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Current Opinion in Food Science

Unexpected possible consequences of plastic packaging reuse

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Reusable packaging is considered among the measures for achieving plastic waste reduction goals, however, some unexpected issues may arise with a shift from single-use to a reuse model for plastic packaging for industrial food applications, involving the hygienic and sensory spheres. Considerations are based on the diffusional properties of polymers leading to contamination with chemicals and to aroma scalping; the degradative effects of aging, of mechanical stress due to multiple use, and of the repeated sanitization with aggressive chemicals; the proneness of plastic surfaces to microbial film colonization. The reuse of plastic packages has the potential to increase the level of chemical contamination and of microplastic particles in foods, and could reduce product hygienic and sensory quality and standardization.

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Current Opinion in Food Science 2024, **56**:101131

This review comes from a themed issue on **Food Engineering & Processing**

Edited by **Xiao Dong Chen**

Available online 26 January 2024

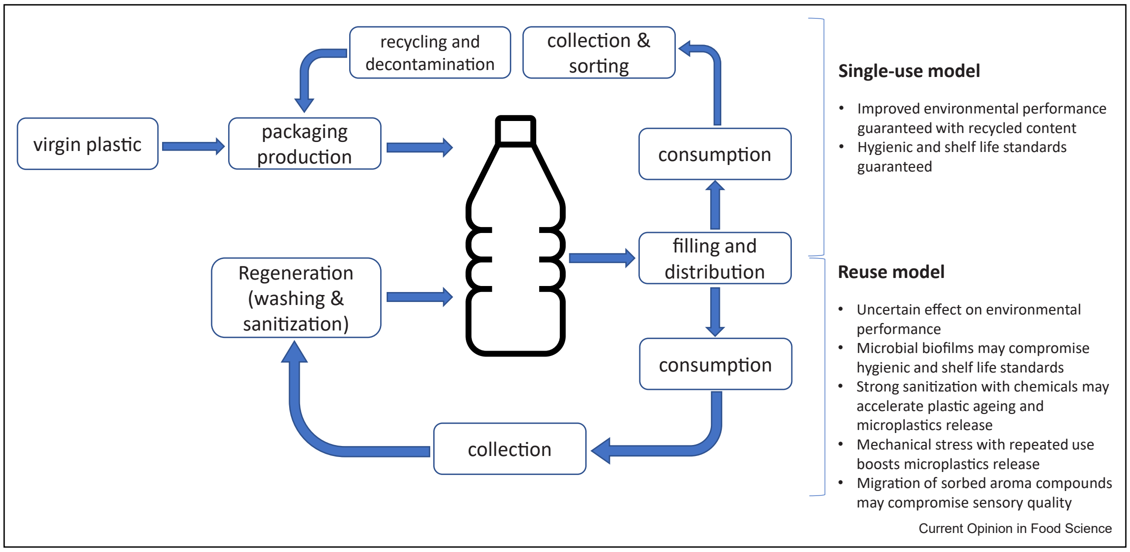
https://doi.org/10.1016/j.cofs.2024.101131

Introduction

Despite the increased awareness and sensitivity toward the environmental issues, packaging waste per inhabitant has increased from 149.9 kg in 2009 to 177.9 kg in 2020 [1]. The recent proposal for a Regulation of the European Parliament and Council on Packaging and Packaging Waste (PPW), amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC, aims at reducing the negative environmental impacts of PPW, "while improving the functioning of the internal market." The proposal sets mandatory targets for packaging reuse and minimum recycled content in plastic packaging. One of the main targets of the Regulation is to reduce the packaging waste generated per capita, as compared with the packaging waste generated per capita in 2018, by 5% by 2030, 10% by 2035, and 15% by 2040.

