Alternatives to single-use plastics in food packaging and production

Area of research interest: Innovative regulator
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Authors: RSM UK Consulting LLP, FSA supported by Dr Samuel Short (University of Cambridge
Conducted by: RSK UK Consulting LLP
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Alternatives to single-use plastics: Lay Summary

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This rapid evidence assessment undertaken by RSM UK Consulting LLP (RSM) and Dr Samuel Short (University of Cambridge) aimed to develop an understanding of the alternatives to single-use plastics in food packaging and production in terms of their risks and opportunities, as well as potential future developments. Literature from within and beyond the UK was gathered from academic databases and reports published by government and non-governmental organisations such as environmental charities. Evidence from the literature was supplemented by findings from a workshop with experts in the field from a variety of industries such as academia, manufacturing, and government.

Two broad groups of alternatives were established: material/product alternatives (traditional materials, natural fibres, biopolymers synthesised from biomass, biopolymers synthesised from bioderived monomers, biopolymers produced by microorganisms) and, and system/process alternatives (reducing, reusing, and recycling food packaging and, active and intelligent packaging). These alternatives and systems vary considerably in terms of their properties, such as effectiveness as a barrier to moisture or contamination, convenience for consumers, production costs, and potential for commercialisation. Our review also highlighted gaps in the current knowledge, for example in terms of consumer acceptance and carbon footprint at each stage of their life cycle.

The capacity to produce bioplastics (i.e. biopolymers that look and feel similar to conventional plastics but are made from natural materials rather than fossil fuels and are biodegradable or compostable) is anticipated to increase globally from 2.1 million tonnes in 2019 to 6.3 million tonnes by 2027. This growth appears to be enabled by increased consumer awareness of environmental issues and existing regulation and legislation encouraging the development and establishment of a circular economy. However, there are barriers that may challenge this growth. These include already established industry regimes, high production cost of novel materials and a lack of waste management guidance.

Overall, fossil-based conventional plastics are a very cheap, versatile material compared to the alternatives currently being developed and tested. Because of this, they might remain the preferred industry choice for certain applications, while alternatives continue to be optimised and commercially scaled. To add to this, the reviewed evidence suggests that there is unlikely to be one single solution to the single-use plastics problem. The solution will likely draw on a range of materials and systems depending on food type and context.

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Alternatives to single-use plastics: Executive Summary

RSM UK Consulting LLP (RSM) in conjunction with Dr Samuel Short (University of Cambridge) and the University of Birmingham Library Services, were commissioned by the Food Standards Agency (FSA) to carry out a rapid evidence assessment of the alternatives to single-use plastics in food packaging and production. This research aims to establish a baseline understanding of the risks and opportunities associated with the use of alternatives to single-use plastics in the food system, identify the main alternatives to single-use plastics, and understand potential future developments in the area.

Methodology

To undertake this rapid evidence assessment, we searched for relevant academic within two databases (SCOPUS and Web of Science) as well as grey literature from relevant national and international governmental and non-governmental organisations. The results were screened for relevance to the research and overall quality, and gaps in evidence were supplemented with additional articles using a further targeted search. Additionally, two co-production workshops with our expert panel including our academic advisor, representatives from FSA and experts from academic, industry and policy backgrounds were undertaken. Conclusions, evidence gaps and areas for future consideration were triangulated across research themes.

Findings

Findings from the review were extracted and mapped against each research question. Gaps in evidence were identified, with a lack of available literature for on the trajectory of alternatives development and use, and any potential need to adapt UK food regulation. Evidence related to the role of the FSA was primarily derived from workshops and consultations with the expert panel.

Table 1 provides a summary of key findings against each research question.

