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# Drivers, advances, and significance of measures for effective circular food packaging

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This paper provides an overview of the fundamental aspects pertaining an effective circular packaging. The main challenges of food packaging systems to comply with the principles of circular economy are addressed. A perspective of the technical issues that drive packaging developments is given, and the main barriers and limiting factors for packaging waste reduction, reusing, and recycling are discussed, particularly as applied to plastic packaging. The state-of-art of recycling plastics for food contact is presented, as well as the gaps for safety assurance. The relevance of consumer and the impact on the whole chain is discussed under the framework of citizens motivation, ability, and opportunity to engage the different measures. Finally, the main measures under the scope of the packaging and waste regulation, and foreseen amendments, and of the plastics recycling directive are briefly presented.

KEYWORDS
**food packaging, circular economy, reusable, recycling, waste reduction, food contact, plastics**

## 1. Introduction

The concept of circular economy (CE) is intensively discussed and addressed by different actors of value chains, politicians, and academia. It is frequently depicted as a combination of reducing, reusing, and recycling activities. It is recognized that CE requires a systemic shift and a transition from the traditional linear patterns of production, consumption, and disposal (Kirchherr et al., 2017). Barriers to this transition have been studied, focusing on specific geographies, business types, or industry sectors. They can be categorized as regulatory, technical, and economic barriers (Bening et al., 2021). These barriers are not independent, and cultural barriers, namely lack of consumer interest and awareness, hesitant company culture, and lack of synergistic governmental interventions, are considered important together with technological limitations (Kirchherr et al., 2018). However, limited progress has been accomplished regarding CE implementation, and only 8.6% of the total material used is cycled (Circle Economy, 2022). Between 2015 and 2021, the global economy consumed an additional half a trillion tons of virgin materials, namely minerals, ores, fossil fuels, and biomass. In only 50 years, global use of materials has nearly quadrupled—outpacing population growth, despite initiatives settled as the Club of Rome, Paris Agreement (COP21), and Glasgow Climate Pact (COP26). Rising waste levels accompany the rapid acceleration of consumption: over 90% of all materials extracted and used are wasted, and most environmental problems, from biodiversity loss, global warming, and air pollution to plastic soup, are connected to waste (Circle Economy, 2022). This report indicates 21 measures (interventions) to allow the world to achieve the COP21 goal of keeping at 1.5°C of warming by 2032. One of these measures focuses on reducing excess consumption, and using less packaging on food products (Circle Economy, 2022).

Packaging plays an essential role in the food supply, protecting and containing food from processing and manufacturing, through distribution, handling, and storage to the final consumer. Without packaging, food distribution would be inefficient and much more costly. Packaging functions may be described as protection and containment, preservation, information, and convenience and service. These functions are, directly or indirectly, essential for the physical, chemical, and microbiological safety of foods. For most food products, the protection afforded by the package is an essential part of the preservation process. The requirements for a packaging system intended for a fresh, frozen, dehydrated, thermal or aseptic processed product, in terms of oxygen, moisture, and light barrier, etc. are all different (Poças et al., 2010). Packaged food products and dietary supplements are essential for human health and have a profound impact on the modern human lifestyle (Verma et al., 2021).

Despite the critical role it plays and its economic relevance, packaging is, in the view of many consumers, a waste of resources, which ends up exclusively as an environmental burden. Such views arise because the functions packaging has to perform are either unknown or not fully considered and appreciated by the consumer (Robertson, 2013).

The packaging sector represents about 2% of the GDP in developed countries, and nearly half of all packaging is dedicated to food (Robertson, 2013). The relationship between the gross domestic product (GDP) and the generation of packaging waste has been reported (European Environment Agency, 2012).

Packaging optimization is more than ever critical to obtain an optimal balance between extra protection, extension of shelf-life, and food losses without the trade-off of an increase in packaging waste. An efficient food package needs to have minimal environmental impact. Packaging is one of the key value chains for the new CEAP – Circular European Action Plan (COM, 2020) - all packaging on the EU market should be reusable or recyclable in an economically viable way by 2030. Mandatory essential requirements for packaging apply to reduce overpackaging and packaging waste and to promote reusability and recyclability. Food packaging solutions have increased complexity, and waste has to be avoided across the entire supply chain, and the end of life includes consumers' and end users' decisions and behaviors.

This work presents and discusses the packaging challenges and barriers in the CE context, the measures across the packaging life cycle, and some of the observed trends.

# 2. Packaging challenges and barriers

In this section, the main challenges are presented and discussed. These are addressed in terms of the level of packaging waste, discussing the reasons for its increase; the existing technical limitations for recycling packages with a brief mention of permanent materials and focusing particularly on plastics and in the most recycled plastic PET; and challenges and barriers related to consumer and how it relates to packaging use and end-of-life strategies.

## 2.1. High and growing levels of packaging waste

The level of packaging waste is high and is increasing. The annual waste of all packaging materials added together in 2010 was estimated as 154 kg per inhabitant in the EU, increasing to 177.2 kg in 2020 (more 15%). The values across countries vary from 66.0 kg per inhabitant in Croatia and 225.8 kg in Germany. The material breakdown for 2020 gives 41% for paper and cardboard, 20% for plastics, 19% for glass, 15% for wood, and 5% for metal (Eurostat, 2022).