Plastic packaging has dramatically contributed to the development of the food industry, thanks to its lightness, low cost, and versatility. It is usually designed to be single-use, ensuring high hygiene standards and low costs, however, this same feature determines the high level of generation and accumulation of plastic packaging waste, even if effective and efficient recycling processes have been developed. Polyethylene terephthalate (PET) represents only about 8% on the European plastic converters' demand [2], however, it is one of the most used plastic materials in the food industry, especially to produce bottles, jars, and cups, due to its technical performances, versatility, and, above all, its circularity. Indeed, PET is recognized as the most circular among plastic food contact materials, thanks to its suitability to be recycled back into new food contact materials for an unlimited number of cycles [3–5]. It has been demonstrated that recycling, and the use of recycled content, is an effective strategy to significantly reduce the impact of PET bottles [6,7]. Since the polymer production represents the main hotspot in PET bottle lifecycle, minimizing the amount of virgin polymer is the most effective strategy in the mitigation of impacts, and the effects would be even more impactful if the rates of bottles recycling further increased. On the other hand, the environmental efficiency of reuse for plastic bottles remains uncertain and dependant on a minimum number of reuse cycles [8,9]. Unlike recycling, which implies the collection, selection, and remanufacturing of plastic materials into new objects, reuse (at the industrial level) consists in the regeneration of packaging that has already been used, through washing and sanitizing operations. No clear guidance for washing reusable packaging is available, however, industrial procedures are usually performed with washing at 55–65 °C and rinsing at 70–85 °C with the use of detergents containing caustic soda [10]. It is evident that higher temperatures assure higher decontamination levels, however, the upper limit for washing conditions depends on the glass transition temperatures (*Tg*) of plastic packaging: for instance, PET has a *Tg* ranging from 69 to 85 °C, depending on the grade, and it has

Figure 1



Single-use and reuse models for plastic packaging: main steps involved and related issues.

been demonstrated that repeated industrial washing cycles cause deformation of containers [10]. It has been reported [11] that consumers expressed scepticism about the environmental impacts of reusable systems and raised concerns, such as about product quality, safety, and contamination. In agreement, Collis et al. [12] found that when consumers notice signs of previous use on packaging for takeaway food, they express negative evaluations of the packaging, product, and restaurant serving the food. Indeed, plastic packaging reuse hides some issues that may cause consequences in terms of product safety, quality, and shelf life (Figure 1).

Food protection comes first

Wasted food causes unnecessary environmental impact, in addition to carrying ethical concern [13]. Unfortunately, the attention of the public opinion and of the policymakers keeps focusing on the direct environmental impacts of packaging, disregarding its indirect role in the prevention of food wastes [14,15]. Wikström et al. [16] contributed to consolidate the growing awareness on that the impact of packaging is not as high as that of food waste for different products; in their paper, the authors showed the greenhouse gas distribution between the consumed food, wasted food, and packaging materials for i) meat, fish, and eggs; ii) dairy; iii) fruits, vegetables, and nuts. The greenhouse gas of consumed food was 80%, 75%, and 60% for the three categories, respectively; the impact of wasted food was as high as 18%, 13%, and 22%, much higher than the impact arising from packaging materials (2%, 10%, and 12%, respectively). Casson et al. [17] recently contributed to the theme and concluded that when food waste effect is considered, the best environmental packaging solution for beef meat is the one that determines the longest shelf life. Food production uses a high amount of resources (including energy): if food is wasted, the corresponding amount of resources have been used in vain, and the related emissions could have been avoided [18]. The cited contributions, among others in the literature, agree on that, even from an environmental sustainability point of view, food product safeguard comes first, and means and technologies that contribute to this aim are welcome. For the same reason, new paradigms in packaging management should be critically assessed in the light of product safeguard, and any measure threatening quality, protection, and shelf life standards should be carefully considered.

Possible side-effects of plastic packaging reuse

Reusable packaging usually works with specific deposit and return systems to guarantee that the higher resources and investments used to make single-use packages reusable, are not spent in vain. This step requires the collaboration of consumers in the correct use and management and in the restitution of used packages. Besides this, the reuse of plastic packaging may have side-effects that are dependent on the intrinsic properties of plastics. Indeed, the multiple use of plastic packages may affect the hygienic and sensory spheres, with potential drawbacks such as the increase of sanitary risk, the shortening of the shelf life, and, consequently, the increase of the overall environmental impacts of food productions. In the following, there will be analyzed some unexpected issues that may arise upon shifting from a single-use to a reuse model for plastic packaging for industrial food applications.

