

Review

Smart Material Choice: The Importance of Circular Design Strategy Applications for Bio-Based Food Packaging Preproduction and End-of-Life Life Cycle Stages

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Abstract: This article provides a systematic literature review on the integrated approach of bio-based plastic food packaging in a circular economy. It focuses on the following key areas: (1) the role of bio-based plastic food packaging in a circular product design strategy and material choice in the preproduction life cycle stage; (2) the role of bio-based plastic food packaging in circular resource management systems and the product disposal life cycle stage; and (3) an optimal bio-based plastic food packaging application in regard to prioritising end-of-life treatment. While there are dedicated publications on the role of packaging in a circular economy, circular packaging design, packaging waste management, and bio-origin plastic applications in food packaging, this article aims to provide an integrated review and recommendations on the best bio-based plastic food packaging material selection, applications based on a circular economy, and scenarios on waste/resource management that prioritise end-of-life treatment. Three of the current most popular bio-based plastic materials in the flexible and rigid food packaging categories were selected: starch blends, bio-PE, and PLA for flexible food packaging and PLA, bio-PET, and bio-PE for rigid packaging. This article highlights the fact that a smart material choice in the circular design strategy is a key factor that has a direct impact on the last packaging life cycle stage (disposal), and concludes that bio-based plastic materials are a way to close the food packaging loop, either by re-use or recycling. This article also provides recommendations on the best bio-based plastic food packaging material selection, and applications based on the circular economy and waste management that prioritise end-of-life treatment. The research results indicate a research niche for the application of re-usable biodegradable materials in food packaging. The findings of this research allow product designers and packaging companies to advance the understanding of the most efficient bio-based plastic food packaging integration into the circular economy via decision making of product material choice and end-of-life treatment. Based on the results of this article, scholars can develop new themes for further research.

Keywords: bio-based plastic; circular product design; circular food packaging; packaging end-of-life; sustainable packaging



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1. Introduction

Food and packaging are daily products we consume. While some are redundant and could be avoided, others serve a purpose and are necessary. The common-sense sustainable behaviour principle of less is more encourages us to take personal steps, and implies that we should think about more rational and responsible behaviour, and avoid unnecessary consumption and waste. While the waste management hierarchy sets a clear sequence of actions to deal with waste in the best way, e.g., avoid, reuse, recycle, recover, and landfill [1], a circular economy model focuses on preventing waste and pollution from being created at all [2]. In a circular economy, waste becomes the materials for the new production, and the

future value is created by keeping materials within the economy for as long as possible, by reusing it again and again [3].

The COVID-19 pandemic has increased food and food packaging waste [4–6], and temporarily replaced plastic pollution, food loss, and negative environmental impact topics as the most important issue we face. The post-COVID period has brought the topics of food packaging innovations, the transition to sustainability, and renewable materials to the fore again. In the current global situation, when fossil fuel prices are experiencing rapid growth, knowing that bio-based plastic prices are more stable [7] makes the argument that fossil-based plastics cost less questionable. Moreover, keeping in mind the political situation and the topic of our dependence on fossil fuels, which is receiving much attention, renewable (naturally replenished on a human timescale [8]) resources are not only a promising alternative to fossil-based plastic but are also both a trend and an obligation.

A circular economy is a viable alternative that businesses have already started exploring. Since a linear approach (take, make, and dispose of) has resulted in pollution, climate change, and a finite supply of resources, the importance of understanding a complete product life cycle has become a key driver for the transition towards more regenerative solutions. Proper material selection, rethinking and redesign in the development stage of food packaging and the more intense integration of the biological cycle into the technical cycle in the waste management stage must be combined in order to achieve the most effective material flow for the food packaging sector.

In recent years, we have experienced changes in the materials of food packaging, where mainstream materials, such as conventional plastic and uncoated and plastic-coated paper, were replaced with novel materials, such as bioplastics, natural fibre-reinforced composites, barrier papers with natural coatings, amongst others. More and more packaging solutions with optimised designs, prolonged shelf lives, and increased food safety are being created and applied. More and more innovative packaging materials have appeared on the market that are marked as sustainable and made of renewable resources. All these novel renewable resources and food packaging materials must be applied properly in order to meet packaging requirements, but also integrate into the cycles of a circular economy and waste management streams in the most efficient and environmentally friendly way.

Renewable resources have lower environmental impacts and contribute to lowering fossil fuel consumption, microplastic pollution, and greenhouse gas emissions, compared with materials derived from nonrenewables [9]. Savings of 241 to 316 Mt CO₂eq per year could be achieved by substituting 65.8% of all conventional plastics with plastics of bio-origin [10]. In this context, the biggest advantage of food packaging made of renewables is achieved if they are made of alternative feedstocks, from the waste and side streams of agriculture or food production, such as nonedible lignocellulosic biomass [7]. Moreover, in terms of the bio-origin, compostable food packaging could bring extra value to the circular economy through cleaning waste streams and capturing and diverting food waste from landfills, becoming mechanically nonrecyclable packaging alternatives that supplement the mechanosphere cycle with the biosphere, and bringing biomaterials back to the soil and giving other advantages associated with biological recycling [11].