The increase during the period 2010–2020 was largest for plastic (23%), following paper and board (17%) and glass (almost 13%). These values are estimated on a weight basis. For the lighter materials, the increase in package unit's basis is much higher.

Figure 1 presents the waste generated *per capita* for each packaging material and the estimates for 2030 and 2040 (Eurosotat 2022). The estimated increase between 2018 and 2030 is 2% for glass, 18% for wood, 19% for paper and board, and 46% for plastic. The steel waste is expected to decrease, and no change is foreseen for aluminum. Different factors contribute to this overall increase, which can be attributed, to a large extent, to the fact that more products are packaged, an increase in single-use compared to reuse, and a general reduction in packaging size.

### 2.1.1. Increase in packaging use

The modern retail organization and structure of supply chains have called for products with extended shelf-life that, in many cases, depend on advances in processing and packaging techniques. These are associated with ease handling and processing, and with protection against tampering and consequent loss of economic value. Fresh and vegetables are a typical example where an enormous increase in packaging has been observed in general markets.

Ready–to-eat and convenient food items have flourished, as well as consumers' demand for foods that are more natural, less processed, and contain less preservatives, commonly referred to as more healthy foods. These products often have more demanding requirements for preservation and protection relying on the packaging. Therefore, an increase in the packaging compatible with the expected shelf-life and with the method of home preparation could be observed.

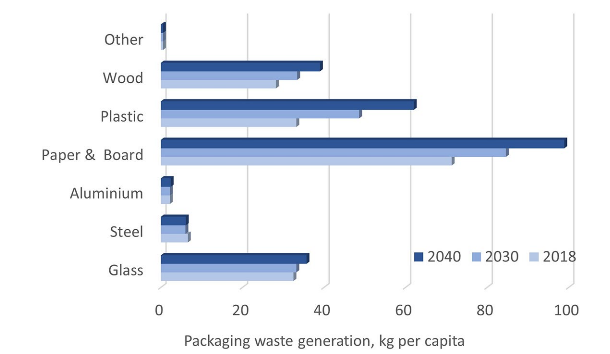


FIGURE 1
Packaging waste generated in Europe *per capita*, for each packaging material and the estimates for 2030 and 2040 (Eurostat, 2022).

These packaging developments driven by food consumption trends also included decreasing average packaging size to accommodate the trends in smaller household sizes and a higher number of products sold in portioned and single-serve packages. The smaller the package, the higher the ratio between the amount of material and the food delivered, therefore, corresponding to an increase in packaging waste generated.

### 2.1.2. Increase of single-use compared to reuse

The globalization of supply chains, the growing importance of large retailers, and the demand for simplified logistics of single-use supply chains have promoted the shift from reusable packaging to one-way (single-use) packaging (Coelho et al., 2020). The market share of refillables for beer and soft drinks, declined significantly between 1999 and 2019. The higher shares are reported for Germany nearly 50%, and Slovak Republic and Bulgaria had shares of 20 and 22%. Some countries presented shares between 10 and 15% (Denmark, Romania, Hungary, and Italy), and France and Finland with share values of only ca 3 and 4% (SWD, 2022). The growth of reusable packaging may follow a gradual increase pattern due to consumers' preferences, or a more rapid increase driven by regulations, such as the measures derived from the CEAP and from the regulation on packaging and packaging waste [Regulation (EU) 2019/1020 and Directive (EU) 2019/904 and amendments as proposed in the draft of 30 November 2022]. An exponential scaling will be possible if disruptive solutions become available (Feber et al., 2022).

Packaging reusability can assume different configurations. Returning the empty package to a store or drop-off point (e.g., deposit-and-return point) is the traditional option, as well as refilling at home durable packages with the product just bought in a less robust, often flexible, package. This latter approach has been used for long in detergents and hygiene products. However, new configurations are considered, such as: refilling on the go, where consumers refill through an in-store dispensing system, and returning from home, where used packages are collected by a pickup service (Ellen Macarthur Foundation, 2019). Reusable packaging solutions face multiple barriers related to logistics, cost, hygiene, food safety, quality, convenience, and acceptance in the supply chain (Feber et al., 2022).

The transition to a reusable packaging system at relevant retailing level is highly challenged by food hygiene, safety and quality requirements, and consumer trust, and depends on good practices implemented, specific packaging physicochemical and mechanical performance, reliable control systems for traceability, and actors/stakeholders' engagement. It requires the implementation of reverse logistics through the whole chain and, consequently, of suitable specifications of primary and secondary packaging, including reconditioning processes, monitoring systems, and service organization. The packaging system (material properties, package geometry, closure system, labelling, etc.) should provide the level of protection and preservation needed and be suitable for the cleaning process conditions for hygiene; specifications for efficient handling, including brand identification, are also necessary. The cost–benefit analysis (in economic and environmental burden terms) should be performed for the specific case as not all distribution systems and supply chains are suitable for reusable packaging systems, or they may not result in environmental gains (Coelho et al., 2020).

Implementation of reusable packages also creates opportunities for the business: increased consumer loyalty and association of the brand to sustainability, the potential for increased product customization, and introduction of advanced labelling, digital and smart, techniques (Ertz et al., 2017).