Table 1: Summary of findings

Research question	Key findings
1. What are the single-use plastic alternatives emerging in food production and packaging, and what risks and opportunities do the alternatives pose?	Two broad groups of alternatives were established: material/product alternatives (traditional materials, natural fibres, biopolymers synthesised from biomass, biopolymers synthesised from bioderived monomers, biopolymers produced by microorganisms), and system/process alternatives (reducing, reusing and recycling food packaging and, active and intelligent packaging).
2. To what extent are the alternatives already in use	Market information on the current extent of alternative usage is both limited and inconsistent. There is a lack of evidence to enable a comprehensive assessment of the extent of use for each alternative. To demonstrate the extent of adoption, five case studies have been developed: • The London Marathon (seaweed) • The University of Cambridge Library Services (traditional alternatives, biopolymers and Polylactic acid (PLA)) • Wagamama UK (recycled materials, cardboard and Crystalline Polyethylene Terephthalate) • McDonald's Europe (traditional alternatives, fibre, edible packaging) • Loop/ Tesco Trial (reusable packaging made from traditional alternatives for example glass and aluminium). Alternatives brought a number of benefits in each case. However, companies typically encountered a number of trade-offs when introducing alternatives. For example, the majority of McDonald's products are consumed off-site meaning they are dependent on consumers and adequate infrastructure for their recyclable packaging to be of maximum benefit.
3. What trajectory are the alternatives likely to take over the next ten years, in terms of innovation, adoption, spread, and becoming established in the industry, and what are the associated enablers and barriers, including regulatory approaches and policy initiatives?	Global production capacity of bioplastics is anticipated to increase from 2.1 million tonnes in 2019 to 6.3 million tonnes by 2027. This will largely be driven by growth in production of PLA and Polyhydroxyalkanoates (PHAs). Current and upcoming legislation in the UK and Europe will encourage a continued focus on the 3R's (reduce, reuse, recycle) and the circular economy. Enablers to support the growth of alternatives include increased consumer awareness of environmental issues and, existing regulation and legislation. Barriers include established industry regimes, consumer practices, perceptions and awareness, high production cost of bio-plastics, and a lack of available waste management guidance.
4. Are there any changes required to UK food regulation in the context of the alternatives, and if so, what are the potential changes at the legislative, governance, training and enforcement levels?	The application of existing legislation to novel materials which serve as an alternative to single-use plastics is unclear. Clarity is needed with regards to the following factors for new materials: appropriate treatment and disposal of packaging, labelling standards and guidance on how to demonstrate safety of new materials.

Overall, fossil-based plastics are a very cheap, versatile material compared with the alternatives currently being developed and tested. Conventional plastics will probably remain the preferred industry choice for certain applications for the foreseeable future while the alternatives are optimised and scaled into commercial products for application in real world industries. As such, there is a need for caution in driving the transition to more sustainable solutions.

The evidence reviewed in this study suggests that there is unlikely to be one single solution to the single-use plastics problem, and that all alternatives have significant limitations which must be considered. The solution will be a range of materials and systems depending on food type and context. For example, zero packaging may be the most sustainable solution for dry goods, edible films for fresh produce, and biopolymers such as PLA to replace single-use plastics in the take-away industry.

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Alternatives to single-use plastics: Introduction

RSM UK Consulting LLP (RSM) in conjunction with Dr Samuel Short (University of Cambridge) and the University of Birmingham Library Services, were commissioned by the Food Standards Agency (FSA), to carry out a rapid evidence assessment to develop an understanding of the alternatives to single-use plastics in food packaging and production.

3.1 Background

The global food industry's reliance on single-use plastics is having large negative impacts on the environment (for example, Sheehan, 2017; Kershaw, 2018). Every year in the UK, 2.5 million metric tons of plastic waste is generated, equivalent to 98.7kg per capita (Statista, 2023). This waste ends up as a source of environmental pollution which damages natural ecosystems and creeps into our food chain through the ingestion of microplastics. While consumer preferences are gradually drifting towards alternatives which are perceived to be more sustainable, the health and safety risks and sustainability credentials of emerging solutions are yet to be fully explored. It is imperative that the FSA are fully equipped with current evidence on the risks and opportunities of alternatives in order to develop an appropriate strategy which considers all aspects in terms of benefits and costs to UK businesses, consumers and the natural world.

