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Aiding the Design of Innovative and Sustainable Food Packaging: Integrating Techno-Environmental and Circular Economy Criteria

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Abstract

Reducing food waste and increasing resource efficiency have become worldwide targets as highlighted by the United Nations Sustainable Development Goal 12 – Responsible consumption and production. Food packaging, in particular plastics-based, is a key component of food-related waste: packaging increases the amount of total waste, but also reduces potential food waste by protecting food products and prolonging their shelf life. Therefore, it is important that packaging is designed as to satisfy both technical and environmental criteria. Hence, this paper seeks to develop a decision-support framework and key metrics to aid development and selection of new innovative food packaging within a circular economy context. A set of indicators is proposed, integrating techno-environmental and circular economy criteria to help designers as well as food and packaging manufacturers develop more sustainable products. The methodology is illustrated through a prototype new plastic packaging developed as part of this project, considering its use for two types of product – raspberries and meat – as illustrative examples.

Keywords: climate change; environmental impacts; food waste; life cycle assessment; plastics; resource efficiency ;

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1. Introduction

Reducing food waste and increasing resource efficiency have become worldwide targets as highlighted by the United Nations Sustainable Development Goal 12: ensure responsible consumption and production patterns [1]. Food waste amounts to 1.3 billion tonnes worldwide and represents 7% of greenhouse gas emissions [2].

Packaging helps to reduce food waste by protecting food, reducing its losses and prolonging its shelf life [3]. However, packaging has also become an environmental burden, particularly single-use plastics, due to its reliance on fossil fuel resources and lack of appropriate waste management practices. Plastic packaging accounts for 26% of the total plastics used and around 72% of these materials are currently lost, with 40% ending in landfills and 32% in the oceans and urban areas [4]. Additionally, the total production of plastics accounts for 6% of the world's oil consumption. Although the recycling rate of plastic has increased, only 14% is recycled and after further treatment, only 5% of the material cost is retained [4].

Environmental impacts of food packaging have been studied extensively. Most studies considered the direct impacts of packaging within the life cycle of a product, accounting for the production and waste management of packaging along the food supply chain. However, the indirect impacts related to the role of packaging within the product's supply chain have also been gaining attention [5-7]. Similarly, studies integrating circular economy (CE) principles have also been carried out, mainly for beverage packaging [8].

With a rapid growth of plastics use and acknowledging the impacts on resource use, climate change and ecosystems, the New Plastics Economy (NPE) aims "to deliver better system-wide economic and environmental outcomes by creating an effective after-use plastics economy, drastically reducing the leakage of plastics into natural systems (in particular the ocean) and other negative externalities; and decoupling from fossil feedstocks" [4].

Hence, this project, carried out in collaboration with industry, seeks to develop key metrics to aid development and selection of new innovative food packaging congruent with the NPE. For these purposes, a set of indicators is proposed, integrating techno-environmental and circular economy criteria to help designers as well as food and manufacturers develop more sustainable packaging.

2. Methodology

The decision-support framework developed in this study to guide the design of food packaging is outlined in Fig. 1. As can be seen, this involves three main steps: 1) evaluation of packaging features related to food and packaging waste (technical issues); 2) application of circular economy principles to evaluate the use of materials and energy and end-of-life management practices; and 3) comparison of environmental impacts of new and existing packaging through life cycle assessment (LCA). These are discussed in more detail in the following sections, followed by the application of the methodology to a packaging prototype developed as part of this project.

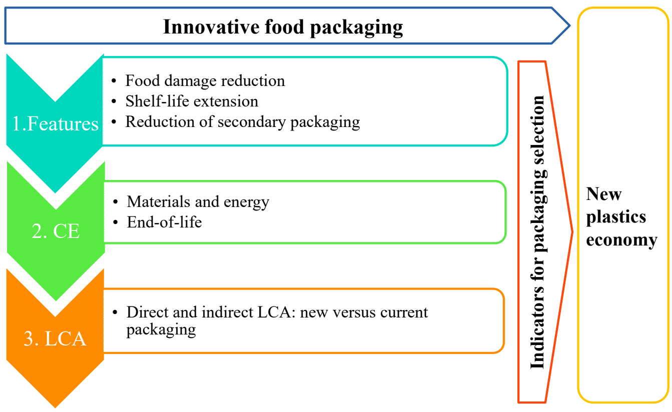

Fig. 1 A decision-support framework for guiding the design of innovative and sustainable food packaging (CE: circular economy; LCA: life cycle assessment).