## 2.2. Recycling limitations

### 2.2.1. Glass and metal packaging

Recycling the so-called permanent materials used in packaging, glass, and metal, is far less discussed than that of plastics or paper and board, as they present fewer challenges in the collection, sorting, and separation processes. Glass and metal packaging are less complex systems (packages are monomaterial), and these materials are easily recognized by the consumer. Color separation of glass bottles is essential for color uniformity throughout the production process, particularly for flint bottles. Metal packages can be in steel or aluminum, and techniques for sorting these materials are well established. Therefore, recycling glass and metal packages is well developed. It was promoted by industry in early 80's to save energy in the process. Permanent materials can be infinitely recycled without losing their intrinsic properties, making them an extremely valuable secondary raw material. Food contact safety is not an issue in the case of glass or metal recycling because the high temperatures used in the process eliminate any contaminant present (Poças et al., 2022).

Recovered glass can be incorporated at high rates. The major limitation for observing higher recycling rates is the cullet shortage, particularly in wine-producing countries that have a high level of exports for the bottled product (Soares et al., 2022). Glass recycling rates correspond to 76% of all post-consumer glass packaging in the EU, leaving a large margin for improvement (European Glass Container Federation, 2022). The rates of metal packaging recycling are reported as 76% for aluminum beverage cans and 86% for steel packaging (Metal Packaging Europe, 2022).

### 2.2.2. Plastics packaging

Recycling plastics poses much more challenges in all steps of the cycle. There are multiple types of materials with similar properties that make the separation more difficult, particularly in the case of combination in multilayer packages. Moreover, plastics undergo gradual chemical changes during the use and processing phases, and therefore, they have limited recyclability because of physical-mechanical degradation, depending on the specific plastic. PET showed to stand up to 11 cycles of reprocessing without compromising quality (Pinter et al., 2021). Additionally, safety issues are very relevant because of potential chemical contamination deriving from interactions between the plastic and the food and other products contained in the package and because of degradation of the material itself and additives and adjuvants initially added. Table 1 presents a selection of substances detected in polyolefins-and polystyrene-based recycled materials, considered of major interest because of potential safety concern or as markers to discriminate recycled from virgin material.

In the EU, plastic packaging waste represents ca 35 kg *per capita* (Eurostat, 2022) and is the material with the highest rate of increase every year. To fight this increase in waste, resource consumption, and the impact on the environment, Directive (EU) 2018/852 sets a minimum of 70% by weight of all packaging waste as the target for recycling and a minimum of 55% for plastic by the end of 2030.

TABLE 1 Substances detected in non-PET recycled materials.

| Material and reference | Reason for selection of substances | Substances |
|---|---|---|
| Polyolefins Su et al. (2021) | Selected substances because of potential safety concern for food contact use | Octocrylene |
| | | 1-Tetradecene |
| | | 1-Dodecene |
| | | Dodecyl acrylate |
| | | 2,4-Di-tert-butylphenol |
| | | 1,4-Benzenedicarboxylic acid |
| | | Benzenamine, 2,4-dichloro |
| | | Diethyl phthalate |
| HDPE Fuller et al. (2020) | Substances identified as a major source of odor directly or as indicator of some odorous residues from personal care products | 2,4-Dimethyl-heptane |
| | | 4-Methyl-octane |
| | | Octamethylcyclotetrasiloxane (D4) |
| HDPE Strangl et al. (2019) | Odor-active compounds quantified in recycled HDPE pellets | Octanal |
| | | (E)-Oct-2-enal |
| | | (RS)-(±)- Linalool |
| | | (trans)-Anethole |
| | | Verdyl acetate |
| | | β-Ionone |
| | | 2-Methoxynaphthalene |
| | | *γ*-Undecalactone |
| | | Dodecanoic acid |
| PE Chen et al. (2022) | Potential volatiles markers of virgin and recycled PE | 2,2,3,5-Tetramethylheptane |
| | | 2,6,10-Trimethyldecane |
| | | 2,2,4,6,6-Pentamethyl-heptane |
| | | Decane |
| | | 5-Ethyl-2,2,3-trimethylheptane |
| | | 2,2,7,7 and 2,3,6,7-Tetramethyloctane |
| | | 2,5,9-Trimethyldecane |
| | | 2,3,5,8-Tetramethyldecane |
| | | 4,8-Dimethylundecane |
| | | Camphor |
| | | 2,6-Dimethyldecane |
| | | (Z)-3-dodecene |
| | | 5-methylene-Tridecane |
| | | 7-Methyl-6-tridecene |
| | | Cedrene |
| | | Dioctyl phthalate |
| EPS Song et al. (2019) | Compounds contributing the most to the discrimination between recycled and virgin EPS | Xylene and Ethylbenzene |
| | | Acetophenone |
| | | α-Ethylstyrene |
| | | 2-Phenylpropenal |
| | | Propylbenzene, Isopropylbenzene |
| | | 2-Phenyl-1-propene |
| | | Undecanal, Decanal, Dodecanal, Nonanal |
| | | Benzoic acid ethyl ester |
| | | 2-Ethyl-1-hexanol |
| | | Benzylcarboxaldehyde |
| | | 2,4-Diphenyl-1-butene |
| | | Benzaldehyde |

However, the recycling rates are still relatively low in many countries: in 2020, the EU had an average plastics packaging recycling rate of 39% (Eurostat, 2022) because of the limitations that will be further discussed.