Policy context

There have been recent changes in the policy landscape for single-use plastics within the UK. In 2022, plans were announced for a ban on single-use plastic plates, trays, bowls, cutlery, balloon sticks, and certain types of polystyrene cups and food containers, to be effective from October 2023 (UK Government, 2023) and previous bills to restrict the use of single-use plastic drink stirrers, straws and cotton-buds (enforced in October 2020) . This has followed the five pence single-use carrier bag charge (now 10 pence minimum), which led to a decrease in plastic bag sales of 95% from 2015 to 2021 (Defra Press Office, 2021). In Northern Ireland (NI), since 1st April 2022, the single-use carrier bag levy increased to 25 pence (NI Government, 2022). Since the levy was introduced in NI, more than £19 million has been raised and used to support local environmental projects (BBC News, 2020).

Furthermore, a Plastic Packaging Tax, first proposed in the UK Budget in 2018 but introduced in 2022, applies to the manufacturing or importation of plastic packaging which is not comprised of at least 30% recycled material (UK Government, 2022). The transition away from single-use plastics is mirrored in policy changes across the globe. A few significant changes include:

- The EU's Directive on Single-Use Plastics, which has caused legislative action in 23 countries since 2019, including single-use plastic bags, plastic taxes, reusable product targets and regulations (EUR-Lex, 2019).
- many countries, including India, Canada and Kenya have established outright bans on the manufacturing, distribution, sale and use of numerous single-use plastic items, with many other countries such as the USA, China, Brazil, Mexico, Chile having similar policies on a regional basis (Behera, 2022).
- the Canadian government is providing support and funding for SMEs to develop sustainable alternatives to plastic packaging through its Canadian Plastics Innovation Challenge (Government of Canada, 2021). The EU has similar funding schemes through Horizon Europe Research and Innovation (European Commission, 2018).

3.2 Study aims

This research aims to establish a baseline understanding of the risk and opportunities associated with use of alternatives to plastics in the food system in terms of:

- sustainability (for example, environmental impact, recyclability, biodegradability)
- food safety (for example, protection from contamination).

This research also aims to identify the main alternatives to single-use plastics in terms of materials and their functions and to understand potential future developments in this area. The outcomes of this research have the potential to inform future policy and regulation decisions as well as guide the development of further research. The scope of the project has been centred on the following research questions:

1. What are the single-use plastic alternatives emerging in food production and packaging, and what risks and opportunities do the alternatives pose?
2. To what extent are the alternatives already in use?
3. What trajectory are the alternatives are likely to take, over the next ten years, in terms of innovation, adoption, spread, and becoming established in the industry and what are the associated enablers and barriers, including regulatory approaches and policy initiatives?
4. Are there any changes required to UK food regulation in the context of the alternatives, and if so, what are the potential changes at the legislative, governance, training and enforcement levels?

STEEPLE theme analysis has been used to analyse the available evidence and inform each research question. STEEPLE analysis involves consideration of the following elements:

- **Social**, for example, food safety for the general public and specific consumer groups (allergens, pathogens, toxicity, cross-contamination); food availability, nutrition, choice; food fraud/crime and traceability; consumer awareness, and attitudes towards alternatives
- **Technological**, for example, materials, functionality, durability
- **Economic**, for example, cost-effectiveness, market maturity, business model innovation (for example, circular business model, retail model), adoption and spread of innovation/solution (current and future)
- **Environmental**, for example, sustainability including carbon footprint, resource use, waste and pollution in production, transport, storage, disposal
- **Political**, for example, legislation, advocacy
- **Legal**, for example, regulatory and enforcement
- **Ethical**, for example, accountability, responsibility.

Alternatives to single-use plastics: Methodology

A rapid evidence assessment was conducted to develop an understanding of the alternatives to single-use plastics in food packaging and production. Research tools and deliverables were co-produced with our academic advisor and our expert panel.

4.1 Project initiation

A project initiation meeting was held with the FSA project team on 21st December 2022. At this meeting, the following was agreed upon:

- Research approach

- Project plan
- Project management arrangements
- Reporting plan
- Risk management procedures
- Mapping relevant stakeholders to invite to join the expert panel

4.2 Literature searching, screening and extraction

4.2.1 Literature search

A targeted literature search was carried out in conjunction with University of Birmingham Library Services, according to the search terms set out in the search protocol (Appendix B). Two academic databases were searched: Web of Science and SCOPUS. Literature was also gathered through the following methods:

- FSA project team (N=2)
- Academic advisor and call for evidence amongst expert panel (N=23).

