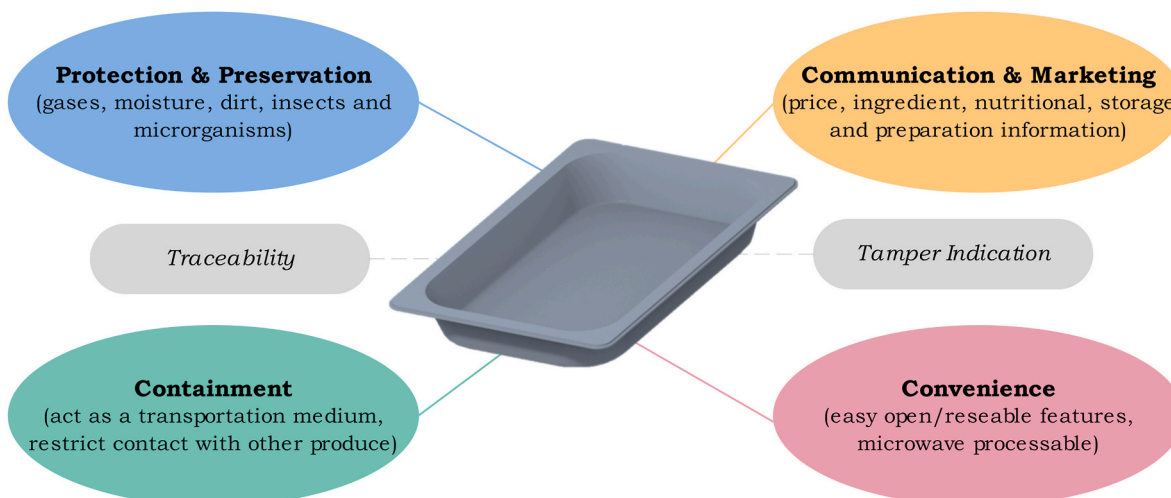


Fig. 1. The primary and secondary functions of food packaging.

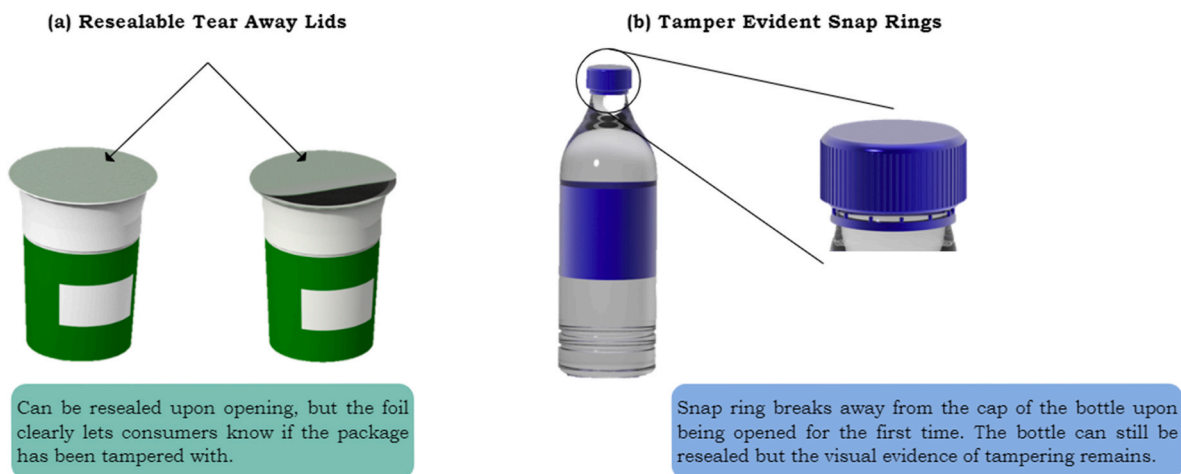


Fig. 2. Examples of tamper-evident packaging features: (a) A resealable tear away lid on a plastic container. (b) A tamper evident snap ring on a beverage bottle cap.

RFID tags or QR codes which machines can readily scan to provide product information [39].

### 3. Food packaging materials

Food packaging plays a significant role in protecting and preserving its contents throughout their distribution and shelf life [46]. As discussed in the previous section, it fulfils this role by carrying out various functions. A package must be capable of carrying out these basic functions to be considered an effective and successful design. To ensure the development of successful packaging design, Paine and Paine suggest that four design factors be considered: the product's nature, the packaging material and its properties, marketing requirements and the hazards associated with distribution [47]. These are all important considerations; however, perhaps the most critical of these is the material's properties and the relationship between them and the remaining three design factors.

Material properties have one of the greatest influences on the packaging's ability to protect its contents and maintain food quality and safety [48]. They determine how a material will perform in its application, and their requirements should be carefully considered. For

example, depending on the product (i.e., fruit/vegetables, dairy, meat, baked goods), material properties that not only provide physical protection but control product maturation and extend shelf life may be required [46]. Similarly, depending on the potential hazards associated with transport (i.e., compressive/impact forces, vibrations, moisture damage), the material may require a certain level of mechanical performance. Marketing requirements such as display features and nutritional information may require specific aesthetic properties or compatibility with a particular process. Wani et al. suggest five critical property considerations when selecting a suitable packaging material, as seen in Fig. 3 [48].

Packaging can be generally divided into two categories: rigid and flexible packaging. Rigid packaging typically consists of items such as bottles, cans, jars and trays; while flexible packaging refers to items such as bags, films and pouches [49]. Throughout history, various materials such as glass, metals, paper and plastics have been used to manufacture these items [46]. The majority of these materials have worked successfully, each having advantages and limitations to their use [50].

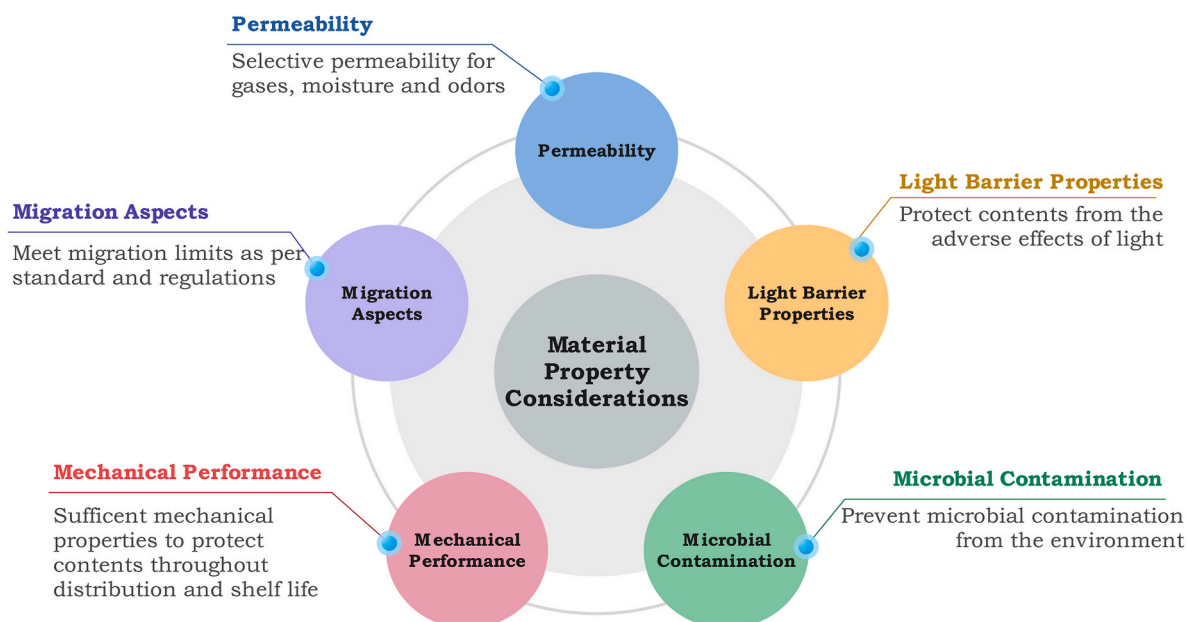


Fig. 3. Five critical property considerations for selecting a suitable food packaging material.

### 3.1. Glass

Bottles and jars manufactured from glass are considered one of the oldest forms of rigid food packaging, dating back to approximately 1500 B C E [51]. Glass produced from the melting and mixture of limestone, soda, sand and silica was traditionally a preferred option for the storage of liquids. This was due to its high chemical inertness and excellent impermeability to gases and vapours which allowed product quality to be maintained for long extended periods without altering taste or flavour [39]. In addition, glass exhibits excellent transparency allowing the contents to be clearly seen, which can also be altered through the incorporation of minerals to protect light-sensitive contents [52]. Glass is also thermally stable, making it suitable for hot-filling applications and compatible with today's heat sterilisation and sanitisation processes [47]. Finally, glass benefits the environment because it is both recyclable and reusable. End-of-life recycling of glass is common place, where glass can be infinitely recycled without an apparent reduction in material properties; however, prior separation of glass by colour is required to achieve process efficiency [53].

Glass reuse typically occurs through deposit return systems (DRS) where a surcharge is placed on purchased products and rebated once the empty packaging is returned [53]. This approach can be sustainable since the material does not have to go through any reprocessing prior to its return into the system; however, Dyer suggests that due to the large variety of glass packaging now available, which can often originate from remote regions, glass return systems can also be uneconomical and impractical in terms of logistics [54]. Therefore, in many countries glass packaging reuse has declined, magnifying the need for recycling [54].

One limitation of glass packaging is its high transportation costs [39, 55]. As glass is a fragile material and will shatter if exposed to impact or vibrational forces, it cannot be stacked/packed into transit containers as tightly as other materials, reducing the number of items that can be transported per shipment [56]. This consideration, combined with the material's increased weight, makes glass a costly and inefficient material to ship [39,56]. Another disadvantage to glass usage is that it is an energy intensive material to produce. Glass used in typical food packaging containers is processed at elevated temperatures of 900–1600 °C, which requires substantial energy input to achieve [52,57]. The incorporation of recycled glass reduces this energy requirement but only by 3 % for every 10 % of glass cullet used in place of virgin raw materials [58]. Carbon dioxide (CO<sub>2</sub>) vapours are also produced during production, further contributing to glass's higher carbon footprint than other packaging materials [57].