2.1. Indicators

To evaluate the viability of an innovative plastic packaging solution, in addition to an economic assessment, it is imperative to consider a range of technical and environmental aspects to ensure that the solution is fit for the NPE [4]. To this end, the packaging should fulfill the following three key aspects of the NPE:

i) effective after-use of plastics, which refers to increasing recycling, reuse of packaging and considering alternative materials;
ii) reducing leakage of plastics into natural ecosystems and other negative externalities, which includes effective after-use management collection, storage and treatment, innovative design and materials that encourage after-use and reduce environmental impacts of packaging; and
iii) decoupling plastics from fossil feedstocks, to help decarbonise the industry and increase resource efficiency.

To satisfy these criteria, 16 techno-environmental indicators are considered, grouped into three categories corresponding to the methodological steps in Fig. 1: technical features of packaging, circular economy and environmental impacts (LCA). As shown in Table 1, technical features comprise three indicators, two related to protecting the food to reduce waste and one to reducing the use of secondary packaging. There are nine indicators related to circular economy principles, grouped into two groups: materials & energy and end-of-life management. Finally, four LCA impacts are considered: climate change impact, primary energy demand, and depletion of fossil fuels and metals. The rationale for their inclusion in the framework is discussed below, together with their application to the development of a new prototype packaging. The latter is described next.

Table 1: Metrics for designing and selecting food packaging solutions with an example application to raspberries

Category	Indicator	Unit	Prototype packaging	Current packaging
Packaging	Food damage reduction	% damage	10-20%	-
	Shelf-life extension	days	0	-
	Secondary packaging reduction	units/crate	8	9
Circular	Amount of material	g/kg product	88	91
	Mono or multi components	no./type	OPP/PE or PP/EVOH[a]	PET[a]+PET film
	Recycling content	%	0	0
	Reuse rate	times	0	0
	Current waste management	I, L, C, R[b]	I+L	I+L
	Current recycling rate	%	33%	33%
	Potential recyclability	%	100%	100%
	Use of renewable materials	%	0	0
	Use of renewable energy	%	UK-grid	UK-grid
Environmental	Climate change	kg CO_2 eq.		
	Primary energy demand	MJ		
	Depletion of fossil fuels	kg oil eq.		
	Depletion of metals	kg Cu eq.		

[a] OPP: oriented polypropylene; PE: polyethyelene; PP: polypropylene; EVOH: ethylene vinyl alcohol; PET: polyethylene terephthalate.
[b] I: incineration; L: landfill; C: composting; R: recycling. Collection rate in the UK: 33% of pots, tubs and trays. On average, 46% of plastic packaging for food and other products is recycled [9].

2.2. Prototype packaging

The proposed methodology is illustrated using a prototype packaging that would prolong food shelf life, reduce the amount of packaging and help avoid food waste along the supply chain. The packaging has a double-layer design, with an outer sealed quad containing a suspended inner cavity (see Fig. 2a). This means that products can be placed in either the inner or outer pack or both. The inner and outer packs can be sealed with a vacuum, air, a modified atmosphere or their combination. The prototype is produced, filled and sealed in purpose-made equipment. For this study, the base of the pack was sealed, product inserted into the inner bag and the top of the pack sealed.

Fig. 2 Prototype (a) and current packaging (b) considered in the study (raspberries shown as an example)

Both the inner and outer packs were sealed together producing a quad pack. Due to the versatility of the packaging, two food products – raspberries and meat – have been tested to see if the prototype would benefit any of these food supply chains. Raspberries have been selected as a representative soft fruit, ideal for testing the packaging feature related to damage protection. Meat (diced beef) has been chosen for consideration for two reasons: first, packed beef requires a high-oxygen environment to maintain the red colour of the product and carbon dioxide, which is used as antimicrobial agent; both gases could be provided and maintained within the different cavities of the prototype. Secondly, beef is one of the most carbon, energy and water intensive food items and hence reducing its waste would help to reduce the climate change impact and resource depletion associated with the life cycle of this product.

2.3. Packaging features

Along with safety, protection is one of the key purposes of packaging, which is directly linked with food waste. Protection is not only related to damage due to manipulation and transport. It also enables shelf-life extension as it helps to conserve physical conditions of the products. Hence, to develop these indicators, the prototype is compared with the current packaging options based on three tests: damage reduction, shelf-life extension and secondary packaging reduction.