By integrating the results from different subject fields, such as the circular economy, circular product design, and waste/resources management, as well as food packaging applications, this article aims to present a holistic view of the best bio-based plastic applications in food packaging, and provides recommendations for priority treatment at the end of life, according to the packaging type, so it could best meet circular economy principles.

2. Research Method

In order to advance the understanding of the integration of the most efficient bio-origin plastic food packaging into the circular economy, and highlight the key importance of material choice in the circular product design stage, this study presents a systematic literature review, with a specific focus on bio-origin plastic food packaging applications, and priority end-of-life treatment options in the frames of the circular economy, circular product design,

and waste management strategies. A systematic approach is beneficial in order to provide collective insights into different theories and practices; therefore, this article aims to present an integrated summary of policy-based, practice-based, and academia-based literature and provides recommendations for the selection of smart bioplastic food packaging materials based on priority end-of-life treatment. This article only covers bio-based biodegradable and bio-based nonbiodegradable (drop ins) plastic categories. Biodegradable fossil-based plastics or bio-based–fossil-based blend plastics are out of the scope of this article as this group of bioplastics does not fit into circular economy. Additionally, this article focuses only on primary food packaging (direct contact of packaging with the product itself).

The theoretical framework of this systematic review was selected based on focus areas. Firstly, the circular economy, circular product design and waste/resources management strategies were analysed, and the food packaging situation/role in the analysed framework was identified. The literature for this focus area was selected by using the following keywords: circular economy strategies, circular product design, circular food packaging, circular packaging design, and waste management strategies FMCG statistics. This initial phase of desk research and literature review investigated policy-based, practice-based and academia-based databases of the European Union, United Nations, organisations (such as Ellen MacArthur Foundation, European Bioplastics, Circular Economy for Flexible Packaging (CEFLEX), Zero Waste Europe, and Scopus, Research Gate, and Science Direct, as well as Google Scholar platforms). The time span coverage is ten years, from 2013 to 2022. This stage of the review allowed us to understand the current situation of fast-moving consumer goods and food packaging as well as future prognoses, general circular product design, circular economy and waste/resources management principles. It also helped us to identify the food packaging role in a circular economy and highlight (1) the importance of material selection in the circular product design stage and the preproduction stage in a product life cycle and (2) the importance of material selection for a closed loop or take back product design stage and disposal in the product life cycle. Finally, it led to the interlinking points between circular product design and circular economy strategies, which are most related to food packaging and are crucial for efficient food packaging integration into resources/waste management systems.

Secondly, practice-based and academia-based literature was selected by the following sequence: using target keywords, identifying articles by reading titles, and selecting articles by reading abstracts. This sequence filtering produced the final sample of articles, which were analysed in depth. Target keywords were bioplastic food packaging, bioplastic applications, bioplastic food packaging applications, reusable bioplastic packaging, recyclable bioplastic packaging, PLA packaging, starch blend packaging, bio-PE food packaging, and bio-PET food packaging. This initial phase was focused on the newest bioplastic applications in food packaging research and covered the recent five-year time span starting from 2018 to 2022. As mentioned above, Scopus, Research Gate, Science Direct, Google Scholar platforms were used. The aim of this phase was to analyse and identify the main bio-based plastic food packaging materials, current bioplastic applications in food packaging and most frequently applied end-of-life treatment scenarios. Based on the information extracted from the selected articles, bio-based plastic food packaging was classified into two categories (flexible and rigid), and three most popular bio-based plastic materials in each category were selected for further phase: starch blends, bio-PE and PLA for flexible food packaging, and PLA, bio-PET and bio-PE for rigid packaging.

Lastly, the insights and results obtained in both stages of the conducted systematic review were synthesised. As a result, recommendations on the best bio-based plastic food packaging material selection based on circular economy and waste/resources management priority end-of-life treatment scenarios were prepared. A flowchart explaining the presented literature review process and research phases is provided in Figure 1.