Migration

In the last decades, sophisticated systems for mechanical recycling of PET have been developed and optimized with high investments, which have allowed this material to be fully recyclable and to close the loop, returning to food contact use. Nowadays, in the EU, it is possible to use 100% recycled PET (rPET) for the packaging of any food products, thanks to advanced decontamination systems: the postconsumer PET packages coming from sorting plants are processed into flakes and decontaminated by 'stripping' possible contaminants absorbed or adsorbed during the material lifecycle. Generally, high-temperature treatments and pressurization/vacuum are applied in order to get rid of the possible contaminants coming from previous food contact and from the environment, in order to produce rPET compliant for food contact use [5]. To ensure safety, the European Food Safety Authority provides opinions on applications for new recycling processes for postconsumer PET and authorizes [19], upon evaluation of the submitted dossier, new manufacturing processes for the production of food-grade recycled material.

The specific conditions and the strict requirements for the mechanical recycling processes highlight some of the issues connected to the repeated use of plastic materials: polymers are not inert and may interact with food components, with inks and with any other environmental chemical. Such interactions are based on the chemical nature and on the diffusional properties of the polymeric network. Based on their mutual affinity, contaminants may be sorbed into plastic materials, and be released afterward during new cycles of use in the absence of decontamination steps. It must be noted that washing does not represent a process of decontamination of plastics, since it can remove, at best, surface residues, while the full decontamination of PET requires its fragmentation into chips, which is, of course, contradictory to the concept of reuse.

A wide range of scientific studies have addressed the diffusional behavior of plastic packages with respect to the migration risk, but only a few have investigated the chemical risks connected with reusable plastic packaging. Some studies have focused on the release of bisphenols, recognized as endocrine disruptors, into reusable bottles. Kovačič et al. [20] assessed the release of bisphenols from reusable sports bottles into food simulants, according to Reg. EU 10/2011; the study revealed that polycarbonate bottles have the highest levels, however, different bisphenol types were also found in polyethylene (PE) and polypropylene (PP) bottles. Another study [21] found very low levels of bisphenols in reusable Tritan bottles: such bottles are sold as a bisphenol-A (BPA)-free alternative to polycarbonate ones. Tisler and Christensen [22] screened the compounds migrating from reusable plastic bottles into drinking water, finding out that plasticizers, antioxidants, and photoinitiators migrated into water even after subsequent flushing of the bottles; some of the detected compounds reported are of particular concern for their possible endocrine-disrupting effects, carcinogenicity, reproductive toxicity, and skin contact toxicity. A recent review on the food contact chemicals migrating from PET [23] highlighted the conditions and phases that may affect the leaching of intentionally and non-intentionally added substances across the material lifecycle, including reuse. Andra, Makris & Shine [24] investigated the antimony (Sb) and bromine (Br) leaching from reused PET and polycarboate (PC) plastic containers and they proved that the frequency of reuse, rather than the temperature or the UV exposure, was linearly related with the Sb leaching from PET bottles. These studies suggest that increasing plastic bottles' reuse calls for a higher attention for the leaching of inorganic and organic chemicals. However, one comprehensive study [25,26], reporting the results of a European project on the effects of reuse on technological, quality, and safety of plastic packages, suggested that the reuse of the articles did not significantly influence the chemical, physical, and surface properties, however, a carry-over effect of sorbed aroma to the newly packed product is unavoidable.