Despite these drawbacks, glass packaging technology has continued to develop, with focus being directed on improving strength and mass properties [52]. Although glass usage will not surpass materials such as metal and plastic in volume, its market does continue to grow, with the FEVE - European Container Glass Federation reporting an 18.6 % increase in container glass production in Europe from 2012 to 2021 [59]. Unfortunately, as a packaging material, widespread glass use is still limited by its high environmental impact due to its heavy weight and high energy requirement to manufacture, highlighted in previously conducted LCA's [60–62]. Reuse of glass packaging does lower its overall environmental impact; however, based on the findings of an LCA carried out by Cottafava et al. a reusable glass cup of 360 g would have to be reused more than 35 times to produce fewer CO<sub>2</sub> emissions than a 7 g single-use polypropylene (PP) cup [62]. In comparison, a 40 g reusable PP cup would only have to be used more than 7 times [62]. Therefore, for glass reuse to be a feasible strategy, aspects such as package weight, transportation distance, and energy use associated with cleaning must be carefully considered in addition to ensuring that the package can withstand the required number of use cycles to compensate for the high environmental impact of manufacture and transport [61].

### 3.2. Papers

Paper is another material with a long history in packaging and is believed to have been used as early as the first or second century B.C.E. to produce food wrappings and is considered one of the oldest forms of flexible packaging [63]. Despite its invention several centuries prior, knowledge of the technique of paper fabrication only reached Europe and America during the 14th and 17th centuries, respectively. It was the latter 19th century that saw paper usage accelerate to meet the needs of the manufacturing industry [64]. Today, paper is increasingly used in food and beverage packaging and represents the largest share of packaging waste in the EU of 32.7 M tonnes (41.1 %), being higher than the next largest materials combined, plastic (19.4 %) and glass (19.1 %) [65, 66].

Paper is regarded as a sheet material constructed from an interlaced network of cellulose fibres derived from wood pulp [64]. As it is fabricated from a natural source, paper is biodegradable and will be decomposed by microbial action if left in the natural environment [52]. Paper is highly printable and has physical properties that allow it to be manufactured into either rigid or flexible packaging. Depending on the type/amount of fibre and fabrication technique, many different types with varying properties can be produced for different applications [64]. For example, heavy-duty Kraft paper used for bags and wrappings is produced from a sulphate treatment process and is considered one of the strongest of all papers. In contrast, the lighter and weaker sulphite paper, which is put through an additional glazing process to enhance its appearance, wet strength and oil resistance, is commonly used in small bags and wrappers for baked and confectionery goods [39].

Although paper and paperboards provide reasonably good mechanical performance for their lightweight and good processability at low cost; they fall short in their barrier properties due to their porous nature and are non-heat sealable. When they absorb moisture, their mechanical properties diminish significantly. As a result, paper often has to be combined with polymeric materials to improve these properties, which increases cost and complicates recyclability [67,68]. Concerning end-of-life aspects, paper recycling is one of the most well-established recycling schemes applied to waste materials today, with EU and U.S. paper recycling rates reaching 73.9 % and 65.7 %, respectively, in 2020 [69–72]. However, one drawback to paper recycling is that it can only be successfully carried out a limited number of times. Presently, paper packaging is recycled on average 3.5 times; however, up to 7 cycles is technically feasible [68,73]. Beyond 7 cycles, significant fibre shortening occurs due to the nature of the recycling process, where fibres become too weak and too short to produce new raw materials [74]. Another barrier to paper and paperboard recycling is that packaging must be separated into their technical grades, which can be a complex process when handling papers combined with metallic or polymeric films [68,73]. Some paper grades, such as those coated with wax, silicone or UV-cured adhesives, are challenging to separate and, thus, are not widely recycled [75]. For example, disposable paper cups lined with polyethylene (PE), although technically recyclable, are not because of the challenges they present to recyclers [76]. Triantafillopoulos and Koukoulas discuss that when PE-coated papers enter a recycling facility, they cause operational problems and additional costs for the recycler [76]. They explain that during re-pulping, the PE layer is broken down into flakes, which can clog the fine screens, separating recyclable fibres from contaminants [76]. The plastic material that remains on the screen ends up melting out on the hot rollers during paper manufacturing causing downtime on the paper production line [76]. To combat these issues paper producers recommend that paper packaging be designed with a maximum of 5 % plastic content [77]. Additionally, contaminated paper waste, such as coffee filters and sanitary napkins, cannot be recycled at all [68]. The final drawback of paper as a packaging material is its negative environmental impact. Paper consumption has increased by 400 % globally over the last 40 years, contributing to mass deforestation, with approximately 3 billion trees being felled each year for the

production of paper-based packaging [78]. Additionally, paper production has a higher energy requirement, with one paper bag reported to require 3–4 times more energy to produce than one plastic bag [78,79].

### 3.3. Metals

Metals are a material that offers excellent versatility in food packaging applications and are perhaps still one of the most trusted materials for the long-term storage of perishable goods [80,81]. The use of metal as a food packaging material dates back to the early 19th century with the invention of the first heat-processed food-can [81]. This invention was possible due to a technique known as tin plating, whereby cheaper metals, such as low-carbon steel, were coated with thin layers of the corrosion-resistant metal tin [63]. This invention changed society, sparking the use of tin plate for similar applications such as beer and aerosol cans. However, when a shortage of tin plate occurred in Switzerland during World War II, an alternative material was sought, and the world would see the utilisation of aluminium in the first seamless cans [81].

Today, metals such as aluminium and tin-plated steels are still widely used to manufacture cans and containers as well as foils and laminates due to their excellent combination of mechanical, thermal and barrier properties in addition to exceptional ease of processability [82]. In the U.S. during 2020, 45.2 % of collected aluminium beverage cans were recycled, while in the EU, 85.5 % and 73 % of steel packaging and aluminium cans were recycled, respectively, making metals one of the most recycled materials [83,84]. Additionally, metals experience no reduction in intrinsic properties when recycled, making them suitable for repeated use [85].

Metal's opaque nature is an advantage when required to protect light-sensitive contents but a disadvantage otherwise, as it prevents contents from being seen [52]. Therefore, metals rely upon secondary packaging such as labels and films, to relay product information to the consumer. Metals also have a higher cost of production and transport in comparison to lighter materials such as paper and plastic due to metal's higher density. Additionally, there have been various environmental concerns over CO<sub>2</sub> emissions from metal manufacturing facilities and the depletion of natural resources [82,86].

When exposed to humid environments or acidic substances, metals containing iron, such as tin-free steels, tend to corrode and produce hydrogen gas that can cause bloating of the container [52,86]. Fine gauge metal packaging such as aluminium foil can also contain microscopic pinhole defects [52]. Therefore, metal packaging must be coated with a resin/lacquer or laminated with a polymeric material to form an inert barrier on the surface of the metal to prevent chemical corrosion and maintain barrier properties [52,81]. However, one drawback to combining metals with these materials is that although each component of the laminate/film is technically recyclable, like papers, layers must be separated from each other via complex processes, preventing feasible recycling [57,87]. Finally, metal packaging also poses various health concerns regarding the migration of packaging components. Metallic substances such as tin (Sn), lead (Pb), aluminium (Al), and chromium (Cr) are all reported as common migrants from metal packaging [86]. The migration of bisphenol A (BPA) from containers coated with epoxy resins has also been reported [88–90].

### 3.4. Polymers

Polymers are the most recent material to have seen success when employed as a food packaging material. First discovered during the 19th century, polymers were primarily reserved as alternative materials to glass and silk for military applications [91]. Only by the 1970s, would commercially available materials used today, such as polyethylene terephthalate (PET), see their initial use as beverage containers [63].

Over the last 50 years, the use of plastics as food packaging materials has increased exponentially due to their advantages over traditional

materials [92]. Although polymers cannot offer the same degree of mechanical performance and thermal stability as some traditional materials, manufacturers are still willing to compromise on these properties to reap the potential benefits of using a lighter and cheaper material. For example, polymer materials cannot provide the same strength and stiffness as glass but have much greater impact resistance, reducing the risk of product loss through damaged packaging. In addition, polymer materials such as PET can be up to 85 % lighter than glass [93]. According to Marsh, replacing glass bottles with PET alternatives on an airline, can yield a potential saving of over \$1 million in fuel costs due to the weight reduction [94]. Compared to metals, polymers are again inferior in their mechanical performance and thermal characteristics; however, they provide other desirable characteristics, such as corrosion resistance and transparency which metals lack [95]. Paper loses mechanical strength when it absorbs moisture; however, polymers retain their mechanical performance and have improved barrier properties in comparison [95]. Polymers also possess excellent processability with the ability to be heat sealed, easy to print, extruded into films, and moulded into various shapes and structures [39].

Polymers have three main drawbacks in the context of food packaging materials. The first drawback is their variable permeability, meaning that different polymer materials exhibit different levels of permeability to light, gases, vapours and other low molecular weight molecules [39]. For instance, polymers such as high-density polyethylene (HDPE) and PP succeed at providing structural support; however, they are far more permeable to gases and vapours than barrier polymers such as ethylene vinyl alcohol (EVOH) and polyvinylidene chloride (PVDC) [67]. For high-performance applications such as modified atmosphere packaging (MAP), no single-layer material can provide an adequate barrier; therefore, polymers are often combined into multi-layer structures with customised property profiles to meet the demanding requirements of food packaging [96].

The second drawback is that most polymers used in single-use packaging (SUP) are non-biodegradable and, while technically recyclable, can be challenging due to current infrastructure. Synthetic polymers are highly durable, which can be argued is an advantage. However, when they are not disposed of appropriately, they will not readily degrade in the natural environment and persist for hundreds of years, which has been the cause of many environmental issues and concerns [95]. According to Kol et al. the biggest challenge faced during plastic recycling is the complexity of current waste streams [97]. Presently post-consumer packaging waste is comprised of a wide variety of polymer materials which, due to their differences in chemical composition and processing requirements, are not compatible with each other [98]. An example of this incompatibility exists between PET and polyvinyl chloride (PVC). When PVC is processed at the higher processing temperatures of a PET recycling stream, hydrochloric acid gas is produced, which readily degrades PET [98]. Conversely, if PET is introduced to a lower processing temperature PVC stream, the resulting recycled PVC material will contain undispersed crystalline regions of PET, reducing material quality [98,99]. Therefore, in waste streams, PET and PVC must be separated into their resin identification codes (RIC) seen in Fig. 4.