Mechanical recycling is the most common approach used for recycling plastics (Singh et al., 2022). This refers to the processing of plastics waste into secondary raw material or products without significantly changing the material's chemical structure. In principle, all types of thermoplastics can be mechanically recycled with varying levels of impact on the quality of the material.

Most of the existing recycling schemes correspond to down-cycling. However, the principles of CE drive the developments toward an upcycling approach, resulting in products of at least the same quality (Cecon et al., 2021). The exception applies to polyethylene terephthalate (PET), which has more than 200 established recycling processes for food contact (evaluated by the European Food Safety Authority – EFSA), primarily bottles. In contrast, currently, there is no significant food-grade recycled polyolefins or polystyrene-based materials available for incorporation in new food containers, for example polypropylene (PP), which is used as yogurt, and margarine containers, bottle caps, ketchup bottles, and beverage cups and accounts for ca 20% of the European plastic demand with more than 40% used in packaging (Plastics Europe, 2019; Singh et al., 2022). In Europe, a few processes for no-PET recycling received a positive opinion from EFSA, and some mechanical processes received a letter of non-objection by the US FDA. However, they regard either close-loop recovery or limited contact conditions, and they apply to relatively less demanding food contact specifications (Singh et al., 2022). So, most plastic packaging is either recycled into lower-performance applications or sent to waste-to-energy conversion or landfilling due to a lack of technology at industrial scale to recycle no-PET plastics.

Polyethylene terephthalate is the material with the highest recycling rate, with varying figures across the continent, depending on the type of collection systems. Higher rates are achieved when schemes of deposit return systems (DRS) are implemented, while lower recycling rates are observed when only employing separate collection systems. However, the levels of incorporation are still relatively low because of market shortage, consumer acceptance, or low efficiency in the recycling chain. Recent data indicates that despite a recycling rate of ca 50% for PET primarily used in bottles, only 17% is used in the production of new bottles, and the remaining are used in lower-grade PET applications such as trays, film, strapping or fibers (Zero Waste Europe, 2022).

Low efficiency in post-consumer collection and poor sorting is appointed, by industrial PET recyclers, as main causes for low overall efficiency in recycling, and packaging design features are determinant in inhibiting recycling:

- Dimensions and position of labels and sleeves in the bottles may limit removal and sorting because they interfere with the optical sorting systems based in NIR/VIS. PET bottles with sleeves may not be recognized by the sorting system being rejected as non-PET. Selection by color may also be affected. Full bottle' shrink sleeves are a very attractive labelling means as they can be used to customize the same blank bottle to different products, resulting in simplification and savings of supply and stocks management. These sleeves are often designed with perforated tabs to facilitate removal after consumption and detachment of the sleeve from the bottle before sending it to the collection bin. However, this measure was poorly communicated and hardly understood and implemented by the consumers.

- PET flakes with opaque dark or white colors are not adequately distinguished from transparent PET types with actual sorting facilities. If included in final recyclates, the high pigment content affects the color, resulting in a loss of clarity and transparency of the package produced with the recycled PET. Opaque white PET bottles, through the inclusion of titanium dioxide ($TiO_2$), have been introduced in the market to protect light-sensitive products such as UHT milk, and have replaced the traditional high-density polyethylene (HDPE) milk bottles. Bottles for milk applications have a multilayer structure containing a layer with a grey color for a better UV–VIS light barrier. The removal of opaque flakes in the recycling stream is difficult because, when pigmented with carbon black, they are unrecognizable by the optical sorting devices as carbon does not reflect the light emitted by the NIR devices (Benyathiar et al., 2022). As a result, black PET such as pots, tubs, and food trays often end up as residue from recycling plants and are landfilled.

- Presence of materials that are difficult to distinguish visually and are more difficult (than polyolefins) to separate from PET due to similar density, as polyvinyl chloride (PVC) and polyamides (PA), but also polylactic acid (PLA), polystyrene (PS), polycarbonate (PC), silicones, and modified polyesters, such as PETG. These non-PET fractions compromise the quality of the PET recyclates. Trace amounts of PVC induce hydrodechlorination, and the release of HCl accelerates PET degradation; PA catalyzes the aminolysis of PET which increases chain scission (Schyns and Shaver, 2020; Thoden van Velzen et al., 2020). PS and PVC have a melting range lower than that of PET, therefore the presence of these contaminants has a major impact on quality.

- Presence of metallic contaminants from closures, springs in trigger packages, aluminum foils, and metal cans fragments are removed in the recycling stream by magnetic bands, Foucault current, and by melt filtration. However, they can cause serious problems in the process and major product defects if they are not efficiently removed.

In addition to those key packaging design-related aspects discussed before, the removal of other materials during the recycling process is important for the good quality of the final recycled flakes. Fines (PET powder particles) cause problems in the flake sorting systems if not removed and cause inefficiencies: due to static, fines build up on reprocessing equipment, and degrade into building blocks such as ethylene glycol (EG), which then promotes further degradation of PET during extrusion; degraded PET powder can become a non-melting particle, and quickly clogs melt filters and creates degraded black deposits. Fines also affect the final product quality because they have a much smaller surface area and oxidize faster during drying and discolor during extrusion (Thoden van Velzen et al., 2016). Current screening and sieving systems are not yet able to achieve complete removal of fines and dust from PET flakes, with typical fines removal rates averaging only around 50%. Better removal of fines and PET contaminants would significantly improve the quality of flakes because of a more complete removal of contaminants.