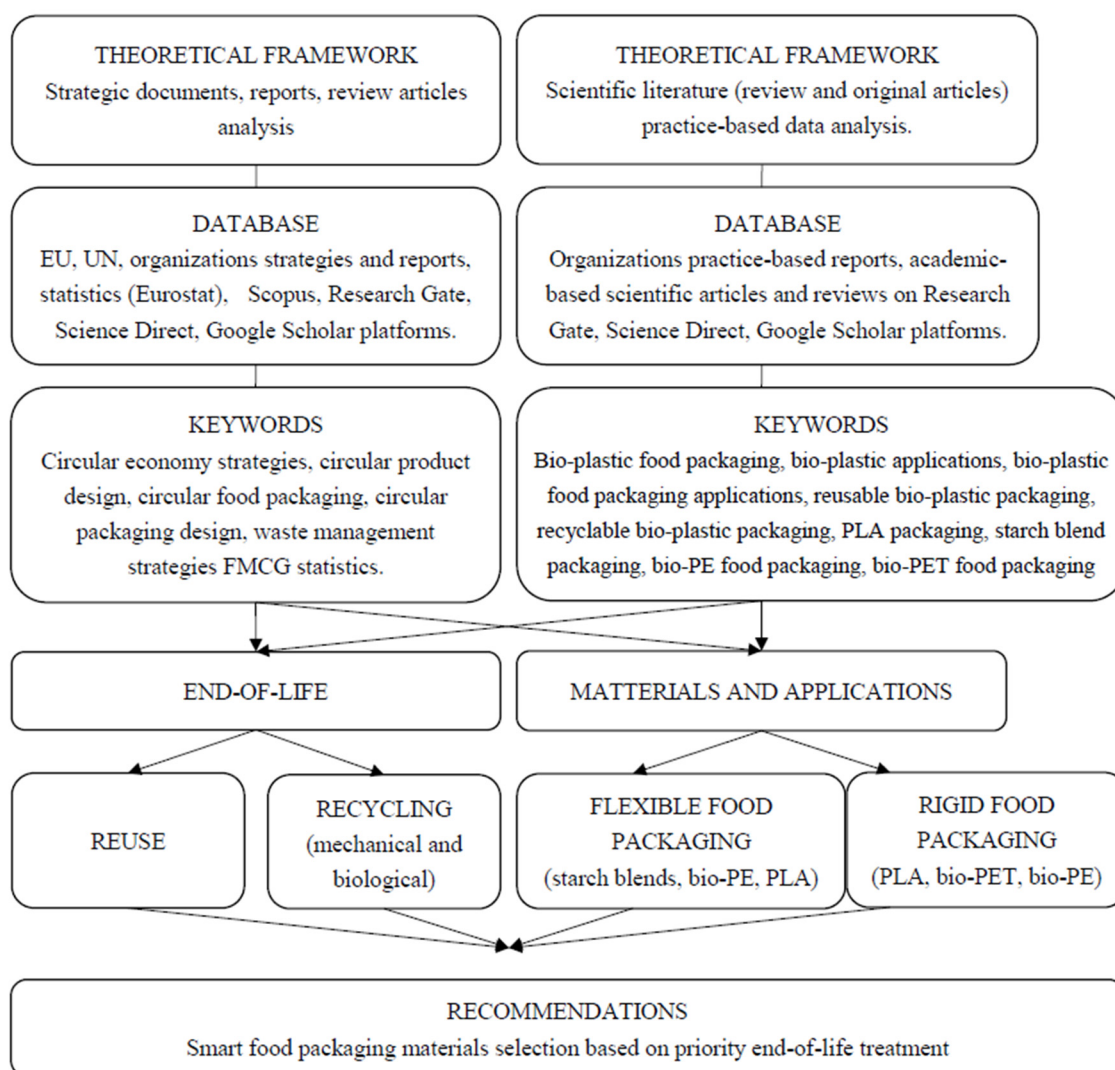


Figure 1. A flowchart explaining the presented literature review process and research phases.

3. Results and Discussion

3.1. Food Packaging—Statistics, Prognosis, the Role

In the past decade, the demand for fast-moving consumer goods has been rapidly rising and is expected to rise further. Among fast-moving consumer goods (FMCG), packed foods and beverages represent the majority. The global middle class that has the biggest demand for FMCG is expected to grow to 5.4 billion by 2030 [12]. This will lead to bigger volumes of production, a higher usage of raw materials and significant pressure on planetary resources. Across the global food systems, food loss and packaging waste are a widespread issue. Over the ten-year period from 2009 to 2019, packaging waste reached the highest value of 79.2 million tonnes. Paper and cardboard contributed 32.2 million tonnes to the total packaging waste as the main material in the packaging waste stream followed by plastic waste, which amounted to 15.4 million tonnes [6].

Food waste is another big issue. According to UN Environment Programme's (UNEP) Food Waste Index Report 2021 [13], around 931 million tonnes of food are wasted each year. Household food waste generated share is 61%, followed by 26% from food service, with the remaining 13% coming from retail. One of the United Nations Sustainable Development Goals is to halve food waste by 2030. Packaging with its main functions to ensure food safety and guarantee a prolonged shelf life plays a significant role in food waste management. A prolonged shelf life, food security and the mitigation of food and packaging waste are crucial from the environmental point of view, as food waste is one of the major contributors

to the global problems of climate change, biodiversity loss and pollution. Food waste is the third biggest source of greenhouse gas emissions [13]. At the same time, packaging waste reduction is a top priority, with efficient usage and the management of resources being of paramount importance, as well as the mitigation of negative environmental impacts caused by visual pollution and microplastic pollution in the food value chain. Optimal food packaging material selection is required to assure food loss, sustainable resources management and packaging waste reduction.