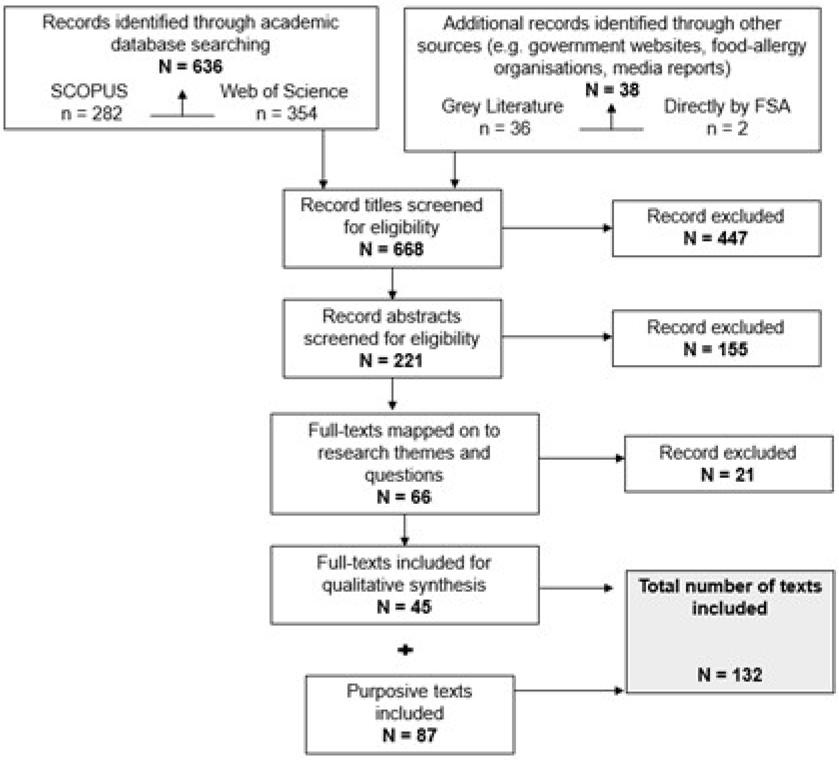
An iterative approach to screening was undertaken. Title screening was conducted, followed by abstract screening of included texts. Texts included following the abstract screening were reviewed for quality and information relating to the research questions was extracted. Following the extraction of all texts, gaps in evidence were identified. A second, purposive search was conducted to fill any evident gaps in evidence for each research question. However, these articles were only used to address the emerging gaps in the literature review rather than conducting a full quality review and extraction of information.

Co-production: A workshop was held with the expert panel on 25th January 2023. Experts were identified in collaboration with the FSA project team and represented a range of sectors (for example, academia, retail, manufacturing, policymakers; see Appendix E for a list of experts). Experts provided feedback on the draft search protocol (including search terms) to ensure the most relevant research in the field was captured. At this workshop, experts also highlighted key materials which should be included in the review (including academic articles and grey literature). Where experts could not attend the workshop at the specified date/time, individual consultations were accommodated.

4.2.2 Screening and extraction

In total, the search resulted in a longlist of 668 articles which were rigorously screened as detailed in Figure 1. At each stage, three reviewers were involved in screening and any discrepancies were resolved through discussion and consensus development.

Figure 1 PRISMA style reporting of records at each stage of screening



This resulted in a shortlist of 45 articles as listed in Appendix C. Gaps in evidence were supplemented with 87 articles from the purposive search following the workshop. In total, 132 texts have been used throughout this research.

4.3 Analysis and reporting

Findings from the literature review were summarised according to the four research questions. Using the populated data extraction spreadsheet, the extracted data was analysed to provide a narrative synthesis of findings. This included information on the volume and quality of evidence base per single-use plastic alternative technology/solution as well as overall information on the identified literature, in terms of types of studies/articles, their location and what the research base is focused on. An assessment of the overall quality and coverage of literature is summarised in Section 5.1.

This final research report was produced in collaboration with our advisor, the FSA project team and the expert panel.