2.3.1 Damage reduction test

This test compares the prototype with the current packaging used for soft fruits – punnets – to determine if it would reduce damage during transit and, therefore, food waste. Raspberries are used as an example of soft fruit and they were packed in both types of packaging (see Fig. 2). The packs were exposed to 'abuse', including transport vibration and drop tests. For the latter, samples were dropped from a height of 76 cm [10]. These tests were carried out for both individual packs and crates. To simulate transit conditions, each crate was filled with one pack type. The crates were packed into the back of a van and driven for 1 hour, before being placed into storage. On each sampling date, images were taken and the total number of raspberries per pack counted. Damaged and moldy raspberries were segregated and counted to determine the number per pack. These were then converted to percentage 'damage per pack'. All sampling was carried out in duplicate packs for each type of packaging.

2.3.2 Shelf-life extension test

This test looks at the use of a modified atmosphere to extend shelf life. The permeation of gases and different modified atmospheres might help to maintain for longer characteristics of products. To test this, diced meat was packed in a high-oxygen atmosphere (75-50% inner chamber, 75-100% outer chamber) to maintain the distinctive red colour, supplemented by carbon dioxide (25-50% inner chamber, 25-0% outer chamber) as an antimicrobial agent. Retail packs of diced beef are commonly packed in a high-oxygen (70-80%) and carbon dioxide (20-25%)

environment resulting in the bright red colour of the beef.

2.3.3 Reduction of secondary packaging

This test determines the amount of packed products that fits in current secondary packaging, in this case reusable plastic crates. Crates were loaded with the same number of layers for each packed product and the results expressed in 'number of packed products per crate'.

2.4. Circular economy indicators

The suggested circular economy indicators (Table 1) are based on the guidelines to measure circularity developed by Ellen MacArthur Foundation (EMF) [11]. These guidelines focus on the materials and energy used in manufacturing as well as on end-of-life waste management. These guidelines and the chosen indicators are directly aligned with the NPE criteria mentioned earlier.

2.5. Environmental impacts

LCA has been selected as a tool to assess the environmental impacts of packaging from cradle to grave. This includes extraction and production of raw materials, manufacturing, transport and distribution, storage, use and end-of-life waste management. Both direct and indirect LCA are carried out, with the former related to the packaging life cycle and the latter to the life cycle of food and the role of packaging in the supply chain.

While LCA enables estimations of a number of impacts, only four are considered here (Table 1). The reason for focusing on a reduced number of environmental indicators is the difficulty in obtaining data for a wider range of impacts during the development of new packaging (or any product). All four indicators are related to use of resources and are linked to the circular economy metrics. In addition, climate change is one of the key policy drivers.

2.6. Proposed framework

The proposed framework to guide the development and final selection of the best option is illustrated in Fig. 3, building on from the overview of the framework in Fig. 1.

The underlying premise of the framework is that it recognises that the replacement of an existing packaging requires significant efforts, as packaging is a strategic and critical aspect of food products. Additionally, issues related to food and plastics waste are becoming more important across governments and societies. Hence, it is suggested here that both criteria related to the packaging features and circular economy (Table 1) are considered as critical when starting the assessment. This also aligns with the fact that several of these indicators will then be used to carry out a LCA study. If neither of the two criteria is positive for the new packaging, the LCA will not be required. In the case that only one criterion is positive, then the LCA is carried out (Fig. 3).

Similarly, if both criteria are overall positive for the prototype, then LCA is performed for both the new and existing packaging, considering the packaging and food product life cycles (direct and indirect LCA). It is expected that, if the packaging features are favourable, the life cycle of the product will be positive, as the features are aimed at reducing food waste and use of secondary packaging. However, this is not guaranteed for all food products as the impacts depend on a range of factors, such as the amount of food waste that is saved, the environmental impacts of both food and packaging, and so on. Hence, LCA could help identify opportunities for improving the design of new packaging if the results are not positive or, ultimately, lead to its selection over the current packaging if its environmental impacts are lower. However, this will also depend on the outcomes of an economic assessment, which is assumed to have been carried out prior to the consideration of the prototype.