The selection of food packaging material depends on its properties and product group requirements. The main packaging functions are product protection, distribution, product storage, brand presentation and information provision. Packaging is classified as flexible and rigid. The properties of these two types are compared in Table 1 [14].

Table 1. Packaging classification and properties.

Description	Rigid	Flexible
Weight	Heavy	Light
Size	Used for bigger packs	Good for small packs
Storage	Bigger space requirements	60% less space required
Re-sealing	Not possible	Possible
Re-use	Can be used	Not re-usable

3.2. Food Packaging in Circular Economy—Interlinks between Circular Product Design and End-of-Life Treatment

This section will be focused on circular strategies and their relevance to food packaging in its production and disposal life cycle stages. The entire food packaging life cycle includes five stages: preproduction stage (material selection, design and refinement processes), production stage, distribution stage (transportation, storage and product packaging), use of product stage and disposal stage with different scenarios such as reuse, remanufacture, mechanical and biological recycling, incineration or landfilling [15]. Along with the whole life cycle of food packaging, the preproduction (material) stage is the main contributor to the overall packaging life cycle effects [16]. Estimates indicate that 80% of product manufacturing costs [17]) and over 80% of product-related environmental impacts are locked at the product design phase [18], meaning that circular design is a key factor for the most efficient material flows. Waste management also plays a significant role and can deeply influence environmental impact results in many impact categories [19]. Both stages, material selection and end-of-life, not only make significant environmental impacts, but also are strongly related to each other, as the choice of the material type affects the choice and availability of its end of life [20]. Therefore, a deeper look at the relevance of material selection (preproduction) and disposal of food packaging life cycle stages to circular economy, circular design and waste management strategies will be presented.

Strategies such as reduce (smarter product manufacture and use), reuse (extended lifespan of product and its parts) and recycle (useful applications of materials), generally known as the “3R’s” or “re-strategies”, refer to circular strategies [21]. These strategies are integral parts of waste and resources management hierarchy systems and strongly correlate with the product life cycle.

While the Waste Management Hierarchy introduced in the Waste Framework Directive (Directive 2008/98/EC on waste) is more focused on the mitigation of negative health and environmental impacts and efficient recycling, the new Zero Waste Resources Management hierarchy (A Zero Waste hierarchy for Europe) integrates social, economic and logistic considerations and highlights the importance of changing consumption habits, rethinking business models and setting waste-free designs as a top priority in the circular economy. The circular economy is defined as a “systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution”. A total of USD 700 million annual material cost savings could be achieved if a circular economy is implemented in the fast-moving consumer goods industry [2].

The success factor of the industrial transition to circularity is that this new economy model is regenerative by design. The Circular Design Guide prepared by the Ellen MacArthur Foundation in cooperation with IDEO distinguishes six circular design strategies:

- Product as a service, i.e., offering access to product leasing instead of sole ownership;
- Embedded intelligence, i.e., improving customer experience via integrated smart data management technologies;
- Extension of product life, i.e., product upgrades, repairs or remanufacture before recycling or disposal;
- Smart material choices, i.e., the best available material choice that guarantees the durability, functionality, and integration of recycled contents as well as easy recycling at the end of product's life cycle;
- Closed loop or take back, i.e., the collection, re-use and recycling of old/used products;
- Modularity, i.e., the availability to divide products into the smaller parts and replace the broken ones or reuse them in another product.

Two circular design strategies are directly applicable in food packaging: smart material choice, considering a product's end-of-life treatment in the choice of materials and inputs (i.e., durable, biodegradable, recycled or recyclable materials) and closed loop or take back, referring to collections of old or used products and recovering the value of the materials by recycling or reusing them to make new products.

The smart material choice circular design strategy (the choice of packaging material), which is applied in the preproduction life cycle stage, directly correlates with all circular re-strategies: firstly, packaging material savings (reduce) could be achieved if optimal material properties and minimum material usage were applied. Secondly, considerations of availability to design reusable packaging instead of single-use packaging must be evaluated. If a reusable design model is selected, material durability should be taken into account. Lastly, material choice is a key factor in mechanical and biological recycling (the last chance for materials to remain in circular material flows) options, meaning that only materials with no negative environmental impacts should be chosen for compostable food packaging and the industrial feasibility of mechanical recycling of materials should be considered if mechanically recyclable packaging is designed.

The importance of material choice in the product design stage and the summarized interlinks between circular product design, circular economy and resources management hierarchy, which are relevant to packaging life cycle preproduction (material) and disposal stages, are illustrated in Figure 2.