Co-production: A workshop was held with the expert panel on 14th March 2023. The expert panel provided feedback on the draft findings and identified gaps. This workshop was also used to discuss how the existing research highlights priority areas of focus for the FSA in terms of innovations in alternatives to single-use plastics.

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Alternatives to single-use plastics: Results

5.1 Overall quality and coverage of literature

The overall quality of the articles reviewed was determined using the Defra guidance on critical appraisal for rapid evidence assessments (footnote 1). This was on the basis of two scores: first on relevance to the research topic (scored from one to three) and second on robustness of the research (scored from one to three). These scores were then combined into one quality score for each article. Across the 45 articles reviewed and extracted, the combined quality was 7.2 out of maximum score of nine.

Table 2 provides information about the coverage of research questions as set out in section 3 in the evidence reviewed.

Table 2 Extent of coverage for each research question, highlighting gaps in the literature reviewed

Research question	Level of coverage and gaps found
Question 1 (alternatives to single-use plastics)	Strong coverage of the technology, social, environmental and economic dimensions, but gaps in terms of legal, political and ethical dimensions.
Question 2 (extent to which alternatives are in use in the UK)	Moderate, information on specific examples of adoption of alternatives rather than systematic evidence, for example in terms of market performance.
Question 3 (trajectory of alternatives)	Moderate, information on influencing factors, enablers and barriers but gaps identified in systematic forecasts and predicted trajectories.
Question 4 (adapting UK food regulation)	Limited. Gaps addressed through workshop discussion with expert panel.

5.2 Research question 1: Alternatives to single-use plastics

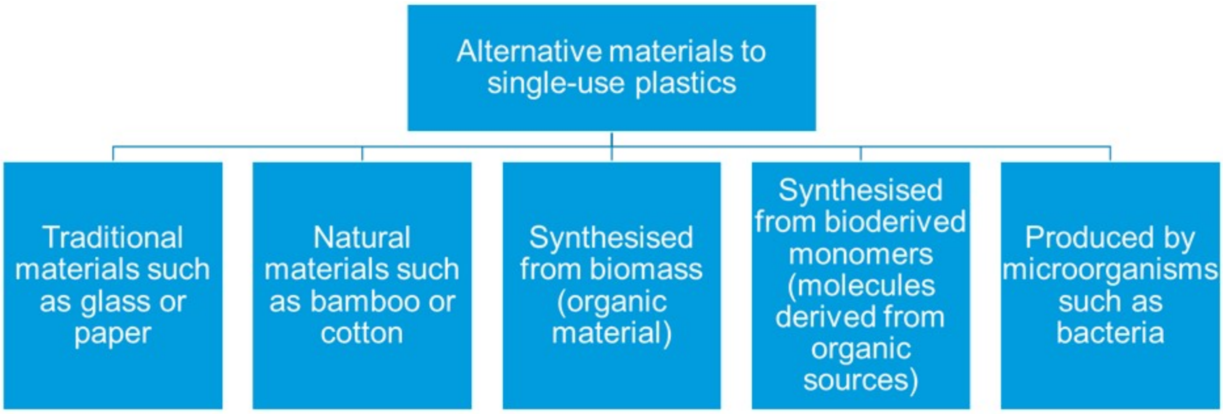
The alternatives to single-use plastics can be categorised into two broad groups: material/product alternatives, and system/process alternatives, with a range of alternatives existing within these groups. The first category is related to alternatives in terms of materials and how they are produced, for example traditional materials such as paper, natural fibres such as bamboo, and materials synthesised from organic materials such as starch. The second category is related to alternatives that are based on systems or processes such as reducing or reusing packaging as well as active and intelligent packaging. Both categories are discussed below.

This section presents different types of alternatives, as found in the literature review. These findings have been supplemented by the guidance, research knowledge and experience of our advisor, who was able to fill gaps and offer critical insight when assessing the advantages and disadvantages of each alternative.

5.2.1 Material and product alternatives

Our classification of the material alternatives is partly based on the system used by Petersen et al. (1999) as illustrated in the schematic below.