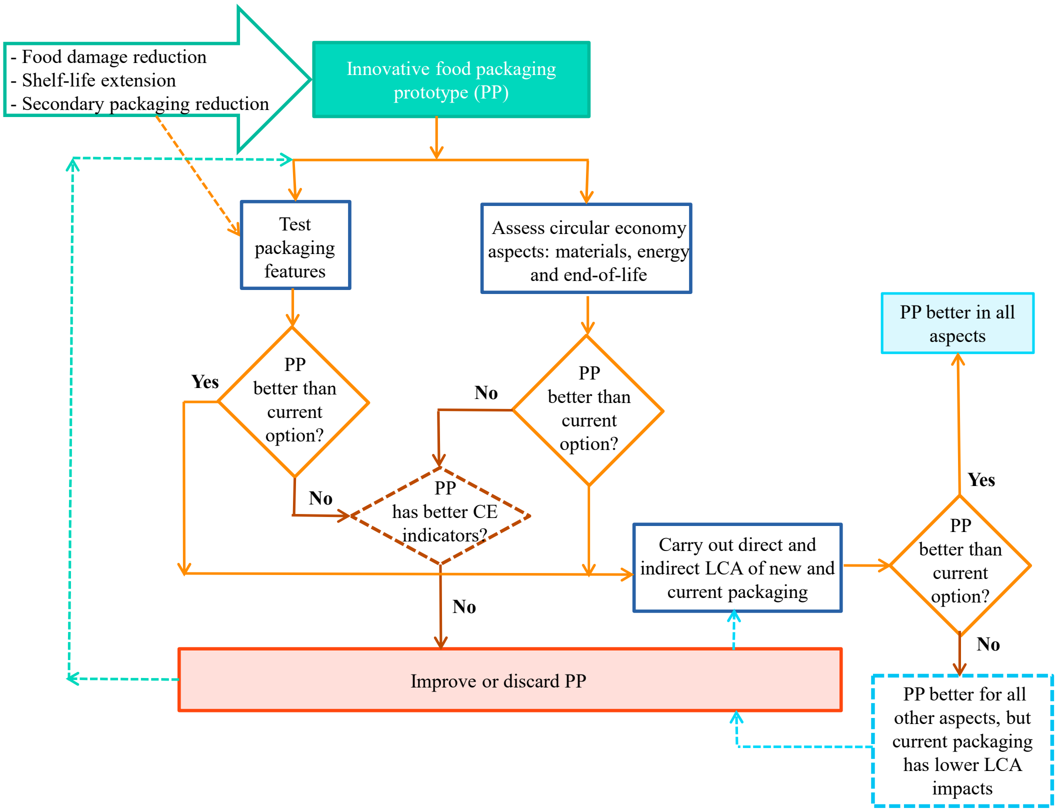

Fig. 3 Detailed methodological steps for the decision-support framework in Fig. 1 (CE: circular economy; LCA: life cycle assessment; PP: prototype).

3. Results

This section first presents the results of the packaging features tests described in section 2.3 and then discusses the results related to the circular economy indicators. The results are shown in Table 1 for the example of raspberries. The results for meat are also discussed.

3.1. Packaging features

The damage reduction test showed that in the ‘abuse test’ there was more damage to the raspberries when they were packed using the prototype packaging. This is mainly due to the raspberries being normally packed on a horizontal line into the current packaging; however, the machine for the new packaging fills the packs in a vertical position, incurring damage to the product due to the vertical drop during packing. Deterioration includes loss of firmness, darkening of the berries and mould growth. The level of damage recorded increased during storage with almost half of the berries being considered damaged by the end of the storage trial. The control berries, which were hand-packed in the new packaging showed considerably less damage (10-20%) than those packed by the machine. Similarly, the control samples that were packed into current packaging by the new machine had high levels of damage. This issue could potentially be avoided in a horizontal machine design, which we understand has been designed but not yet built.

Considering the ‘drop test’, the raspberries that were dropped using the prototype packaging showed a higher level of damage compared with the control samples (dropped using current packaging). The damage was also higher for the raspberries in current packaging that were packed by the new machine. In the ‘transit test’, raspberries packed in the prototype had higher levels of damage compared to the raspberries packed in current packaging. Overall, these tests showed that the new packaging does not offer a better protection than the existing, neither in individual packs nor in crates. Moreover, it is clear that the vertical filling plays a critical role, as the product is mainly damaged in this stage.