## 2.3. Recycling for food contact

Since late 90's, numerous recycling processes employing different technologies were settled and produce the so-called super-clean and food-grade PET recyclates from post-consumer used food contact PET materials (Franz and Welle, 2020). Decontamination technologies rely on high temperature, vacuum, gas flow, high polymer melt surface exposure to the temperature and low pressure, and residence time to efficiently remove unwanted substances and potential contaminants from the recovered PET. Many of these technologies include a step of solid-state polymerization (SSP), typically with long residence times, during which hydroxyl and carboxyl end groups of broken chains react together to reverse chain scission (Schyns and Shaver, 2020). In this step, there is an increase of PET intrinsic viscosity important for the mechanical properties: the higher the intrinsic viscosity, the lower the probability of environmental stress cracking (Chacon et al., 2020), but SSP also promotes a reduction of chemical contamination, therefore is an important step in the process to obtain food-grade post-consumer recycled PET.

Recycling of plastics containers for food contact is regulated by the recent Commission Regulation (EU) 2022/1616, which lays down rules for "… (a) the placing on the market of plastic materials and articles falling within the scope of Article 1(2) of Regulation (EC) No 1935/2004, containing plastic originating from waste or manufactured therefrom; (b) the development and operation of recycling technologies, processes and installations, to produce recycled plastic for use in those plastic materials and articles; (c) the use in contact with food of recycled plastic materials and articles and of plastic materials and articles which are intended to be recycled …". This regulation indicates that a recycling technology shall be considered suitable if it is shown to produce recycled material complying with Article 3 of Regulation (EC) No 1935/2004, relative to chemical safety and organoleptic properties, and is microbiologically safe. It should be highlighted that this regulation indicates that the whole cycle consisting of collecting, recovering, recycling and decontamination, and re-application in food contact articles, should be considered when addressing the suitability of a recycling technology. The (a) type, mode of collection, and origin of the input material; (b) the specific combination of physical and chemical concepts, principles and practices used to decontaminate that input material; and (c) the type, and the intended use of the recycled plastic materials and articles should be considered in the assessment of the recycling technology, and will determine if an evaluation and authorization of the recycling process by EFSA are needed, and which criteria apply.

Chemical safety of recycled plastics depends firstly on the input material, which determines the range of chemical compounds that may be present and that should be removed during the decontamination steps of the recycling process. These substances are food residues from the intended first packaging use, or thy are additives, production aids, and degradation thereof used initially in the material, or they consist of residues of non-food products also packaged in PET bottles, such as shampoos, detergents, etc. that are mixed in the recovery stream. They may also be present due to misuse of the articles by the consumer before returning them to the collection system. However, this source of contamination tends to be sporadic and affects only articles that can be filled, like bottles, and not trays and alike. An overview of typical migrants from all types of recycled food packaging materials is presented in the literature (Geueke et al., 2018; Tsochatzis et al., 2022). Table 2 presents the most common chemicals detected in PET in flakes or pellets after passing the recycling process, and ready to use in food contact applications. The origin of these chemicals is briefly indicated.

The impact of mixing of non-food PET containers in the collection and recovery stream was recently studied and confirmed that, given the nature and concentrations of substances found in non-food PET containers post-consumer, the safety criteria of a maximum fraction of 5% of non-food PET applications in the recycling feed stream are safe for food contact (Franz and Welle, 2020).

Currently, the decontamination processes for producing food-grade recycled PET are evaluated through a challenge test using model contaminants to represent different physic-chemical properties of potential contaminants (molecular weight, volatility, polarity) relevant to the decontamination efficiency, and following a mathematical modeling approach. FDA guidelines recommend, among others, chloroform, chlorobenzene, toluene, benzophenone, methyl salicylate, methyl stearate, and phenylcyclohexane to be used as surrogates in the preparation of challenge tests (FDA, 2021).

Limitations to the current approach of assessing safety in the context of CE can also be raised. It is recognized that the surrogates for the challenge test were selected primarily to address hazards originating from misuse and non-food PET articles mixed in the recovery stream. Additional quality markers and process controls are needed, with respect to migrating substances, potential non-intentionally added substances (NIAS), contaminants, and known polymeric degrading compounds (Tsochatzis et al., 2022). For example, a relation was established between the concentration of chlorine in PET, possibly due to contamination with PVC, and the migration of benzene from the recycled PET into water (Thoden van

TABLE 2 Most common non-intentionally added substances (NIAS) detected in recycled PET (Geueke et al., 2018; Thoden van Velzen et al., 2020; Tsochatzis et al., 2022).

| Substance | Origin |
|---|---|
| Acetaldehyde | From DEG monomer |
| 2-Methyl-1,3-dioxolane | |
| Ethylene glycol | |
| Limonene | Food flavor |
| Benzene | Heat-induced reactions with contaminants (PVC) |
| Styrene | Thermal degradation of PS present as contaminant |
| Acetone | Residues of solvents in mold maintenance products |
| Butanone | |
| Furan | Organic impurities (pyrolysis of biomass) |
| Ethylbenzene and xylene | Thermal degradation or misuse of containers |
| Toluene | Ink solvent |
| Benzophenone | Additive UV stabilizer |
| Benzaldehyde | Degradation |
| Nonanal and other aldehydes | |
| Oligomers (cyclic dimers and trimers) | |
| Other NIAS | Contaminants |
| | Degradation of additives and stabilizers used in the first life-cycle |

Velzen et al., 2020). Therefore, it is in the interest of safety that PVC articles and fragments are absent from the recycling stream, either by collection strategies or efficient sorting techniques. Benzene is considered a CMR substance (carcinogenic, mutagenic, and toxic to reproduction) and a maximum concentration of 1 ppb in water is set as limit.