Another aspect that complicates disposal is materials featuring additives/coatings and contaminated materials [100]. As mentioned previously, polymer materials are often coated, printed with dyes, filled with additives and combined with other materials, such as metals, papers and other polymers, to meet the high property requirements of food packaging [96,97]. However, these additives/coatings must be removed for successful recycling, which can be a huge hurdle to overcome [100]. Removal of these substances requires advanced and sophisticated technology, which not all recycling facilities currently possess [101]. Consequently, recycling facilities lacking this required infrastructure tend to concentrate on more easily separated waste, such as rigid mono material structures like PET beverage bottles and HDPE milk containers [98]. Concerning contaminated plastics such as food packaging, these

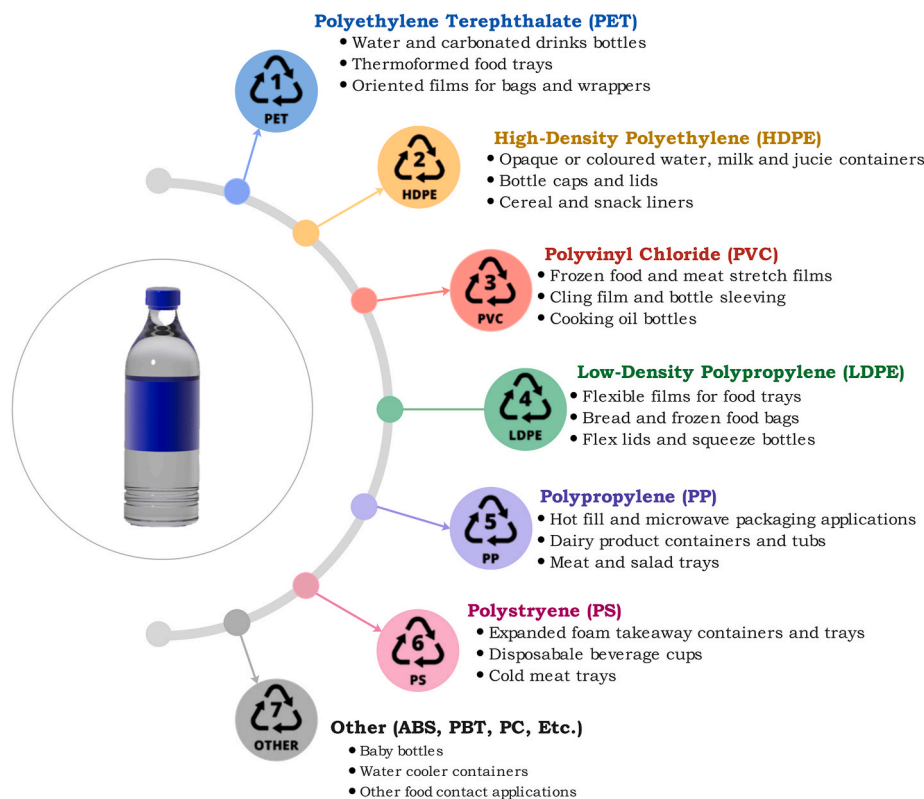


Fig. 4. The most commonly used plastic packaging materials, their typical applications and resin identification codes (RIC).

must be cleaned and purified before processing; however, this can be costly owing to the need for chemical detergents, drying and wastewater treatment [100]. It can also be quite challenging to remove food contaminants, such as odour components which are only partially removed by caustic cleaning [102]. Therefore, plastic food packaging suffers from poor recycling efficiency [100,102].

The final drawback is that the use of polymers in food contact applications can give rise to safety concerns among consumers [48]. In recent years the issue of the potential migration of additives and non-intentionally added substances (NIAS), such as oligomers, has been raised on numerous occasions and addressed in several papers [103–106]. These works often highlight that additives/monomers such as phthalates and BPA are endocrine disruptors, meaning they interfere with the function of the endocrine system, which regulates hormone secretion [106]. In response to this concern, the migration of these compounds is continuously monitored, and permissible limits are set by regulatory authorities such as the EU and FDA to ensure the safety of available food products [48].

Despite these three drawbacks, polymer materials remain a popular choice for food packaging applications. They are still considered a cost-effective solution that offers a wide variety and an overall good balance of mechanical performance, thermal stability and barrier properties combined with ease of processability [52].

#### 4. Polymers used in food packaging

Presently, polymers used to produce food packaging are predominantly petroleum-based, meaning they are derived from petrochemicals such as olefins, aromatics and other synthetic gases [107]. For a long time, petroleum-based polymers such as PET, HDPE, PP and PVC have been extensively used due to their economic abundance and advantageous properties, accounting for almost 10 % of global oil consumption in 2019 [108]. The process in which polymers are produced is referred to as polymerisation, and generally speaking, there are two types:

addition and condensation polymerisation. Addition polymerisation consists of polymer chain growth as a result of addition reactions between two or more unsaturated monomers, typically containing a double carbon bond [109]. However, condensation polymerisation involves the reaction of monomers containing functional groups such as amides and esters to produce a polymer and smaller molecules such as water as a by-product [109].

Polymers can be broadly classified into two groups: thermoplastics and thermosets [94]. Thermoplastics are those that can be softened and reprocessed multiple times when exposed to heat. In contrast, thermosets cannot be reprocessed due to the formation of chemical cross-links within their molecular structure [94]. As thermoplastics can be easily reshaped and moulded, they are ideal for the manufacture of food packaging, while thermosets, despite their strength and durability, tend to be reserved for engineering applications [39]. Many different types of thermoplastics are being used as food packaging materials. These materials consist primarily of polyolefins, polyesters and other barrier-type polymers. These materials are used to fabricate both rigid and flexible packaging; however, only plastic materials currently used or with the potential to be used in rigid reusable packaging will be considered and discussed. Examples of commercially available reusable plastic packaging products can be seen in Table 1.

As mentioned earlier, to our knowledge, the amount of literature available concerning the suitability of polymer materials for reusable packaging applications is sparse. Few studies investigate the effect of repeated contamination and cleaning on the cosmetic quality, intrinsic properties or functionality of the packaging material/object. However, having said that a small number of studies do exist that attempt to fill this knowledge gap, an overview of which can be seen in Table 2. The findings from these studies, along with other relevant works, will be discussed in the following sections with the aim of assessing the suitability of various polymer materials for reusable food packaging applications.

**Table 1**

Examples of commercially available reusable plastic packaging products.

Company/Product Name	Material	Reference
Vytal Reusable Bowl	PP <sup>a</sup> bowl & TPE <sup>b</sup> lid	[110]
REBOWL Lunch Dish	PP bowl & lid	[111]
Thermohausser Good Bowl	PP box & lid	[112]
Petainer Refillable Bottle	PET <sup>c</sup> bottle	[113]
EcoBox Bowl	PBT <sup>d</sup> bowl & PE <sup>e</sup> lid	[114]
reCircle Box	PBT/GF <sup>f</sup> bowl & PP lid	[115]
FIRPLAST R'Box Bowl	PBT/20 % GF bowl & PP lid	[116]
reCircle Transparent Box	Tritan™ container & lid	[115]
FIRPLAST Reusable Bowl	Tritan™ bowl & PP lid	[117]
Monbento MB Gourmet	Tritan™ container & lid	[118]

<sup>a</sup> Polypropylene.<sup>b</sup> Thermoplastic elastomer.<sup>c</sup> Polyethylene terephthalate.<sup>d</sup> Polybutylene terephthalate.<sup>e</sup> Polyethylene.<sup>f</sup> Glass fibres.

#### 4.1. Polypropylene (PP)

PP is an addition polymer produced from the polymerisation of propylene monomers into a linear structure with protruding methyl groups (CH<sub>3</sub>) as seen in Fig. 5 [130]. PP is widely used in the food packaging industry because of its low density (0.89–0.91 g/cm<sup>3</sup>) combined with relatively low cost [131]. PP has three stereochemical forms; isotactic, syndiotactic and atactic; however, only isotactic PP has common commercial use [132]. Formed through the utilisation of a Ziegler-Natta catalysis during polymerisation to promote the formation of crystallisable polymer chains, isotactic PP (iPP) is semi-crystalline and, as a result, has a good balance of physical, mechanical and thermal properties [133]. PP is also produced as a copolymer by incorporating a small amount of ethylene comonomer. The addition of ethylene serves to reduce the crystallinity found with the homopolymer to produce a grade with increased optical clarity and flexibility and a reduced melting point. Impact modified grades are also available, where PP is blended with an elastomeric phase such as ethylene-propylene rubber (EPR) to enhance impact properties [132].

##### 4.1.1. PP homopolymers (PPH)

PPHs are most extensively used for the application of rigid packaging [133]. High molecular grades (≈600,000 g/mol) are typically used to produce blow-moulded bottles and thermoformed trays, while low molecular weight grades (≈200,000 g/mol) are used for injection moulded products [132]. Flip-top lids and closures are commonly manufactured via injection moulding because PP can provide a durable *living hinge* feature, i.e., a lid/cap that can be opened and closed repeatedly without being removed from the container, e.g., sauce bottles [130].

PPHs are characterised by their high crystallinity (40–70 %) [134]. Although their percentage crystallinity is not high as HDPE (70–80 %), they still exhibit a higher melting point of 160–180 °C [134,135]. As a result of this high melting point, PP can be used in microwaves and for hot fill and sterilisation applications up to 115–130 °C making it a good candidate for reusability [130,136]. PPHs also exhibit improved tensile properties over HDPE but at the cost of impact resistance [132]. This becomes significant when PP is exposed to sub-zero temperatures. Unlike HDPE, PPHs become increasingly brittle below 0 °C and exhibit stress cracking below –5 °C [130]. This is because PP has a glass transition temperature (*T<sub>g</sub>*) of –20 °C to –5 °C compared to HDPE of approximately –125 °C [137]. At 0 °C, PP begins to transition into the hard-glassy state and, as a result, loses a degree of impact resistance. Therefore, caution must be exercised when using PPHs for frozen food applications.

PPHs are chemically inert and resistant to most commonly found organic and inorganic chemicals, as well as oils and fats [130]. However,

**Table 2**

An overview of existing work dedicated to assessing the suitability of polymer materials for reusable food packaging applications.