The application of the smart material choice circular design strategy in the food packaging preproduction life cycle stage is a key factor that directly affects the selection of end-of-life treatment and accordingly influences food packaging integration into the circular material flow. When designing food packaging, the durability, functionality, and integration of recycled content as well as material choice for easy recycling should be considered. As mentioned before, the most applicable food packaging material choice is determined by material properties and product requirements. In the next section, the most popular bio-based plastic food packaging applications based on the packaging type (either flexible or rigid) are reviewed.

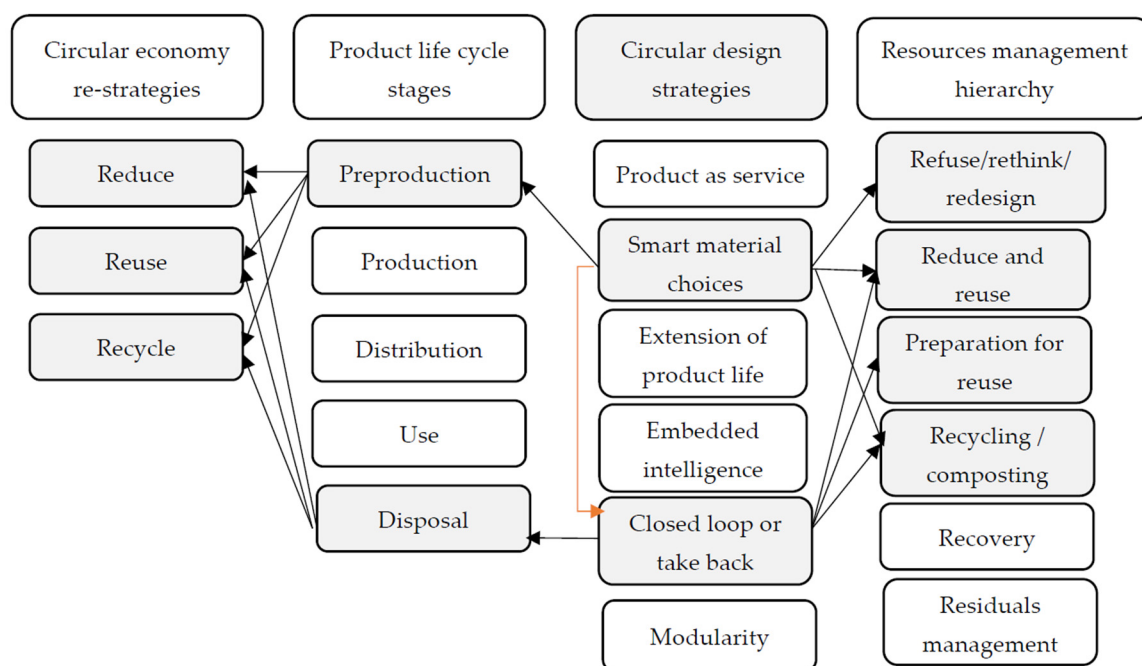


Figure 2. Interlinks of a circular economy and product design strategies with the resources management hierarchy relevant to food packaging life cycle preproduction and disposal stages. Prepared by authors.

3.3. Bioplastic Market and Bio-Based Plastic Food Packaging Applications

Global bioplastics production market share is less than 1% of the more than 367 million tonnes of plastics produced in 2021, reaching 2.41 million tonnes [22]. In the next five years, the production capacity is expected to triple. The main bioplastic applications are food packaging, making up 48%, which amounts to 1.15 million tonnes of total bioplastic markets [22]. Currently, bioplastics are successfully applied in flexible as well as in rigid food packaging. The global production capacities of bioplastics in 2021 by market segments are provided in Figure 3. Bioplastic applications in flexible and rigid food packaging are reviewed in the next two sections.