The representativeness of the material used in the challenge test is also questionable as it depends on geometrical parameters such as size and thickness, affecting the bulk density of the material to be decontaminated, which then affects the operational parameters of the process that should be controlled. Therefore, the inherent variability of those parameters in the input should be characterized, and the sensitivity of the decontamination efficiency should be considered in the process evaluation. Current guidelines of EFSA do not address these technological aspects.

To create an effective CE, closing all loops to ensure that post-consumer plastic waste is consistently and efficiently turned back into new packages is required (Singh et al., 2022). However, due to some degradation, there is a finite number of cycles that can be performed. Furthermore, even PET needs additives to prevent reactions that result in diminishing of mechanical properties during reprocessing, such as radical scavengers to prevent the radical attack on chains (e.g., organic phosphates) and/or chain extenders to reverse some of the damage caused by PET chain degradation (e.g., oxazolines, isocyanates, epoxides, lactams, hydroxyls, carboxylic acids, and organic phosphites and phosphates, commercial extenders such as Joncryl derivatives). There is still poor knowledge of the behavior of these additives when submitted to several recycling loops and their effect on material safety.

## 2.4. Consumer issues

Although many products are handled and marketed in a package, food packaging accounts for the largest share of the total packaging sector (85%). Therefore, domestic consumers play a crucial role in many aspects related to packaging and in issues pertaining to its impact on the environment and resources consumption, particularly in the strategies for managing packaging end-of-life. It is recognized that carbon emissions can often be considerably reduced through changes in consumer behavior (Moran et al., 2020), although the studies did not focus specifically on packaging. The two stages of the packaging cycle considered relevant for the reduction of packaging waste are either the production selection/acquisition and the post-use, namely the integration in collection schemes and sorting (Jacobsen et al., 2022). Various studies have classified drivers of and barriers to sustainable consumer behavior according to the framework formed by the variables MAO, standing for motivation, ability, and opportunity (Jacobsen et al., 2022).

### 2.4.1. Motivation

Consumer motivation to recycling and other measures intended to reduce packaging waste depends mainly on awareness, personal values, and social-cultural context. Many studies have found a positive willing-to-pay more for recyclability in general and a higher willingness for the recyclability of plastic than for other packaging materials (Klaiman et al., 2016, 2017). However, economic incentives remain a decisive factor in the purchasing decision (Paletta et al., 2019; Herbes et al., 2020). For example, buying a 3 L bottle of olive oil instead of three 1 L bottle of the same product gives an interesting decrease in the ratio of the amount of plastic per amount of product delivered, but it must compensate by a significant lower price. Otherwise, the consumer does not adhere.

Very relevant for the success of any collection scheme is the trust in the recovery process and the belief that returning the package to the collection scheme makes a difference and contributes to environmental sustainability. This is fundamental for the volume and for the quality of the recovered stream that consumers are motivated to correctly disposing the waste into the different eco bins, or to participate in selective collection schemes. Especially among teenagers, the perception that many recovered packages end up being incinerated or landfilled, instead of recycled because of a lack of technology to sort adequately and recycle commingled waste, especially no-PET plastics, had led to a general distrust and non-cooperative attitude toward the collection of recyclables (Escario et al., 2020). This ultimately affects the recovery of those materials with a well-established recovery and recycling stream.

### 2.4.2. Ability

In addition to being motivated, consumers need to have the ability to adopt behaviors that contribute to plastic packaging waste avoidance and recycling, including skills, task knowledge, habit, and resources (Jacobsen et al., 2022). Knowledge has been associated with ability, and limited understanding about an issue and how to address it is recognized as a barrier to engaging in sustainable behavior by consumers (Gifford, 2011). Literature studies show that there is a relationship between knowledge and will to support waste and plastic-reducing policies (Moran et al., 2020). It is also easily recognized that the general consumer has poor knowledge of different plastics materials and their impacts and the role they can play in the product system sustainability (food and packaging systems analyzed together) – most consumers do not realize that plastic packaging is currently key to ensure quality and safety of foods and minimize food waste.

In the present times of "plasticphobia" even eco-efficient packaging solutions are often perceived as not "sustainable" because of public perception. According to the results of a consumer survey regarding wine packaging, the three top concerns regarding packaging are, by order, being plastic-free, recyclable and reusable, and there is deficient awareness of the importance of lightweight or monomaterial structure as measures to improve sustainability. More than 80% of the respondents indicated the increase in recycled content as the measure contributing the most to sustainability (Soares et al., 2022). To overcome this status, it is necessary to address consumers through better communication using information that is consistent, reliable, and yet simple. It is also fundamental to increase the level of knowledge of stakeholders (packaging producers, converters, end-users – food companies, and recyclers), regarding packaging systems and their interaction with the food system, considering the supply chain and food waste and losses. Stakeholders have an enormous responsibility for the information conveyed to the consumer, and it is compulsory to validate their decisions and commercial/marketing messages by qualified persons using recognized tools.