Polymers Investigated	Focus of Study	Characteristics Assessed	Reference
PP <sup>a</sup> , PET <sup>b</sup> , PC <sup>c</sup>	Investigation into the effect of repeated washing on PP, PET and PC bottles to determine their feasibility for reuse in food packaging	Barrier properties Hydrophobicity Migration aspects Microbial safety Retention of odours	[119]
PP, PET, PC	Evaluation of PP, PET and PC for the application of reusable cups and bottles.	Barrier properties Hydrophobicity Migration aspects Microbial safety Cosmetic quality	[120]
PP, PET, PEEK <sup>d</sup> , FEP <sup>e</sup> , PCTFE <sup>f</sup> , PP/PA6 <sup>g</sup> , PP/PA6/PP	Evaluation of the stain resistance of different commodity and performance packaging films exposed to various food colouring substances.	Chemical changes Thermal characteristics	[121]
PC	To identify and describe the kinetics of release of different molecules migrating from reusable PC food contact containers.	Migration aspects	[122]
Ag <sup>h</sup> -Graphene-TiO <sub>2</sub> <sup>i</sup> PLA <sup>j</sup> Composite	To characterise and evaluate the preservation efficacy of nano-Ag-graphene-TiO <sub>2</sub> PLA films during storage of curd cheese.	Mechanical properties Barrier properties Migration aspects Antibacterial activity	[123]
PHBV <sup>k</sup> and PHBV Composites	Study of the structural and physical-chemical stability of PHBV/PHBV composites under dishwashing conditions.	Cosmetic quality Thermal characteristics Mechanical properties Morphology Migration aspects	[124]
PP, PS <sup>l</sup>	Investigate the influence of reusable PP and PS packaging crates on citrus loss during transportation.	Material durability during transport Environmental impacts	[125]
ZnO <sup>m</sup> /LDPE <sup>n</sup> Composite	Determine the effect of repeated contact to food simulants on the properties of ZnO/LDPE composite films for reusable packaging.	Chemical changes Morphology	[126]
rPET <sup>o</sup>	Investigate the challenges associated with cleaning and assess the suitability of existing rPET thermoformed trays for cleaning and reuse.	Physical deformation Mechanical properties Thermal characteristics Chemical changes	[127]
PP, PBT <sup>p</sup> , SAN <sup>q</sup> , PC, Tritan™	Investigate the effects of repeated contamination and washing on various types of reusable meal containers.	Physical deformation Cosmetic quality Odour retention	[128]
AgNPs <sup>r</sup> /PP Composites, Silicone	Assess the degree of silver and microplastic release from AgNPs/PP antibacterial food containers under conventional use and microwave heating.	Migration aspects Chemical changes	[129]

<sup>a</sup> Polypropylene.<sup>b</sup> Polyethylene terephthalate.<sup>c</sup> Polycarbonate.<sup>d</sup> Polyetheretherketone.<sup>e</sup> Fluorinated ethylene propylene.<sup>f</sup> Polychlorotrifluoroethylene.



- <sup>g</sup> Polyamide 6.  
<sup>h</sup> Silver.  
<sup>i</sup> Titanium dioxide.  
<sup>j</sup> Polylactic acid.  
<sup>k</sup> Poly (3-hydroxybutyrate-co-3-hydroxyvalerate).  
<sup>l</sup> Polystyrene.  
<sup>m</sup> Zinc oxide.  
<sup>n</sup> Low-density polyethylene.  
<sup>o</sup> Recycled polyethylene terephthalate.  
<sup>p</sup> Polybutylene terephthalate.  
<sup>q</sup> Styrene acrylonitrile.  
<sup>r</sup> Silver nanoparticles.

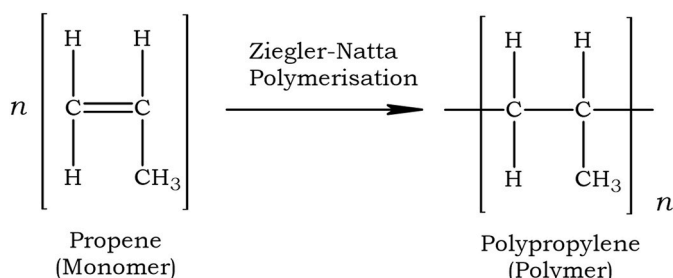


Fig. 5. The polymerisation reaction of propene monomers into polypropylene.

they can emit odours and exhibit stains when used for substances such as sauces and soups even after washing, as demonstrated in white paper by YOYO Boost Reuse [128]. When used to store curry and tomato sauces for periods of 1 h, 1 day and 3 days, opaque PP containers retained odours of the food substance and displayed staining post-washing [128]. Containers also displayed scratches; however, this was believed not to be caused by dishwashing, as control samples also featured scratches to the same extent. The authors suggest that scratches most likely occurred during transport and handling of containers at the retailer premises [128].

The barrier properties of PP are again comparable to that of HDPE. They have a reasonably good barrier to water vapour but a poor barrier to oxygen ( $O_2$ ) and  $CO_2$ , making them unsuitable for oxygen-sensitive foods when used alone and thus must be laminated with a barrier material such as EVOH or PVDC [130]. Another method of improving barrier properties that has emerged in recent years is through the incorporation of nanocomposites. In a study by Khalaj et al. samples of PP nanocomposites containing montmorillonite (OMMT) and iron nanoparticles (FeNPs) showed promising improvements in  $O_2$  and water vapour barrier properties [138]. This improvement was believed to be attributed to two distinct reasons. The first reason was that the OMMT nanofiller acted as a physical obstacle within the PP matrix, creating a longer and more complex path that the  $O_2$  molecules had to navigate in order to diffuse through the material [138]. The second reason was that the FeNPs acted as oxygen scavengers capable of intercepting oxygen through chemical reactions [138]. Similar observations were also recorded by Ozcalik and Tihminlioglu, who investigated the permeability of PP films containing OMMT and coated with a corn zein nanocomposite (CZNC) [139].

Concerning their environmental impact, PPHs are widely recyclable but not without an apparent deterioration in the material's mechanical performance. This was demonstrated in a study by Eriksen et al. where PP, along with HDPE and PET, were analysed with respect to mechanical performance, thermal degradation and processability after industrial reprocessing to evaluate material quality and sustainability for closed-loop recycling [140]. In the study, the reprocessed PP samples exhibited an overall reduction in both tensile and impact strength values when compared to reference values of virgin PP materials [140]. Similar observations were also made in a study by Dahlbo et al. on the recycling potential of post-consumer plastic packaging in Finland [141]. In this

study, yield strength and modulus were recorded to be 26 % and 21 % lower than virgin reference values [141]. Dahlbo et al. commented that the reduction in mechanical performance was most likely due to the chain scission that occurs from reprocessing [141]. Eriksen et al. also refer to this type of inevitable degradation and further suggest that contamination from other polymers contained in attached foils also plays a role [140]. This suggestion was based on the fact that the reprocessed PP samples with no attached foil exhibited better mechanical performance than those on which the foil remained [140]. Considering this, it can be said that the variety of PP packaging (i.e., multilayer materials, coated materials) entering waste streams and the material degradation that occurs during reprocessing, perhaps represent the two greatest hurdles towards effective PP waste recycling.

#### 4.1.2. PP random copolymers (PPC)

As mentioned previously, PPCs are produced by copolymerising propylene with small amounts of ethylene (1.5–7 wt%). The incorporation of ethylene interrupts chain regularity and thus hinders the ability of the polymer to crystallise [132,133]. Depending on the ethylene content, thermal resistance and mechanical performance can be altered. For example, the inclusion of 7 wt% ethylene can reduce the melting point of PP to as low as 152 °C [132]. Regarding their mechanical performance, PPCs are generally less stiff and more flexible than homopolymer grades [142]. Additionally, they exhibit greater impact resistance even at lower temperatures. The optical clarity of the copolymer is also enhanced, with the translucent haze associated with the homopolymer being reduced [132]. Barrier properties largely remain unaltered, with the copolymer having an adequate barrier to water vapour but a poor barrier to  $O_2$  and  $CO_2$ .

PPCs are resistant to most organic and inorganic chemicals, except for aromatic hydrocarbons [132]. However, one drawback observed by YOYO Boost Reuse is that transparent PP grades emit odours and exhibit staining to a greater extent than opaque PP grades [128]. In their white paper study, transparent PP containers emitted a stronger odour and displayed discolouration post-washing compared to the opaque PP containers when used to store curry and tomato sauces [128]. An explanation for this difference was not provided, but it was suggested that opaque PP containers are perhaps more suitable than transparent PP containers for food storage and washing applications due to staining and discolouration not being as apparent on opaque materials [128].

Another interesting observation made during this study was that the degree of staining and retention of odours was more pronounced on PP containers containing tomato sauce rather than curry sauce [128]. Narses et al. who carried out a trial of similar nature on a variety of commodity and performance packaging films, provide a detailed explanation for this difference in staining behaviour of different food substances on different polymer materials. They explain that in the case of tomato sauce, the organic pigment lycopene contained within tomatoes which is responsible for their red colour, has a non-polar chemical structure [121]. As mentioned earlier, PP also has a non-polar structure consisting of only carbon and hydrogen atoms. As illustrated in Fig. 6, due to the similarities in chemical structures and following the general rule that “like dissolves like”, polyolefins such as PP have relatively poor stain resistance to lycopene and other non-polar pigments such as beta-carotene, absorbing the molecules of these pigments into their structure [121].