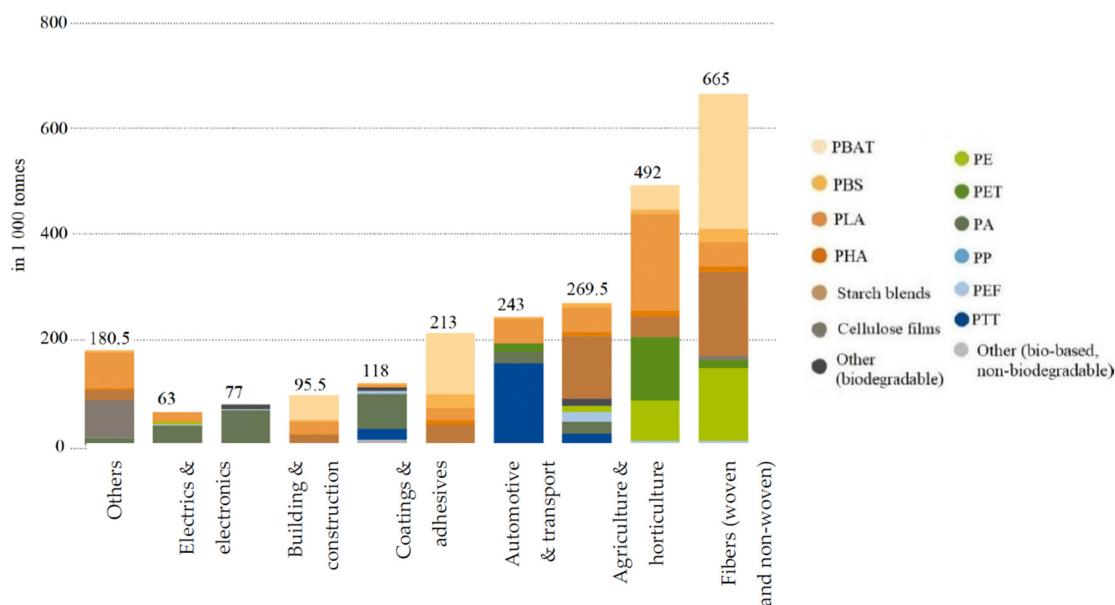


Figure 3. Global production capacities of bioplastics in 2021 by market segments (European Bioplastics, 2021).

3.3.1. Flexible Bio-Based Plastic Food Packaging

The global production capacities of flexible packaging made of bioplastics amount to 0.665 million tonnes. The main bioplastic material used for flexible packaging is Poly (butylene adipate-co-terephthalate) (PBAT). PBAT is a fossil-based or partly bio-based polymer. It is fully biodegradable and compostable, but as it relies on fossil-based resources (and all PBAT blends), it does not fit into a circular economy [9] and is not a subject of this article. Besides PBAT, starch blends, bio-polyethylene (bio-PE) and polylactic acid (PLA) are three main bio-based plastics used in flexible packaging production (European Bioplastics) that are circular.

Starch blends are complex blends in which the starch content is usually lower than 50% [23]. These biomaterials are mostly valuable for packaging, where biodegradability is an advantage, such as food waste bags. Starch-based materials are not suitable for fully transparent food packaging applications; however, they can be used for semi-transparent films, bags and pouches [24]. Starch films have a high permeability to water vapor [25], and due to their hydrophilic nature, they have poor water-resistant properties, which can be improved by adding 10% (wt) kaolin [26] or, as one of the most recent studies has revealed, hydrophobicity could be increased by adding caffeine [27]. Even though starch blends have a low gas permeability, they are suitable for food packaging as they prolong shelf life [28].

PLA is highly transparent, but it is rigid and sensitive to tearing; therefore, it cannot be used for stretch films. However, PLA is perfectly suitable for clear films that are used for fresh food, such as vegetables and fruits. Like starch blends, PLA has poor water vapor and oxygen barrier properties, and without additional barrier, this bioplastic is not suitable for long-storage products that are water sensitive and require a high water vapour barrier. While PLA is not suitable, for example, for frozen food or long-shelf-life bakery products [7], it can be used for fresh/warm bakery products as these do not require a long shelf life, and a high water vapour transition is a benefit. Some research has indicated that PLA nanostructured composites exhibit improved film properties [29,30], and therefore can be successfully applied to a wide range of food packaging, such as margarine [31] or fresh curd cheese [32].

Bio-PE, like other drop-in plastics, has an identical chemical structure to fossil-origin PET, polyethylene (PE) and polypropylene (PP) [33]; thus, their applications for food packaging are identical—clear and stretch films, pouches, and bags.

3.3.2. Rigid Bio-Based Plastic Food Packaging

The global production capacities of rigid food packaging are lower compared to flexible food packaging and amount to 0.492 million tonnes. As illustrated in Figure 3 (see above), novel material PLAs, followed by the drop-in plastics bio-polyethylene terephthalate (bio-PET) and bio-PE, are the most popular renewable materials for rigid packaging production (European Bioplastics).

PLA is suitable for packaging containers of food, such as vegetables, mushrooms, and berries, and can replace fossil-based polystyrene (PS). Additionally, this bioplastic is used for cups and bottles. However, because of its higher water permeability, it cannot compete with polyethylene terephthalate (PET) in long-shelf-life bottles/containers [7], although a recent study conducted by Aversa et al. [34] has revealed that it is possible to obtain good quality wine bottles using a PLA/PBSA (poly (butylene succinate-co-butylene adipate)) blend. The possibility of PLA as a replacement for PET bottles has been highlighted in other sources [35,36]. PLA and a starch blend with PLA have an advantage compared to conventional plastic or PE-coated paper and boards that are used in single-use tableware (cups, plates, takeaway food containers, etc.) and cutlery [7] and are a significant source of packaging waste due to their low recyclability [37].