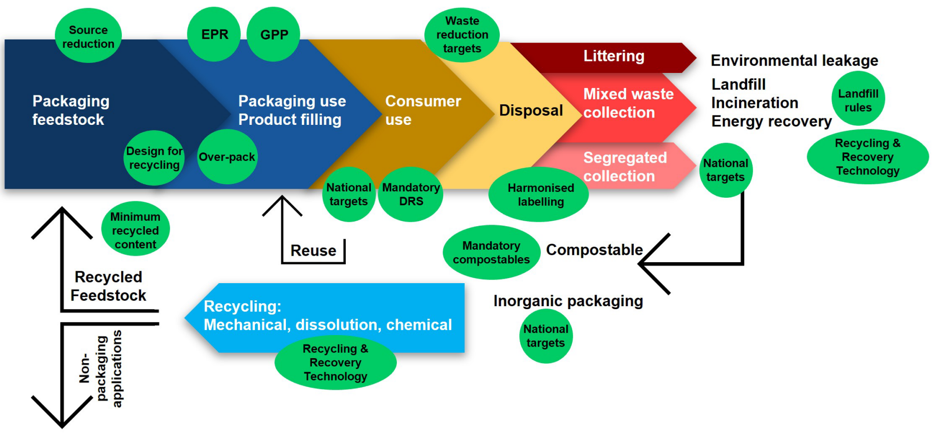


FIGURE 2
Packaging measures across the packaging life-cycle.

### 2.4.3. Opportunity

The opportunity for the consumer to actively answer to and integrate recovery and recycling schemes is highly determined by the structure available and consumer expectations for convenience, and therefore, by the characteristics of the waste collection and pre-sorting schemes, and by existing rules and policies.

Consumers perceive the government and the industry to be the main actors responsible for plastic reduction (Dilkes-Hoffman et al., 2019). Different aspects associated with convenience have been found to influence engagement with recycling. Kerbside collection systems attract more consumers than drop-off collection, measured by household waste weight (Thoden van Velzen et al., 2016; Hahladakis et al., 2018; Jacob et al., 2022). Short distances to the waste sorting bins (Aprile and Fiorillo, 2019) and the number of collecting bins per inhabitant and their relative accessibility are relevant (Hage et al., 2018; Oliveira et al., 2018).

Requiring consumers to clean the packaging after use before disposal and forwarding it to collection has a negative effect on the willingness to recycle (Klaiman et al., 2017). Implementation of single-stream of recyclables is more convenient to the consumer, and relying only on centralized operations of sorting, led to increased recycling, compared to multiple-streams requiring more effort in pre-separation by the consumer (Bell et al., 2017; Berardocco et al., 2022).

Overall, research suggests that consumer engagement in packaging end-of-life approaches is driven by environmental awareness, which is high, particularly if related to plastic pollution, but motivation and ability through economic incentives and through clear and consistent information to promote a good understanding and trust in the system are needed, together with convenience associated to the design of the waste collection on sorting scheme.

## 3. Packaging measures across the cycle

Figure 2 presents the whole packaging cycle to be considered when addressing measures to improve sustainability and under the framework of the Circular European Action Plan. The most relevant measures undertaken and foreseen are briefly presented. Some of the measures are under discussion on the proposed revision of the (PPWD) Packaging and Packaging Waste Directive [COM (2022) 677 final 2022/0396 (COD)], to ensure that all packaging on the EU market is reusable or recyclable in an economically viable way by 2030. This draft Regulation presents:

- targets for packaging waste reduction at Member State level, and mandatory reuse targets for economic operators for selected packaging groups;
- restricts over-packaging and certain forms of unnecessary packaging, and supports reuse and refill systems;
- establishes criteria for design for recycling to be applied to all packaging;
- defines minimum inclusion rates for recycled content in plastic packaging;
- establishes mandatory deposit return systems for plastic bottles and aluminum cans;
- promotes harmonized labelling of packaging and waste bins to facilitate correct consumer disposal of packaging waste.

Under the proposal, the Member States will be required to reduce packaging waste *per capita* by 5% by 2030 and 15% by 2040, compared with the levels in 2018.

### 3.1. Source reduction and waste prevention

Source reduction by design can assume different approaches, all valid to be considered. Avoiding unnecessary and overpackaging (OP) and limiting void space by geometrical optimization, and reduction of material use are measures that target the reduction of packaging waste. The challenges in addressing OP, derive from limitations from the technical point-of-view, for example in the filling/sealing machinery and in the performance of the packaging in protecting and preserving the product (safety and quality). OP also has important consumer implications, and changes may affect consumer trust or willingness to purchase. OP is still used effectively by marketeers to increase sales in market segments such as wines, spirits, and personal care products, for which consumers perceive a heavy package as a quality cue (Soares et al., 2022). Labelling legislation, communication and marketing aspects influence the packaging surface to be used as message support and, therefore, size is an additional variable.

The new draft version of PPWD also addresses reusable packaging formats and reuse systems and sets reuse and refill targets on economic operators of specific products: cold or hot beverages filled into a container at the point of sale and ready-prepared food for take-away, alcoholic beverages including still wine and non-alcoholic beverages. Furthermore, it defines the obligation to set up deposit and return systems (DRS) for single-use plastic beverage bottles and single-use metal and aluminium beverage cans containers with a capacity of up to 3 L. This measure supports the achievement of the separate collection target for single-use plastic beverage bottles laid down in Directive (EU) 2019/904 (77% for 2025 and 90% for 2030) and further drives high collection rates of metal beverage containers.