In the case of curry sauce, curry contains curcumin, which has a polar structure; therefore, curcumin molecules are not readily absorbed into PP's chemical structure [121]. Narses et al. do explain that in polar polyesters such as PET, the reverse would be true, meaning these polymers would have a greater stain resistance to lycopene rather than curcumin; however, they do suggest that due to the higher  $T_g$  and chain stiffness of PET, it would still have an overall higher stain resistance as was the case in their study [121]. For example, in their study, even though PET was more prone to staining by curry rather than tomato sauce, the stain resistance of the PET to both substances was still higher

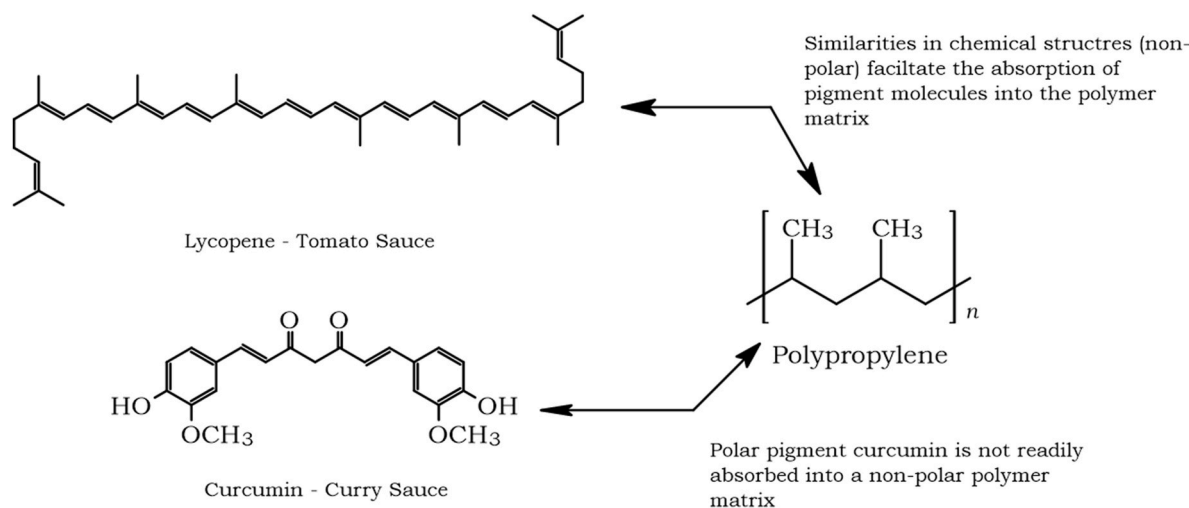


Fig. 6. The chemical structures of lycopene (tomato sauce), curcumin (curry sauce) and polypropylene [121].

than PP [121]. The authors suggest that temperature plays an important role in staining behaviour as no material during the test with a  $T_g$  above the testing temperature exhibited substantial staining [121]. Taking this into account when selecting a polymer for a food packaging application, it is important to consider the chemical structure and heat resistance of the polymer material, the constituents of the food substance to be contained and any chemical interactions that may occur between them.

#### 4.1.3. PP impact modified copolymers

PP impact-modified copolymers can be considered a two-phase mixture of the homopolymer, and copolymer formulated to give an overall ethylene content of 6–15 wt%. The copolymer acts as a rubber phase dispersed in the homopolymer and typically has ethylene content in the range of 40–65 wt% [133]. The addition of the rubber phase removes a degree of stiffness and thermal resistance from the polymer but greatly enhances impact resistance. This impact resistance is maintained at sub-zero temperatures making the material suitable for frozen food applications [132]. PP impact-modified copolymers maintain similar chemical resistance and barrier properties to other PP types but exhibit reduced optical clarity, typically being opaque because of their two-phase structure [132].

Although incorporating ethylene or other monomers to form PP copolymers can enhance desirable properties such as impact resistance and optical quality, it can also have adverse effects in relation to migration aspects due to reduced material crystallinity [143–145]. In a study by Alin and Hakkarainen investigating the migration of antioxidants from food packaging to food simulants during microwave heating, the type of PP material was shown to influence migration [146]. It was observed that antioxidant migration decreased in relation to increasing percentage of crystallinity, with the greatest migration occurring in the random copolymer with a crystallinity of 29% and the least in the homopolymer with a crystallinity of 41% [146]. Li et al. made similar observations when investigating stabiliser migration from PP in food simulants. In their study, the migration of additives also decreased with increasing the order of crystallinity [144]. Wang et al. who investigated the diffusion of limonene through different PP types, suggest that the degree of migration is related to the accessible free volume of the polymer, with the free volume being larger in PP random copolymers than in homopolymers [145]. Contradictory results were obtained by Chen and Hu, who studied the influence of PP types on ZnO nanoparticle migration where the migration rate increased with the increasing degree of crystallinity [147]. Shi et al. also recorded a similar occurrence with copper nanoparticles (CuNPs). Shi et al. suggest that in regards to CuNPs, highly semi-crystalline structures may prevent them from fully entering the polymer matrix due to their tightly packed structure. This forces the

CuNPs to embed on the surface where they can detach easily and migrate from the material [147]. Taking these findings into account, further studies are required to verify the influence of molecular structure on the migration of various additives and nanocomposites.

#### 4.2. Polyethylene terephthalate (PET)

Over the years, PET has become ubiquitous in the plastic packaging of water and carbonated beverages [148]. PET is a remarkably balanced material combining excellent transparency with good mechanical performance and barrier properties at lightweights. As a result, PET has been predominantly used as a substitute for glass [148]. PET is categorised as a polyester, meaning it belongs to a family of polymers containing ester functional groups along their main chain [149]. It is produced when terephthalic acid (TPA) or dimethyl terephthalate (DMT) is copolymerised with ethylene glycol (EG) by a condensation reaction as shown in Fig. 7 [132]. PET can exist as either an amorphous or semi-crystalline polymer depending on its processing and cooling conditions. Crystallinity in PET is usually promoted by either thermal crystallisation or stress-induced crystallisation. Thermal crystallisation involves heating the polymer above its  $T_g$  and slowly cooling it so that crystallites can form and arrange themselves in highly ordered structures [150]. However, in stress-induced crystallisation, the heated polymer is stretched and orientated, encouraging the polymer chains to align themselves in a parallel and tightly packed fashion [150]. Both methods result in a polymer that is typically opaque, referred to as semi-crystalline PET (CPET). In contrast, if PET is quenched-cooled, the polymer does not have sufficient time to form crystallites resulting in an entirely amorphous structure referred to as amorphous PET (APET). The material properties of APET and CPET can be substantially different depending on the percentage of crystallinity and morphology between the two polymers.

##### 4.2.1. Amorphous PET (APET)

First appearing as a high molecular weight grade during the 1970s, APET is ubiquitously used as an economical alternative for glass in the manufacture of water and carbonated drink bottles [132]. There are many reasons for APET's appeal in the beverage industry. The first reason is that APET, having a density of 1.29–1.39 g/cm<sup>3</sup>, is lighter than traditional packaging materials [149]. It is estimated that a 1 L APET bottle designed for containing water, weighs approximately 25 g. In comparison, that is almost 15 times less than a standard glass wine bottle (750 ml) weighing 360 g, and an improvement over metals with an aluminium can (500 ml) recorded to weigh 18 g. Another reason for APET's success as a bottle material is its excellent optical clarity which

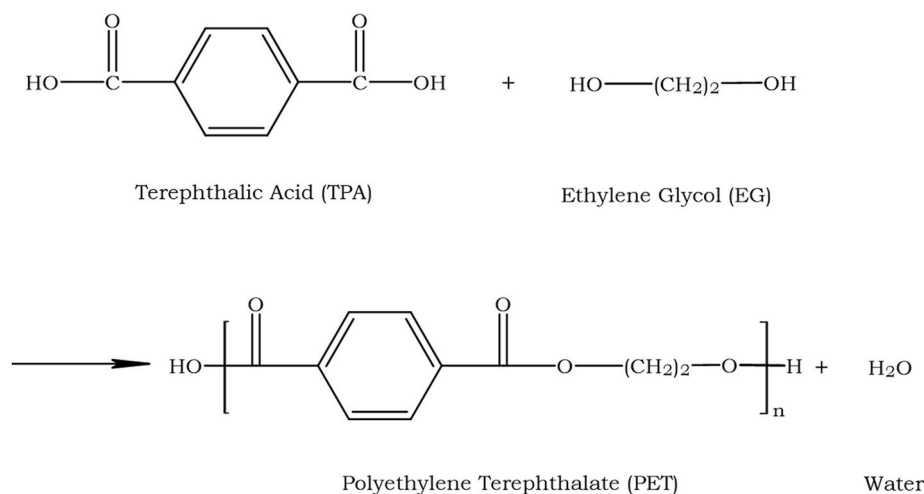


Fig. 7. The condensation polymerisation of terephthalic acid and ethylene glycol to produce polyethylene terephthalate and water as a by-product.

rivals glass. As mentioned in the previous section, APET is fully amorphous and therefore features no crystallites within its structure [149]. Crystallites tend to scatter light particles and, depending on the degree of crystallinity of the polymer and crystallite size, can result in the material exhibiting a translucent haze or being completely opaque [151]. However, since APET lacks these crystallites, it remains transparent, which has been one of APET's main appeal factors allowing contents to be displayed in an attractive manner [149].

Like most polymer materials, PET's thermal resistance and mechanical performance are influenced by its degree of crystallinity. As APET is completely amorphous, it is inferior in terms of these properties compared to CPET, which typically features a percentage crystallinity of up to 60 % [132]. However, the aromatic rings and polar ester groups present in both polymers restrict chain movement and rotation; therefore, APET retains a significant degree of strength and thermal resistance [149]. APET has a  $T_g$  of 60–84 °C and, as a result, can only be used up to 55–65 °C. Consequently, APET is unsuitable for microwave use and other hot fill applications. In terms of mechanical strength, APET proves stiffer with a Young's modulus of approximately 3.0 GPa compared to other commodity-type polymers such as HDPE (1.1 GPa) and PP (1.4 GPa). Additionally, APET exhibits significant elongation at break (280–320 %), approximately four times larger than CPET, but at a reduced tensile strength of 55–60 MPa [149].

APET has good chemical resistance to several solvents and reactants but not to strong acids, bases and hydrocarbons, particularly at temperatures approaching its  $T_g$  [149]. This vulnerability to elevated temperatures was observed in a study by Nahar et al. investigating the challenges associated with cleaning rPET food trays. During the investigation, trays exhibited physical deformation after being contaminated with various food items and subjected to a hot caustic detergent wash (55–70 °C) multiple times [127]. Additionally, increases in tensile strength and Young's modulus values were recorded after five washes. The authors suggest that this increase in mechanical properties was attributed to the polymer's chains gaining the mobility to relax and orientate themselves in a more tightly packed structure while exposed to a temperature close to its  $T_g$  during washing, supported by the observed shrinkage of packaging dimensions [127]. Finally, Nahar et al. propose that further work is required to design plastic food packaging capable of withstanding repeated washing conditions without displaying any adverse effects [127].