Figure 2 Schematic illustrating the main categories of material or product alternatives to single-use plastics



5.2.1.1 Traditional materials

Paper

Paper is one of the oldest materials used commercially for food packaging. Examples of its use include cereal boxes, cartons and bags. While the global market for paper is mature, it is still expected to grow at a compound annual growth rate (CAGR) of 3.9% from 2023 to 2028 (Mordor Intelligence A). There are many advantages of paper and card as an alternative to single-use plastic packaging, based on its acceptance by consumers (Herrmann et al., 2022), competitive pricing due to an established manufacturing process and its recyclability and biodegradability.

However, there are also some significant limitations to paper, particularly regarding food safety and general functionality. It is not fully sealable and is permeable, which can reduce shelf life. It also offers weaker protection from physical impact. Furthermore, paper has limited reusability, and recycling can be prevented if paper is contaminated with grease, food waste or has a bonded plastic film layer. There are also environmental concerns. Paper releases methane in landfills during anaerobic respiration (Ishii & Furuichi, 2013), a gas which has a greenhouse effect 28 times larger than carbon dioxide over 100 years (Centre for Science Education). Additionally, the production of new paper requires significant amounts of water, chemicals, inks and energy, and can cause deforestation (Herrmann et al., 2022).

Glass

Glass is a versatile material that has been used for centuries. It is made from abundant raw materials such as sand, soda ash, and limestone. In the UK, glass is often used for food packaging products such as jars, bottles, and containers. The UK glass packaging market is expected to grow at a CAGR of 4.4% from 2023 to 2028 (Mordor Intelligence B).

Functional advantages of glass are impermeability, transparency, sealability and strong physical protection. It can extend food shelf life, as it performs highly as a barrier of resistance for oxygen, moisture and UV light. Glass is fully reusable and can be easily collected and recycled within current recycling infrastructure systems (72.5% of UK glass packaging waste is recycled; Defra, 2022). Food waste, grease and other contaminants are not a concern when recycling glass, making the process easier than paper.

However, there are some limitations to using glass as a food packaging material. Given that the production and recycling process for glass is very energy-intensive (Stefanini et al., 2021), there are concerns surrounding its carbon footprint. While this may be negated by using renewable sources, the high energy requirements represent an opportunity cost, as that energy could be used for other economic activities. Furthermore, glass is far more expensive than plastic for packaging products in terms of production, disposal and transport. This makes it less viable as a substitute for profit-maximising businesses and cost-minimising consumers. Glass products can also be less convenient than plastic for consumers, due to being heavier and more fragile than plastic products.

Metal

Tin, aluminium and steel are common metals used for food packaging products such as cans and foil. Metal is also used for transport and bulk packaging such as barrels and drums. It has a predicted CAGR of 3.4% from 2018 to 2028 for the UK metal packaging market (Mordor Intelligence C).

Product shelf lives can be greatly extended using sealable metal cans, helping to reduce food waste. Other metal products such as aluminium foil, are light and thin, making them efficient and price competitive. Metal packaging is also impermeable and can offer strong physical protection. Typically, metal items are reusable for extended periods of time. The material is also the subject of a well refined recycling system which uses significantly less energy than new metal production. This helps to explain why aluminium cans are able to compete in price to plastic bottles. 66% of all metal packaging waste is recycled (Defra, 2022). This reduces waste and the need for raw material extraction.

While some metals are reusable, consumers cannot reseal most types of cans, and may find washing the packaging inconvenient. The recycling process currently generates carbon emissions; however this will be reduced as the UK transitions to a renewable energy economy. New metal production is also costly, and the raw material is more difficult to source compared to other alternatives.

5.2.1.2 Natural fibres

Natural fibres capture a wide range of food packaging products. Materials and products fall into this category if they are biological materials (coming from organic matter) which have proven packaging applications without the need for an extended and transformative production process. Specific materials include, but are not limited to, bamboo, cotton, jute and coconut coir.

The advantages of using these materials are mainly environmental. Many of these materials are reusable, they all biodegrade naturally, and many are non-toxic. Furthermore, there are low energy and labour requirements for production compared to other alternatives.