Source reduction by material restriction has been reflected in Directive (EU) 2019/904 on the decline of the impact of certain plastic products on the environment, the so-called Single-Use Packaging (SUP), and the Plastic Bags Directive (Directive (EU) 2015/720) addressing the use of lightweight plastic carrier bags (bags with a wall thickness below 50 μm), which were at the time one of the top 10 littered items in Europe. This latter has led to a substantial reduction in overall plastic weight consumption in bags (despite replacement of the lightweight bags with thicker ones) and to the development of habits of reusing bags among Portuguese population (Luís et al., 2020). The new directive will impose new limits to these bags.

#### 3.1.1. Recyclability

The new draft of PPWD includes a definition of recyclable packaging and sets targets for recycled content in plastic packaging (for 2030 and 2040). The targets are different for different packaging categories and depend on whether refer to application food contact-sensitive or non-contact sensitive. The establishment of the measurement method is foreseen.

Recycled plastic intended to come into contact with foods (FCM) are addressed in the Commission Regulation (EU) 2022/1616, that repeals Regulation (EC) No 282/2008. This directive indicates that is no longer possible to use recycled plastic FCM subject to national legislation. All types of plastics and recycling technologies are in the scope of the Regulation and not only mechanical recycling. Chemical recycling is also included although it is not fully clear if some technologies, such as treatment with supercritical fluids, are considered. Recycling of plastic products from a closed and controlled product chain, and the use of recycled plastic behind a functional barrier are also in the scope of this new directive.

The input characteristics (type, origin, and mode of collection and sorting), the decontamination principles, and the conversion technological operations, as well as the type and conditions of intended use, affect safety and quality control. All these factors should be considered in evaluation of the recycling technologies and processes.

### 3.2. Compostability

Compostability is a concept very attractive for consumers, although not fully understood. It is defined in the PPWD proposal: compostable packaging' means packaging capable of undergoing physical, chemical, thermal, or biological decomposition such that most of the finished compost ultimately decomposes into carbon dioxide, mineral salts, biomass and water, and does not hinder the separate collection and the composting process or activity into which it is introduced in industrially controlled conditions. Contamination of recyclables streams with compostable articles is a problem for the quality of the conventional recovery streams intended to be recycled. Therefore, it is required that compostable articles do not affect the recyclability of other waste streams.

The PPWD determines that certain packaging types should be compostable in industrially controlled conditions in bio-waste treatment facilities: sticky labels attached to fruits and vegetables, very lightweight plastic carrier bags, and tea or coffee bags and single-serve units intended to be used and disposed of together with the product.

### 3.3. Substances of concern in packaging

Substances in packaging that may be hazardous are barriers to recycling because they compromise the quality and safety of the recycled product. Therefore, measures on restrictions of their use, updating of the definition of hazardous substances in packaging, and notification rules of these substances of concern are expected.

### 3.4. Labeling

Differences between regulatory approaches in Member States were detected namely in labelling requirements for packaging. Therefore, measures for harmonization of labelling requirements to facilitate consumer sorting for the disposal of recyclable packaging (materials identification), labelling of reusable packaging, and criteria for recycled content are addressed in the new draft version of PPWD. It is envisaged to establish the conditions for identifying the material composition of packaging through digital marking technologies. QR codes or equivalent may be used in reusable packaging to facilitate recovery.

### 3.5. Extended producer responsibility and green public procurement

Extended Producer Responsibility (EPR) is an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle (OECD, 2016). It is considered a key economic instrument to encourage a change in behavior of all actors involved in the product value chain while providing support to cover costs of waste management, data gathering and reporting, as well as measures developed to raise awareness among stakeholders and consumers. The revision of the PPWD includes measures aiming at harmonizing obligations regarding monitoring and reporting, including producer reporting obligations under EPR schemes.

Green Public Procurement (GPP) is a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured (European Commission, 2016). As applied to packaging, it is intended to promote reduction of packaging consumption and reusable alternatives. Mandatory GPP criteria are expected for packaging of priority products and services.

## 4. Conclusion

It is well recognized that food and its packaging, is a complex system and that managing the impact in the environment and in resources consumption are influenced by many factors that are strongly interrelated, and that depend on technical, economical, and societal aspects. Packaging is responsible for the access of population to hygienic and safe foods. It is also true that society has evolved to an unbalanced and disproportionated consumption of materials in many cases. These differences occur across geographies, and across social-cultural levels as depending on expectations to convenience and what is perceived as wealthy lifestyle. This has promoted a major discussion in all fora about packaging sustainability. Materials suppliers and packaging producers, recycling industry, food companies, waste management sector, public sector, and consumers, are all responsible collectively and individually for the success of the measures. The impact and benefits to the environmental of these measures should be examined, to reinforce those approaches proved to provide better achievements. It is fundamental to harmonize the decision criteria on packaging minimization and how to measure packaging-related food losses and waste.

## Author contributions

FP: conceptualization, methodology, writing – original draft, preparation, and writing – review and editing. FP and MS: editing. All authors have read and agreed to the published version of the manuscript.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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