Because of the identical chemical structure to fossil origin plastics, applications of drop-in plastics bio-PET and bio-PE for food packaging, as already mentioned, are similar; bio-PET is mainly used for bottles, clear and other trays, and bio-PE is used for trays, caps and food containers.

3.4. Circular Food Packaging

3.4.1. Re-Use

The circular economy approach, the 3R circular strategy and the resources management hierarchy prioritise reuse over recycling (mechanical and biological). This is due to energy savings, efficient resources management, waste generation reduction and littering prevention. Moreover, reusables are a shift toward more conscious consumption. Packaging-free shops [38], refillable solutions with optimised material use [39] and global platforms for reuse (the loop) have already been introduced on the market.

There are a number of comparative life cycle assessments (LCA) of the environmental performance of reusable and disposable products that provide very case-dependent results and conclusions, depending on the chosen material as well as the LCA methodological choice and assumptions. In most cases, reusable packaging is more environmentally friendly [20] however, there are some cases where single use is a preferable option and the main factors are long transportation distances, the number of cycles of reusable packaging, packaging weight and volumes that impact the fuel consumption and space needed. Almeida et al. [40] analysed a different type of material reusable and single-use cups. This study has concluded that reusable PP and glass cups are a better option than PLA single-use cups after around 10 uses. Similar data on the number of cycles were revealed by Cappiello et al. [19], who compared single-use tableware of PLA-PBS (polybutylene succinate) blend with reusables. The LCA in meal kit packaging performed by Guðmundsson [41] considered the whole life cycle from cradle to grave and pointed to a conclusion that reusable packaging can mitigate a significant environmental impact on climate change and the depletion of fossil fuels.

In industrial practice, flexible food packaging is not reusable. However, one of the latest studies on reusable packaging investigated a PLA film enhanced with a 0–3% (wt) nanostructured composite based on silver, titania and graphene fat and oxygen permeability as well as antibacterial activity properties for the new and reused film. The used film after usage was cleaned and washed three times with distilled water and with 95% ethanol, dried in air and applied again. The authors concluded that this PLA film can be reused with a reproducibility of 100% in the case of 0.5% PLA and with a reproducibility of 85% in the case of 3% PLA3 [32].

3.4.2. Mechanical Recycling

Full material circularity is a priority of a circular economy. Recycling in the 3R strategy is the last chance for materials to remain in circular material flows and is an attractive end-of-life treatment option, where reuse is not applicable or is economically unfeasible. As much as 20% of single-use plastic could be replaced by reusable systems [42]. Recycling is a favourable option for sustainability, as energy inputs are substantially lower compared with primary resources and influence the GHG balance positively [9].

Plastic Recyclers Europe [43] reports that recyclates reduce CO₂ emissions by up to 90%. An LCA case study with a cradle-to-grave approach in China, where fast food delivery in single-use packaging is a rapid growing sector, revealed that if recycling rates achieve 35% (currently a lot of packaging is incinerated or landfilled), it would reduce the emissions of single-use packaging by 16%, and a further 60% decrease could be achieved if half of the packaging was made of recycled material [44].

Bio-origin plastic drop-ins (bio-PE, bio-PET) are fully compatible with existing recycling streams and are currently recycled. Other bio-based plastics, such as PLA [9] or a PLA/PHB-type blend [45] can likely be recycled; however, because of the small scale, they are financially unattractive. The amount of plastic recycling in Europe equates to over 8.5 million tonnes, with the aim to quadruple this by 2030 [43]. The Circular Economy for Flexible Packaging (CEFLEX) [46] initiative reports that only 30% out of 10–14 million tonnes of European end market flexible packaging and other films may be recycled. For the remaining quantity, additional recycling capacities, including mechanical/physical, chemi-

cal and biological ones, are needed. The report also highlights the need of improved sorting systems, clear quality requirements and Designing for a Circular Economy guidelines.

It is important to note that high recycling rates depend on a set of factors, such as efficient collection by source and post-consumer separation, as well as through a deposit system, and the availability of recycling capacities. Circular product design applications are also important, meaning that products must be designed to assure the easiest available sorting and recycling experience for end-consumers and recycling streams.

3.4.3. Biological Recycling

The best applicable end-of-life treatment depends on sorting and collection systems, waste volumes, the availability of waste processing infrastructure and its properties [7], such as biodegradation in case of biological treatment. In most cases, bio-origin plastic packaging is perceived as biologically recyclable single-use packaging; the reason for this is that essential applications of renewable materials have been developed in order to mitigate single-use plastic visual pollution and negative environmental impacts. An EEA expert on sustainable resource use and waste (Almut Reichel [47]) indicates that biodegradable and compostable plastics in some cases and for certain applications can help to mitigate environmental plastic pollution, but it is not a stand-alone solution. Odegard et al. [9] emphasise that composting biodegradable packaging does not produce compost as a final product and the process is CO₂ neutral. In case of digestion treatment, bio-based plastics yield biogas. GHG emissions can be lowered if compostable bio-based plastics have co-benefits.