Another reason APET is a popular material choice in the food packaging industry is its low permeability to O<sub>2</sub>, CO<sub>2</sub> and water vapour compared to other commodity polymers. APET is reported to have a permeability coefficient to O<sub>2</sub> of 1.5 cm<sup>3</sup> mm/m<sup>2</sup> day atm, while HDPE and PP permeability coefficients to O<sub>2</sub> are 60 and 70 cm<sup>3</sup> mm/m<sup>2</sup> day

atm, respectively [149,152]. Although PET has acceptable barrier properties for many applications, Fernandez-Menendez et al. suggest APET requires improvement for use in MAP where long shelf life is required [153]. Typically, APET is combined with barrier materials such as EVOH to form multilayer materials to enhance barrier properties; however, in recent years, the successful use of nanotechnology has been documented in multiple studies [153–155]. Fernandez-Menendez et al. produced PET trays reinforced with organically modified sepiolite fibrillar nano clay and observed an 8–24 % and 8–35 % improvement in O<sub>2</sub> and CO<sub>2</sub> barrier properties, respectively. Additionally, improvements were also recorded in tensile and impact properties [153]. Majdzadeh-Ardakani et al. made similar observations investigating the physical and barrier properties of clay/PET nanocomposite bottles. Their study recorded a decrease (53 % and 74 %) in O<sub>2</sub> gas permeability and an increase in mechanical performance [154]. Mohd Noh et al. also reported increased mechanical performance and barrier properties of graphene nanoplatelet (GNP)/PET composites [155]. Considering these studies, nanotechnology could be a potential method of increasing the suitability of APET for reusable packaging applications; however, its use is still constrained by the food safety concerns associated with potential nanoparticle migration [156]. Before nanoparticles can be incorporated into commercialised packaging, questions about the migration of nanoparticles from packaging materials into food, their potential toxicity, and their long-term effects on human health need to be thoroughly addressed.

According to Nistico et al. PET can be efficiently recycled through different methods. The majority of these approaches can be categorised into either chemical or mechanical recycling [157]. Chemical recycling involves the depolymerisation of PET waste to obtain the initial monomers. Depending on the substances and the recycling conditions (temperature and pressure) utilised, chemical recycling may be carried out to open the ester bonds of polymer chains by either hydrolysis, methanolysis or glycolysis [158,159]. When initial monomers have been obtained, they may be re-polymerised via polycondensation [149]. The main advantage of this recycling route is the opportunity for possible purification of monomers from post-consumer contaminants [149]. In contrast, mechanical recycling involves taking advantage of a thermoplastic's ability to be reprocessed multiple times, whereby PET waste is sorted, washed and melt-processed. Although a relatively simple procedure to carry out, irreversible changes, such as a reduction in mechanical and thermal properties, is often caused in the material through hydrolysis, esterification and transesterification mechanisms [149]. Eriksen et al. observed these effects in a study where PET bottles and trays were mechanically recycled and reprocessed. The tensile and impact strength of the reprocessed samples was recorded to be

12.9–34.6 MPa and 2.2–10 kJ/m<sup>2</sup>, respectively, which was a considerable reduction compared to the quoted virgin values of 50–80 MPa and 130–160 kJ/m<sup>2</sup> [140]. Eriksen et al. suggest that these reductions were most likely due to hydrolysis reactions due to water exposure during the washing process [140].

Although APET is considered one of the most inert food packaging materials, multiple substances have still been reported to migrate from its structure into beverages and food simulants [160]. In the last few decades, extensive research has been carried out to identify these substances and evaluate their concentration. For example, Thoden van Velzen et al. investigated the migration of volatile substances such as benzene, styrene, and acetone from virgin and recycled PET bottles into mineral water. Although all concentration levels of detected substances were well below specific migration limits, it was noted that the concentration of benzene and styrene did increase with increasing recycled material content [161]. It was suggested that the increased styrene concentration may have resulted from the thermal degradation of polystyrene contaminants originated at the recycling step in the PET matrix. However, the increased benzene concentration is believed to have originated from the chlorine content of PVC contaminants in the recycled PET pellet mixture, which, when exposed to heat and pressure, resulted in a reaction that produced benzene [161]. Brenz et al. also conducted a study to investigate the migration of linear and cyclic oligomers from bottles manufactured from PET and other co-polyesters [162]. Across all samples Brenz et al. tested (PET, PETg and Tritan™), over 100 different types of linear and cyclic oligomers were identified [162]. The highest amount of isolated oligomer content was obtained from the PETg and Tritan™ samples, and the lowest amount from the PET samples. This led the authors to suggest that glycol-modification of PET can increase the number of polyester oligomers formed and their migration potential [162].

#### 4.2.2. Semi-crystalline PET (CPET)

CPET is characterised by its increased crystallinity over APET, which arises due to its linear macromolecular structure produced through the controlled crystallisation/use of nucleating agents during processing [163]. Crystallisation is promoted to grant thermal and dimensional stability to the packaging material [163]. CPET has an elevated melting point of 255–265 °C, which makes it suitable for use up to 120 °C unlike APET [149]. As a result, CPET has discovered widespread use as a microwaveable packaging tray. In addition, CPET can also be used for freezer storage applications, being reported to maintain impact resistance at temperatures as low as -40 °C [164]. In terms of mechanical performance, CPET exhibits similar stiffness to APET (≈3 GPa) but a greater tensile strength (70–75 MPa); however, this does come at a compromise of ductility whereby CPET exhibits a reduced percentage elongation at break of 65–75 % when compared to APET [149]. As CPET contains crystalline phases within its morphological structure, it is typically opaque, which is a disadvantage when it is required to display contents. As discussed in the previous section, crystallites scatter light particles and, depending on the degree of crystallinity of the polymer and crystallite size, semi-crystalline materials are typically opaque [151].

The chemical resistance of CPET remains similar to APET. CPET is resistant to several solvents and reactants but not to strong acids, bases and hydrocarbons [165]. There is limited research available investigating the effect of simulated use and washing on CPET packaging therefore its potential for reusable food packaging applications has yet to be fully evaluated.

In terms of barrier properties, CPET also has an acceptable barrier to O<sub>2</sub>, CO<sub>2</sub> and water vapour. Like APET, there is potential to further improve these properties by either laminating with a barrier material or through the incorporation of nanoparticles. As demonstrated by Galdi et al. who produced and characterised CPET copolyester nanocomposite-based films suitable for microwaveable food packaging applications, slight improvements in barrier properties were obtainable

when small amounts (<2 wt%) of Cloisite 20A were incorporated [163]. Higher concentrations (≈4 wt%) of Cloisite 20A did not yield any more significant improvements and resulted in a reduction in barrier properties in some cases. It was believed that this behaviour could have been due to the degradation of the polymer by thermomechanical stresses in the presence of silicate during the melt compounding processing [163]. Literature is sparse regarding CPET barrier properties and how they may be influenced using novel nanotechnologies. The majority of research focuses on amorphous grades, most likely due to their predominant use in the beverage bottle industry and as a film material [166–168]. More work is required to investigate the effect of various nanoparticles/clays, particularly with rigid CPET packaging and if they can be used to enhance the suitability of CPET for reusable packaging applications.

Like APET, CPET has also been investigated in the past for the potential migration of additives and oligomers into food substances. Begley and Hollifield investigated the migration of various oligomers from CPET, PET-coated paperboard and aluminised PET-coated paperboard trays (susceptor packaging) into corn oil during microwaving [169]. Using a high-performance liquid chromatography (HPLC) technique, they found that after 3 min of microwaving at 577 W, multiple oligomers had migrated from the susceptor packaging into corn oil, with the PET cyclic trimer oligomer recorded to have the greatest concentration [169]. Migration of only the PET cyclic trimer was then compared from all three packaging types, showing that its migration rate was approximately 70–80 times less from the CPET tray than the susceptor package [169]. It was believed that this stark difference in migration rate occurred due to the susceptor package's design. This tray was metallised with aluminium and allowed the susceptor tray to reach a higher temperature during microwaving, facilitating increased migration [169]. Concerning the PET-coated paperboard tray, migration rates of the cyclic trimer from this tray were 6–7 times greater than the CPET tray and thought to be due to the difference in the materials crystallinity, whereby material's with a greater percentage crystallinity generally exhibit lower migration rates [169]. Gramshaw et al. also conducted a study investigating the potential migrants from dual-ovenable plastics. In their study, 14 different compounds were identified from CPET. However, this was less than the 83 identified from a thermoset polyester [170]. Other studies include the identification of antimony from CPET into food simulants and food by Haldimann et al. and the effect of microwave energy on the specific migration of substances from food contact plastics by Jickells et al. [171,172].

#### 4.3. Polybutylene terephthalate (PBT)

PBT is a semi-crystalline thermoplastic polyester similar in both composition and properties to PET [173]. PBT typically exhibits lower strength and stiffness and is slightly softer than PET but provides greater impact resistance. Additionally, as it tends to crystallise more rapidly, it is favoured over PET in moulding processes allowing for the use of lower mould temperatures and shorter cooling times [173,174]. Due to its good balance of properties, PBT has been primarily used in automotive, electrical and other engineering applications; however, recent years have seen attempts to use it as a food packaging material due to the demand for more robust and sustainable food packaging options. For example, reusable food packaging companies EcoBox and reCircle have utilised PBT to manufacture their lunch bowls [175,176].

PBT is produced through the polycondensation of TPA or DMT with 1,4-butanediol (BD) in the presence of a polyesterification catalyst as shown in Fig. 8 [177]. This reaction produces a semi-crystalline polymer with a longer sequence of four (CH<sub>2</sub>) groups between ester linkages along the backbone chain compared to the two (CH<sub>2</sub>) groups between esters, as seen in PET. Due to this difference in spacing, the main chains of PBT are more flexible and allowed to rotate more freely, while the greater distance between ester groups reduces the polarity of the polymer. As a result, PBT exhibits a lower melting point of 220 °C and a T<sub>g</sub> of 30–60 °C compared to PET [177]. Since PBT has a heat deflection



packaging material is quite sparse. The majority of available research investigates PBT blends for use in engineering applications. For example, Kuram et al. investigated the effect of recycling on the mechanical, chemical, thermal and rheological properties of PBT/Poly-carbonate (PC)/Acrylonitrile butadiene styrene (ABS) blends reinforced with glass fibres [190]. Sanchez and Maria conducted a study investigating the mechanical properties and recycling potential of PC/PBT blends for automotive applications [191]. Pham characterised PBT samples recycled from toothbrush bristles and compared them to virgin samples [192]. As previously mentioned, a possible reason for this trend in literature could be due to the fact that PBT has only recently seen use as a food packaging material and is more established in other fields, such as the automotive and electronics industries [190].