Loss of quality and standardization due to aroma scalping

Diffusional properties of plastics make plastic packaging prone to the sorption (*scalping*) of food components. While migration of chemicals from the packaging to the food endangers the safety of the product, scalping may affect its sensorial properties. Aroma compounds diffuse into plastics based on their partition coefficient, representing the affinity of the target molecule for the food matrix and for the plastic phase. The polarity of such components with respect to the polarity of the plastic phase mainly affects the sorption behavior of contaminants: indeed, volatile compounds migrate at a higher extent into a polymer if they have similar polarity [27]. If the scalping of aroma compounds may reduce the aroma perception of beverages packed in plastic, the release of sorbed volatile compounds in case of reuse may add extraneous flavors to the newly bottled beverage. Compounds sorbed into plastic may be released into newly packed products if favorable conditions occur, that is, higher affinity of the sorbed molecules for the food phase, high refilling or storage temperatures. Even if polyesters show a lower scalping proneness compared with polyolefines, a significant amount of volatile compounds characterized by low-odor thresholds may be sorbed [28]. Safa & Bourelle [29] assessed the ability of washing treatments with NaOH solutions to remove compounds that had been sorbed into PET bottles intended for reuse: the study demonstrated that limonene was sorbed at significant concentrations and that it was retrieved after washing, thus supporting the assumption mentioned above: sorbed compounds cannot be removed with common washing procedures, since they are trapped in the bulk of the polymer and would need specific conditions to desorb. Jetten, de Kruijf, and Castle [25] exposed PET and PC bottles and PP cups to contact with misuse substances (such as fabric softener, detergent, diesel, and urine) and with strongly flavored food products (such as mixed fruit syrup and anise syrup), and assessed the sensory effect on refilled water after 15 washing cycles: the refilled water always acquired distinct off-flavors upon contact with the reused package. The release of aroma compounds sorbed into plastic packages, therefore, may impact the overall quality of products newly packed into the reused containers, thus compromising quality and endangering standardization.

Increased risk for microplastics in food

Microplastic pollution has emerged as a growing cause for concern in the last years, since scientific evidence has been gathered on the abundance, dispersion, and persistence of plastics — from macro to nano — in the environment and their effects on ecosystems. Microplastics are plastic particles or fibers whose maximum length is below 5 mm, which have been recovered in marine and terrestrial environments, as well as in animal tissues [30–32]. Microplastics from any source represent a worldwide health issue: even if the mechanisms of toxicity still need to be clarified and confirmed, an increasing number of publications have highlighted the potential health hazards for humans, including gastrointestinal disorders, respiratory problems, cancer, infertility, and so on [33]. Cleaning and disinfection procedures, that are necessary to make reusable packaging suitable for successive cycles, have the potential to accelerate the aging process and result in the fragmentation of plastics [34]. Hence, since reuse implies repeated cycles of cleaning and disinfection operations, it is reasonable to assume that reused plastic packaging would undergo faster aging with increased microplastic release by fragmentation. As a matter of fact, a study addressing microplastics in bottled water [31] found that water in single-use PET bottles had the lowest number of particles, while water filled in reused aged PET bottles had more than 3-fold higher number of microparticles. Various studies in the latest years [35–38] have reported that the repeated use of plastic bottles determines the mechanical abrasion and the formation of microplastics from screw cap, with significant contamination of the contained products. Interestingly, microparticles were originating both from the bottle plastic (PET) and from the screw cap material (PE or PP). All of these studies demonstrate that water from single-use bottles has far-lower number of microplastic particles per liter compared with reusable bottles, assuming that the latter release more microplastics due to abrasion, since they are exposed to higher levels of stress.

Microbial recontamination and biofilm formation

Another critical aspect in the reuse of plastic packages is the risk for food/beverage recontamination, which would have serious implications for public health and for shelf life standards. Sanitization procedures of packaging materials are able to guarantee hygiene in newly produced packages, thanks to the heat-based production processes (i.e. extrusion, blow-molding, and injection molding), which allow to minimize microbial contamination. Heating applied during converting operations is usually sufficient to inactivate environmental microorganisms contaminating the material; hence, the sanitization procedures applied for aseptic packaging, for instance, do not need to be very harsh. Obviously, since one of the important functions of packaging is to protect food products from the activities of microorganisms, packaging materials should not be a source of microorganisms themselves. Sanitizing procedures commonly applied would not be sufficient to decontaminate packages that have been already used, raising the need for stronger chemical treatments and harsh conditions, which, in turn, would cause chemical residues to contaminate the food and a faster aging of the polymer with increased risk for microplastics (see previous paragraphs).