The shelf-life extension tests showed that the new packaging did not offer significant improvements over the current type. In the case of raspberries, the control samples for both types of packaging showed little difference in the shelf life of the product and, if there was any, the outcome was worse for the prototype. In the case of diced meat, the trials using different atmospheres did not show consistent results and were inconclusive. Overall, the diced beef packed in the prototype maintained red colour but did not show a significant difference compared to the control samples. However, two issues affected the performance of the prototype. First, the meat that was in direct contact with the surface (barrier) changed colour – from red to brown – much faster than the other pieces. This occurred at differing levels, depending on the combination of gases used, as the degree of beef browning varies with the volume of gas within the inner pack. However, as no microbiological testing was carried out, it is not known whether the colour change was also associated with a change in the microbiological load. The second issue was the presence of liquid (meat juice), due to the lack of absorbent materials (drip pads), typically used in packed meats. As the appearance of meat is particularly important for consumers, the presence of uneven colour and liquid could increase the amount of rejected products, hence increasing food waste.

Regarding secondary packaging, nine packs of current packaging filled a single layer of a returnable plastic crate. Depending on the depth of the crate, two layers could be placed in the crate, totaling 18 packs per crate. The orientation and the size of the new packaging determined how many could fit into the same size crate. The prototype can be placed into the crate flat or on its side, which is a limitation for the existing type. When the new packs were laid flat in a returnable crate, eight packs were able to fit with minimal overlapping. Again depending on the depth of the crate, an additional layer could be placed in the crate. If the prototype was packed on its side within the crate, 16 packs could be fitted in. However, it is unlikely that another layer could be added because of the height of the pack. Furthermore, there is more weight on the raspberries at the bottom of the pack, which could potentially cause damage. However, with a different type of product, the pack on its side may not be an issue. Nevertheless, based on this test, the new packaging does not offer an advantage since in the best case it is similar to the current type.

3.2. Circular economy indicators

As shown in Table 1, the circular economy indicators show no advantages for the prototype used for raspberries in comparison to the current packaging type. As both options are single-use products made from 100% virgin materials, both show the same performance in terms of the recycling content and reuse rate (0%). Similarly, almost all indicators of waste management and end of life are similar if not the same for both. The only difference is related to the amount and kind of materials used. The prototype used for raspberries shows an advantage for the ratio of materials per product, using 3% less material; for diced beef, it offers a greater advantage with 34% lower amount of material. However, the prototype is made from a mix of oriented polypropylene (PP) and PP or PP and ethylene vinyl alcohol (EVOH), while the current packaging is made of only one material type (PET). Therefore, the latter is a better alternative as the use of mono-materials helps to produce a higher-value recycled product and promote closed loop recycling, which is important in the food industry [12]. Additionally, comparing the materials use, PET shows a greater advantage as it is considered a more desirable material compared to a mix of materials and particularly to EVOH, which are less and least desirable, respectively [12]. Finally, PP/oriented PP and PET used for food containers have similar recycling rates (33%) in the UK [9]. In terms of using renewable resources, both materials are currently made using virgin fossil feedstocks and predominantly grid electricity. However, it should be noted that the prototype could potentially be made of mono-substrates with recycled content and/or be recyclable. For the purposes of this test, OPP/PE and PP/EVOH were used as these materials were available at the time.

Therefore, given that both the packaging features and circular economy indicators are unfavourable for the prototype packaging, the LCA was not performed. However, previous LCA studies have shown that PET has a higher climate change impact than PP (2.27 vs 3.77 kg CO_2 eq./kg) [13]. Hence, if the prototype packaging can be improved with respect to the technical performance and circular economy indicators, LCA might also show potentially positive attributes. At present, there are no LCA data for oriented PP and EVOH.

4. Conclusions

This study has developed a decision-support framework to guide the design and development of new food packaging solutions within the new plastics economy. The criteria include packaging futures related to food and packaging waste (damage reduction, shelf-life extension and reduction of secondary packaging), circular economy aspects in terms of materials, energy and end-of-life waste, and finally the environmental impacts of the packaging and the food supply chain considered. The methodology has been tested by application to a plastic packaging prototype. Although the prototype does not show benefits in comparison with current packaging, it helps to exemplify the use of the suggested criteria and indicators in the design and decision-making related to the selection of the best alternative.

The proposed approach encourages the integration of key issues, such as circular economy and life cycle thinking in both the design and selection stages, which should be considered along with technical performance when developing and selecting innovative solutions for food packaging. This will be of interest to packaging and food manufacturers looking to develop new products and test their technical and environmental performance, in addition to the economic viability.

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