Looking at the recyclability of PBT from a general perspective, PBT can be recycled through both mechanical and chemical means. Mechanical recycling is perhaps the more convenient and inexpensive option; however, it often reduces material quality due to hydrolytic degradation causing a reduction in molecular weight [193]. Additionally, the presence of contaminants can induce phase separation within the material, which also has negative impact on mechanical properties [194]. As a result of these drawbacks, there has been increasing interests in chemical recycling methods. For example, Goje et al. depolymerised PBT waste into TPA and BD via alkaline hydrolysis reactions in a batch reactor, while Wang et al. reported the depolymerisation of PBT through hydrolysis in hot compressed water [195,196]. More recently, Ohki et al. demonstrated acid/base free depolymerised of PBT along with other polyesters into their starting monomers by transesterification with ethanol [197]. Despite chemical recycling's higher associated costs and complexity, purified starting monomers (TPA and BD) can be obtained in high yield (90%–95%), leading chemical recycling to be considered a more resourceful method than mechanical recycling [193]. Additionally, considering that the standards of materials intended for food contact applications are carefully regulated, chemical methods are often favoured over mechanical methods in the food packaging industry [193].

Being a polyester, PBT has also been the subject of a number of investigations regarding the potential migration of oligomers into food and food simulants. These oligomers are reported to be comparable in chemical structure to those found in PET, being cyclic and linear and accounting for approximately 1.6% of the polymer's weight [160,198]. This value is just marginally greater than the approximate oligomer content for PET of 0.5%–1.3% reported by Hoppe et al. [199]. Another study by Hoppe et al. explored the oligomer content and migration behaviour of PBT and polyethylene naphthalate (PEN). Their study identified ten different oligomers in extracts of PBT and seven oligomers in PEN extracts. The oligomers identified were both linear and cyclic, consisting of different compositions of TPA and BD and containing side monomers diethylene glycol (DEG) and dibutylene glycol (DBG). The total concentration of these oligomers accounted for less than 1% of the polymer's total weight for both materials [160]. For PBT, only the migration of the cyclic and linear PBT dimers oligomers into 20% ethanol was recorded at 40 °C, while only the cyclic and linear PBT dimers and cyclic PBT trimers were reported to migrate at 60 °C. When potential migration was modelled for 900 days at 23 °C, total oligomer migration from a 0.5 L PBT beverage bottle was predicted to be 28 µg/kg. The author concludes that this relatively low migration value would not raise any safety concerns [160]. Brenz et al. also conducted a study to investigate the oligomer content and migration from PBT food contact materials. Their study identified twenty-seven different oligomers (linear and cyclic) from PBT raw pellets and kitchen utensils. The total amount of oligomer content isolated from the PBT pellets and kitchen spoon was 0.69% and 0.71% of the sample's weight, respectively, aligning with findings from the study carried out by Hoppe et al. It was observed during their study that although cyclic oligomers accounted for 90% of the total oligomer composition, linear oligomers proved more relevant for migration into aqueous food substances [200].

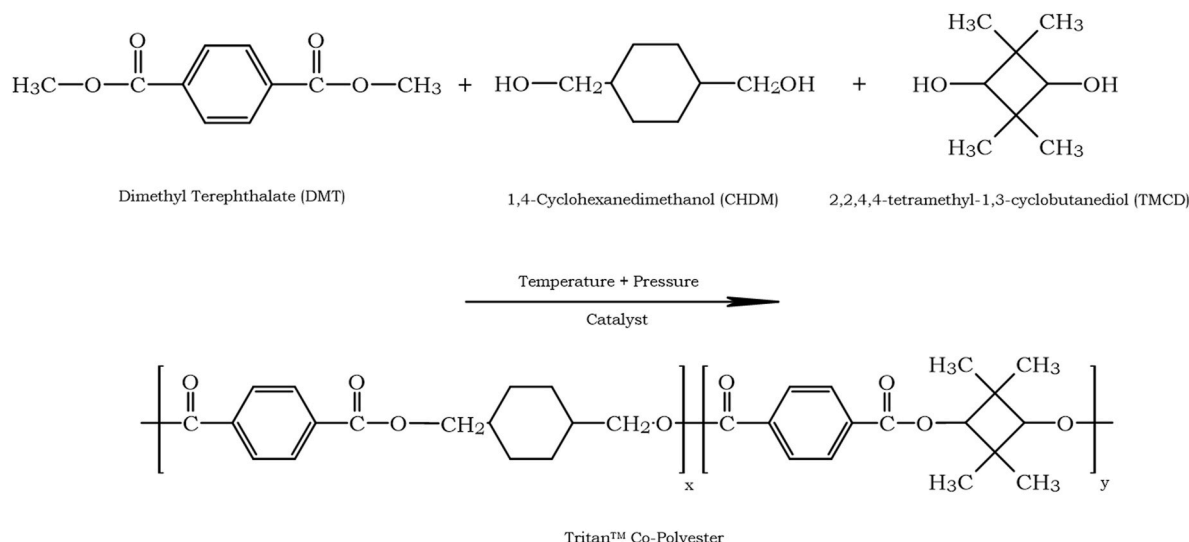
Migration testing of PBT spoons under repeat use conditions in water at 100 °C for 2 h revealed total migration values of 0.29 mg/item and 0.05 mg/item during the third migrate for linear and cyclic oligomers, respectively [200]. The authors comment that these values were significantly less than those reported for PA 66 by Sager and Simat and conclude that PBT may be a suitable alternative for food contact applications at elevated temperatures [200,201].

#### 4.4. Tritan™ Co-polyester

Developed by the Eastman Chemical Company and launched in 2007, Tritan™ co-polyester (1,4-benzenedicarboxylic acid, 1,4-dimethyl ester, polymer with 1,4-cyclohexanedimethanol and 2,2,4,4-tetramethyl-1,3-cyclobutanediol; CAS-261716-94-3) is a new generation co-polyester that features the versatility of typical polyesters such as PET and PBT but introduces additional advantages such as easier processing, improved thermal stability and enhanced mechanical performance [202–204]. Combining exceptional clarity with impact resistance and the ability to be sterilised, Tritan™ has proven itself as an excellent candidate to replace glass in applications such as blender bowls, serving trays and other kitchen products. Additionally, as Tritan™ is a BPA free polymer, it also experiences use as an alternative for PC in applications such as reusable beverage bottles, food containers, tumblers and infant care products [205,206]. One specific application that Tritan™ has begun to find a use in is reusable packaging. For instance, reCircle provides a range of Tritan™ bowls, dishes and cups along with their existing PBT range. They state that their Tritan™ products are heat-resistant, dishwasher safe, tasteless, BPA free and contain no plasticisers [207]. Multinational food chain McDonald's is another example of a company that has recently begun to use Tritan™ as reusable food packaging material. Since January 1, 2023, in compliance with the Agec law (anti-waste for circular economy), McDonald's restaurants in France have been utilising Tritan™ for their reusable cups and unspecified recycled plastic for their food containers [208,209].

Tritan™ co-polyesters are produced from the melt-phase copolymerisation of three different monomers, dimethyl terephthalate (DMT), 1,4-cyclohexanedimethanol (CHDM) and 2,2,4,4-tetramethyl-1,3-cyclobutanediol (TMCD) as shown in Fig. 9 [210]. In this configuration, CHDM and TMCD interrupt chain regularity and inhibit crystallisation giving rise to a co-polyester with a unique set of properties [202]. The TMCD component, in particular, grants Tritan™ good thermal stability granting a  $T_g$  of up to 120 °C, a substantial improvement over traditional co-polyesters, which are usually limited by a  $T_g$  of 80 °C [202]. Additionally, as Tritan™ is slow to crystallise, it can be easily moulded into amorphous components with excellent optical clarity. Exhibiting a level of light transmission of 90–92%, Tritan™ offers transparency that surpasses other high-clarity materials such as PC, multiphase transparent ABS (MABS) and impact-modified acrylics [202].

Generally speaking, Tritan™ grades offer mechanical performance similar to traditional polyesters such as PET and PBT. As seen in previous sections, PET and PBT typically have a tensile strength range of 55–75 MPa, while Tritan™ is typically marketed with a tensile strength value of 50–60 MPa [212,213]. However, when comparing impact strength values, Tritan™ far surpasses both PET and PBT and even contends with polymers such as PC. Beavers discusses in an article the results of an experiment carried out by Eastman to characterise the impact properties of Tritan™, PC and a generic co-polyester, where it was found that when notched Izod testing was carried out using 1/8-in specimens, Tritan™ had a greater impact resistance than PC [214]. PC, which has a long-standing reputation for high thermal stability and impact resistance, could withstand 14 ft-lb/in ( $\approx 747$  J/m) of impact, exhibiting a partial break, while Tritan™ could resist an impact of 15.9 ft-lb/in ( $\approx 845$  J/m) without breakage. In comparison, the co-polyester grade could only withstand 5 ft-lb/in ( $\approx 267$  J/m) of impact [214]. An interesting observation made during the study was that when specimen thickness was increased to 1/4-in, the impact strength of PC drastically



**Fig. 9.** The melt-phase copolymerisation of dimethyl terephthalate, 1,4-cyclohexanedimethanol and 2,2,4,4-tetramethyl-1,3-cyclobutanediol to produce Tritan™ copolyester [211].

reduced to 2.2 ft-lb/in ( $\approx 117$  J/m) while the impact strength of Tritan™ remained unchanged. The author concludes that the reduction in impact strength of PC was due to its thickness/notch sensitivity concerning impact, a characteristic which does not affect Tritan™ [214].