Plastic surfaces are prone to microbial colonization and to the development of microbial biofilms, which are very difficult to remove. Biofilms can develop on wet food contact surfaces and may be produced by pathogenic microorganisms, by spoilage microorganisms, or both together. Microorganisms in biofilms are usually protected against chemicals and sanitizers since these agents are unable to penetrate the protective layer of microbial biopolymers. For this reason, bacteria in a biofilm are much more resistant to conventional sanitizers compared with planktonic cells. Various studies have demonstrated that viable *Listeria monocytogenes* biofilm remained even after cleaning and disinfectant application [39]. Much research has been carried out for the development of antimicrobial surfaces intended to come in contact with food [40], however, such applications are mainly based on stainless steel, while plastic is intrinsically more susceptible to colonization by microorganisms, both spoilage and pathogen agents. By nature, plastic materials cannot guarantee the same hygienic performances as stainless steel or glass, especially in the case of a repeated use. The multiple domestic use of PET bottles with water generates taints, which are due to microbial development on the plastic surface: the situation would be much more critical if the contents were juice, nectars, milk, or plant-based drinks instead, due to a richer composition able to feed the microorganism. A few works have investigated the microbial contamination of reused bottles, for instance, Abrokwah et al. [41] found high levels of contamination by total and fecal coliforms in 60% and 40% of the assayed bottles, respectively. Similarly, Sun et al. [42] found high concentrations of heterotrophic bacteria and coliform bacteria, suggesting that improperly cleaned water bottles may present a potential reservoir for bacterial colonization and thus be a risk for foodborne illness. For this reason, reusable containers would not be suitable for aseptic technology, which should continue to rely on single-use containers in order to guarantee the product stability and hygienic standards. In any case, reusable plastic containers may represent a threat based on the variability of the hygienic level, depending on the conditions of the previous use. Finally, microbial biofilm formation may also raise another issue, related to the possible incorporation of allergens and to the risk of cross-contamination of products that should be free from such allergens.

Conclusion

Being single-use does not represent, in itself, a limit for sustainability for plastic packages, since they offer proved economic and environmental advantages for the food value chain. Undoubtedly, the management of plastic packaging waste needs to be improved. Plastic is not inert and may interact with food components and nonfood substances that are absorbed and cannot be eliminated through washing treatments. For this reason, the reuse of plastic packages such as bottles would threaten the quality standards, since sorbed contaminants would affect the safety and sensory properties of the new content. Plastic surfaces are prone to colonization by bacterial biofilms that are very hard to remove by physical or chemical treatments, hence, the reuse of plastic packages would endanger the protection performance of packages. The repeated use of plastic containers would increase the risk for microplastic contamination of foods: the material aging, the mechanical stress due to repeated cycles of use, and the sanitization procedures and products needed for the regeneration of plastic containers would boost degradation processes, thus enhancing fragmentation and microplastics release. Plastic packaging should be specifically designed for reuse (i.e. thicker walls, materials with higher glass transition, etc.), otherwise the repeated industrial washing procedures could cause deformation and compromise mechanical performances, with negative consequences on machinability, logistics, and consumer acceptance. This review highlights an urgent need for filling a scientific gap, in the light of the proposed strategies for packaging waste reduction. In particular, the effects of reuse conditions, including sanitization procedures, should be evaluated in relation to chemical migration, sanitization effectiveness, and technological properties of packages. Any measure aimed at reducing the environmental impacts should not impair product safety, quality, and shelf life, while the reuse of plastic packages implemented at the industrial level may have detrimental effects on product quality and shelf life standards, on consumers' health, and on the overall sustainability of food value chains.

Data Availability

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

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.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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