Biodegradable packaging made of bio-based plastics is recommended in those applications where it can add extra value. In cases when biodegradability is not an important functionality and does not provide any co-benefits, such as the increased separation of food waste, nonbiodegradable mechanically recyclable packaging is the first choice. A study conducted by Tamburini et al. [48] revealed that the recycling of PET bottles allows reducing the global warming potential (GWP) by up to about 30% compared with PLA, as composting does not lead to any GWP savings. The importance of co-benefits has also been highlighted in Bishop et al.'s [7] case study, where the maize-based compostable PLA packaging of fresh fruit and vegetables showed lower footprints only in 6 of the 16 impact categories in comparison with fossil-based packaging with modelled recycling and incineration end-of-life treatment. The authors conclude that the co-benefit of diversion of PLA-packaged food waste to organic recycling is compensation, meaning that overall environmental performance improvements are achieved in the bioplastic packaging scenario. Kakadellis and Harris [49] in their critical review have emphasised the target application of biodegradable bioplastics, where mechanical recycling measures fail. An advantage and the best application in the food packaging of industrially compostable PLA films that can be composted together with fruit and vegetables were also highlighted by Martien van den Oever et al. [7].

Compostable packaging co-benefits food and the packaging waste stream as a solution for nonrecyclable packaging, capturing and diverting food waste out of landfills, cleaning mechanically recyclable waste streams in such a way so that food leftovers in the conventional waste stream do not contaminate recyclable material, and bringing about a simplified consumer experience [11].

Recommendations on the best bio-based plastic food packaging material selection and applications based on the circular economy and waste management priority end-of-life treatment are provided in Table 2.

Table 2. Recommendations on the best bio-based plastic food packaging material selection and applications based on the circular economy and waste management priority end-of-life treatment.

	Novelty Bioplastic	Re-Strategy and End-of-Life (in Order of Priority)	Drop-in Bioplastic	Re-Strategy and End-of-Life (in Order of Priority)
		Flexible food packaging		
Pouches	Starch blends PLA, PLA blends	Recycle as non-reusable Composting	Bio-PE	Recycle as non-reusable Mechanical recycling
Clear films	PLA, PLA blends	Recycle as non-reusable Composting	Bio-PE	Recycle as non-reusable Mechanical recycling
Stretch films	-	-	Bio-PE	Recycle as non-reusable Mechanical recycling
Shopping/waste bags	Starch blends PLA blends	Reuse if possible Recycle Composting	Bio-PE	Reuse if possible Recycle Mechanical recycling
		Rigid food packaging		
Bottles	PLA, PLA blends	Reuse if possible Recycle Composting	Bio-PET	Reuse if possible Recycle Mechanical recycling
Single use tableware (cups, plates)	PLA, PLA blends	Reuse if possible Recycle Composting	-	-
Single use cutlery	PLA, PLA blends	Reuse if possible Recycle Composting	-	-
Clear trays	PLA	Reuse if possible Recycle Composting	Bio-PET	Reuse if possible Recycle Mechanical recycling
Other trays/containers	-	Reuse if possible Recycle Composting	Bio-PE Bio-PET	Reuse if possible Recycle Mechanical recycling

4. Conclusions

Although recycling capabilities vary, all the bio-based plastic food packaging materials analysed in this article are suitable for recovery through either biological or mechanical means. In order to improve sustainability and increase bio-based plastic food packaging circularity, the most efficient use of bio-based materials (primary and recycled) should be a key strategy.

The application of the smart material choice circular design strategy in the preproduction life cycle stage plays a major role in having a direct impact on the last packaging life cycle stage—disposal. With regard to the food packaging disposal life cycle stage, closing the loop or the take back design strategy is an effective tool to mitigate packaging waste and optimise resource regeneration. Using bio-based plastic materials is a way to close the food packaging loop, either through reuse or recycling.

Due to energy and resource savings as well as waste generation reduction and littering prevention, the 3R circular strategy and the resources management hierarchy prioritise reuse over recycling. Most researchers conclude that reusable packaging is more environmentally friendly; however, in each case, factors such as transportation distances, the number of reusable packaging cycles and packaging volumes and weight should be considered as recycling could be more environmentally favourable and economically feasible.

With regard to recycling, drop-in plastic food packaging made of bio-PET or bio-PE has already been successfully integrated into existing mechanical recycling streams. Novel plastic food packaging, such as PLA and starch blends, should focus on those applications where mechanical recycling measures fail or in cases where biodegradability is an important functionality. The most valuable novel plastic application in food packaging is achieved when it brings co-benefits, such as the increased separation of food waste or cleaner mechanical waste streams. It is worth noting that reusable compostable packaging is still niche in terms food packaging applications.

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