Chemical resistance is perhaps the most attractive characteristics Tritan™ has to offer. Tritan™ is marketed as having excellent durability in hot and caustic environments typically associated with dishwashers [202]. The extent of this durability was observed in a trial by Eastman where beer mugs moulded from Tritan™, PC, Styrene acrylonitrile (SAN), methacrylate-styrene (MS) and acrylic (AC) were subjected to a drop test after repeated residential dishwasher cycles using a powder detergent [215]. Mugs were dropped from a height of 4 feet while filled up to 25 times at washing intervals of 0, 30, 50, 75, 100 and 125 cycles. SAN, MS and AC mugs failed, exhibiting cracks after two drops and without going through a single washing cycle showing they had inferior impact properties to Tritan™ materials. PC mugs survived 25 drops before washing but failed within the dishwasher after 30 washing cycles. However, Tritan™ outlasted 125 washing cycles followed by 25 drops after each washing interval without exhibiting any cracking and while retaining clarity [215]. The dishwasher durability of Tritan™ was also observed in a white paper study carried out by YOYO Boost Reuse. In this study, Tritan™ containers and other materials were subjected to 50 washing cycles at 62 °C and rinsing at 84 °C for 90 s. Post 50 cycles, Tritan™ containers displayed no scratches, cracking or noticeable deformation. However, when Tritan™ containers were used to store food sources (curry and tomato sauce) for periods of 1 h, 1 day and 3 days and then washed, Tritan™ exhibited yellow staining, discolouration and retained odours mainly from contact with curry sauce [128]. Tritan™, like PBT, has a polar structure; therefore, this result aligns with the previously discussed reasoning from Narses et al. that polar polymers are more susceptible to staining from food substances containing polar pigments [121]. Finally, as mentioned in the previous section, the influence of washing and food storage on material physical and mechanical performance was not investigated during this study; therefore, it is difficult to conclude the suitability of Tritan™ for reusable packaging applications. Further work is required to determine the full extent to which cleaning and contamination influence material properties.

Regarding the barrier properties of Tritan™, to our knowledge, minimal literature exists concerning their investigation. Perhaps a reason for this is that Tritan™ has only emerged in recent years as a possible material for reusable food packaging and thus it has not yet established a strong presence in the market. In other words, because

Tritan™ is not as commonly used as commodity materials PE, PP and PET, it has not been a primary subject of investigation. Having said all that, Eastman does provide values for barrier properties, O<sub>2</sub> permeability and water vapour transmission rate for some of its medical grades. These values are 32–44 cm<sup>3</sup> mm/m<sup>2</sup> day atm and 4 g/m<sup>2</sup> day for O<sub>2</sub> permeability and water vapour transmission rate, respectively [216, 217]. These values suggest that Tritan™ has inferior barrier properties to polyesters PET and PEN but superior to polyolefins PE and PP [152]. However, further work is still required to understand the barrier performance of Tritan™ and to determine its suitability of for food packaging applications.

One disadvantage of Tritan™ as a food packaging material is its incompatibility with existing recycling streams. Tritan™ co-polyesters belong to RIC 7, along with many other recyclable and non-recyclable mixed and multilayer plastics [218]. For these materials to be recycled, they must be separated from each other first. However, due to the large variety of plastic types existing within RIC 7, separation becomes quite a complex process which some recycling facilities currently do not have the infrastructure or technology to handle [219]. As a result, RIC 7 plastics are not usually accepted or widely recycled in municipal waste streams [220]. However, recycling Tritan™ co-polyesters is still technically possible. In recent years Eastman has developed a chemical recycling process which they have coined "molecular recycling", which involves disassembling Tritan™ and other polyesters at the molecular level into their starting monomers via methanolysis and glycolysis mechanisms [221]. The monomers can then be used to produce Tritan™ Renew, a new 50 % recycled content grade of Tritan™ which Eastman claims exhibits no reduction in performance [222]. Eastman has also announced plans to start a new facility dedicated to the production of Tritan™ Renew via this technology [223]. Therefore, considering these developments, recycling of Tritan™ co-polyesters in current municipal waste streams could be possible in the future.

Since its release, Tritan™ co-polyesters have been commonly marketed as a safer and BPA-free alternative to PC, particularly for food contact applications. As mentioned previously, BPA, from which PC is derived, is considered an endocrine disrupting chemical that can negatively affect human health [224]. Perhaps the most likely way a person may be exposed to BPA is if they consume food or liquids stored in containers manufactured from a material containing BPA [225]. In response to this health concern, numerous studies have investigated the concentration and migration of BPA from PC containers. For example, Brede et al. investigated the migration of BPA from PC baby bottles after

dishwashing, boiling and brushing, while Nam et al. investigated the migration of BPA from baby bottles under repeated use [226,227]. More recently, Agarwal et al. analysed the migration of BPA from microwaveable PC cups into coffee during microwave heating [228].

As Tritan™ has been seeking to replace PC in food contact applications, it has also been a material of interest and subjected to investigation for the potential migration of monomers and additives. Guart et al. aimed to compare the migration of monomers and additives from Tritan™ and PC [229]. Their study investigated the migration of monomers from Tritan™ sports bottles, two Tritan™ prototype carboys and a PC carboy over three incubation periods. During the first incubation period, BPA and butyl benzyl phthalate (BBP) were the only detected migrants from the Tritan™ water bottles in concentrations of 0.027 µg/kg and 0.032 µg/kg, respectively, while the BPA concentration of the PC carboy was 0.681 µg/kg. Going into the second and third incubations, the BPA concentration of the water bottles fell below the limit of detection while BBP concentration increased to 0.042–0.043 µg/kg. At the same time, the BPA concentration of the PC carboy increased further to 2.416 µg/kg. In the Tritan™ bottles, the continuous presence of BBP was attributed to its use as a plasticiser during the manufacture of the bottles. However, for the presence of BPA, it was believed this might have been introduced superficially into the material via the manufacturing process, explaining its reduction below the limit of the detection after just one incubation period [229]. A similar conclusion was made in a study by Holmes et al. who investigated the effect of consumer washing methods on BPA release from Tritan™ drinking bottles [225]. In this study, ten different brands of Tritan™ water bottles were investigated for the presence of BPA, two of which tested positive. The initial average concentration of BPA in these samples was recorded to be  $0.445 \pm 0.159$  µg/L. Bottles testing positive for BPA were then subjected to 1, 2 and 6 dishwashing cycles or handwashing using soap and water. During dishwashing, BPA concentration reduced to 0.344 µg/L after 1 cycle, 0.173 µg/L after 2 cycles and 0.016 µg/L after 6 cycles. In contrast, there was no significant reduction in BPA concentration for samples that were handwashed up to 6 times, with average BPA concentration remaining at approximately 0.386 µg/L. The authors suggest that any BPA release observed from Tritan™ was distinct from that observed from PC in previous works [225,230]. They speculate that dishwashing detergents appeared to reduce and eventually eliminate any residual BPA that may have been present on the material's surface rather than promote the release of BPA through polymer degradation, as has been reported with PC [225,230]. Considering these results, Tritan™ material exhibits good potential for the application of reusable food packaging and, more specifically, compatibility with the industrial cleaning process.

## 5. Conclusions

With plastic waste reduction and sustainable development targets set by public and private bodies globally approaching on the horizon, more than ever, research and innovation are required to enhance the sustainability of current plastic packaging. Since its invention, the majority of plastic packaging has been designed for single use and based on a linear model where its value is immediately lost upon disposal [9]. As a result of this design, vast quantities of post-consumer waste are generated annually, which has been the cause of major environmental concerns [2,13].

Replacing plastic materials with recyclable alternatives is not a straightforward solution. Despite the many environmental issues plastics present, they are a highly capable packaging material that offers numerous benefits over traditional materials such as glass, metal and paper [4,5]. As discussed in this review, glass exhibits excellent transparency, high chemical inertness and impermeability to gases; however, it is heavy, shatters upon impact and results in high transportation costs [39,52]. Papers are one of the lightest and most inexpensive packaging materials being highly printable and processable into various rigid and flexible packaging structures; however, they possess limited

recyclability and have poor barrier properties requiring lamination or coating with a polymeric material [64,67,73]. Metals provide excellent structural support, thermal resistance and are widely recyclable, but again have higher production costs, are prone to corrosion, and, like papers, require additional treatments to ensure food safety and preservation [39,52]. Although polymers generally cannot provide the same degree of impermeability to gases as glass or thermal resistance as metals, they compensate for this by providing a wider variety and well-rounded balance of material properties at a relatively more affordable price [1]. Therefore, considering the range of benefits polymers have to offer, perhaps it would be more prudent to invest efforts not in replacing plastic materials but rather in redeploying them in a way that enhances their sustainability and circularity, such as in reusable packaging.

Reusable packaging schemes are just one solution that may assist us in meeting the 2030 sustainable development targets [26]. In recent years, these schemes have been receiving an increasing amount of interest, with many companies and small businesses making efforts to redesign their business models and transition from single-use packaging to reusable packaging [26]. According to the findings of various LCA's, reusable packaging can potentially reduce the overall environmental impact associated with the use of plastic packaging; however, numerous factors such as the choice of packaging material, method of cleaning, logistics and consumer willingness must be thoroughly considered to ensure their viability and success [26–29].

As pointed out on multiple occasions throughout this review, one aspect of reusable packaging schemes often not considered is the influence of repeated use on the properties of the packaging material. Throughout its lifetime, reusable packaging can be subjected to numerous cycles of microbe contamination and rigorous washing conditions and to date, very little literature is dedicated to investigating the influence of these conditions on the material's intrinsic properties. Instead, most of the available research focuses on the effect of repeated use on package cosmetic quality or additive/monomer migration behaviour [119–122,125,128]. Although these studies provide relevant and beneficial knowledge, the information is insufficient and does not allow us to conclude on the suitability of the materials investigated fully. Apart from two studies, few articles address whether repeated use can significantly alter key packaging material properties such as mechanical performance and thermal stability [123,124,127]. For reusable packaging schemes to be a viable solution for the future, maintaining the properties of the packaging material is essential to ensure it can safely and effectively contain, protect and preserve its content throughout its lifetime. Therefore, to fully assess the suitability of polymer materials for reusable packaging applications, more work is required that serves to comprehensively investigate the influence of multiple use cycles not only on packaging integrity and cosmetic quality but also on materials properties.

## Author contributions

Conceptualization, R.F., Y.J.C, D.M.D and R.P.; investigation, R.F., Y. J.C and R.P.; resources, D.M.D and N.G.; writing—original draft preparation, R.F.; writing—review and editing, Y.J.C, D.M.D, M.R., L.R. and R.P.; supervision, Y.J.C, N.G., D.M.D and R.P.; project administration, D. M.D; funding acquisition, N.G., D.M.D and R.P. All authors have read and agreed to the published version of the manuscript.

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## 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

No data was used for the research described in the article.

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