The disadvantages of using natural fibres are mostly to do with food safety concerns. Food packaging products from natural fibres are not sealable, which results in a shortened shelf life of food when compared to plastic and other alternatives. This, combined with the permeable nature of these materials means that there is also an increased risk of food contamination. Some materials may also cause mild allergic reactions from inhalation or contact.

Additionally, some natural fibre products can be resource intensive. Cotton, for example, needs significant water and land inputs. This high initial resource cost means that a cotton bag needs to be reused 50-150 times before it has a lower environmental impact than single-use plastic bags

(UNEP, 2020).

No predicted growth data was found on the natural fibre food packaging market.

5.2.1.3 Biopolymers synthesised from biomass

This category is within the broader group of materials known as 'bioplastics' which are either bio-based, biodegradable, or both (Ronzano et al., 2021). Materials in this category are made from naturally occurring biopolymers found in biomass. Examples of biomass sources include polysaccharides (including starch and chitosan), proteins (including casein, gelatine and whey) and lipids (including essential oils and wax). Commercial product examples typically fall into two specific groups. Edible coatings (such as Apeel (footnote 2)) are primarily aimed at reducing moisture loss and oxidation, whereas containers with film products are more centred on offering strong physical protection (Petkoska, 2021).

Seaweed polysaccharides

Researchers have spent considerable time assessing the use case of seaweed derivatives as an alternative to single-use plastics, particularly as an edible film. This is because seaweed species are some of the fastest growing organisms on the planet, which means it could be an abundant and renewable material (Froehlich et al., 2019) which provides economic benefits to coastal communities around the world (Rana, 2022). Abundance and renewability could lead to low costs of food packaging production compared to other materials in the future.

There are also characteristics which make seaweed derived packaging convenient for consumers. Some seaweeds have been shown to have antioxidant and antimicrobial effects, which extends the shelf life of foods (Carina et al., 2021). Packaging products are also transparent and sealable.

Seaweed derived packaging also offers significant environmental benefits. One benefit is their ability to biodegrade quickly in natural conditions. The London-based sustainable packaging start-up Notpla (footnote 3) has shown that their seaweed derived alternative completely biodegrades in three to six weeks (Price, 2020). Furthermore, seaweed cultivation combats ocean acidification and therefore helps to mitigate the adverse effects of climate change on sea-living organisms (Xiao et al., 2021).

However, the evidence on the material's ability to maintain structural integrity for extended periods of use is inconclusive. Some research has also raised concerns about toxicity and allergenic risks associated with seaweed, and whether the production process for packaging is able to eliminate these risks or not (Trindade, 2022). Currently, this industry is still young compared to other alternative food packaging solutions, meaning it is not yet scalable and competitive in terms of price (Future Bridge, 2022). Knowledge on the local ecological impacts of large-scale seaweed farming is also limited (Eggertsen and Halling, 2021). Therefore, continued research, innovation and investment will be needed for some time before seaweed alternatives can become a competitive alternative to single-use plastics through mass production and mainstream commercial adoption.

Market research company Data Bridge (2022) have predicted a CAGR of 16.5% for the global seaweed packaging market from 2021 to 2029.

5.2.1.4 Biopolymers synthesised from bioderived monomers

Bioderived monomers are individual molecules which are sourced from biomass. Bioderived monomers can be combined to create synthetic polymers for food packaging applications. Examples include polybutylene succinate (PBS) and the commonly found polylactic acid (PLA).

Polylactic acid (PLA)

PLA is one of the most established bio-based polymers (Aeschelmann & Carus, 2015), and has been forecasted a CAGR of 16.3% from 2019 to 2025 in the UK (Orion Market Research, 2020). Changing consumer preferences away from traditional plastics, alongside the convenience of having similar properties to them, has meant that the bio-based PLA market has expanded dramatically in recent years. The material is sealable, impermeable and can be designed into products which give food strong physical protection against impact. The material can also be made to be transparent. Currently, PLA is being utilised as a packaging for fruit, vegetables, juice, yoghurts and sweets (Ludwicka, K., et al., 2020). Lactic acid, the monomer used to synthesise P LA, can be sourced from fermenting agri-food wastes such as sugar beet, which improves resource efficiency and circularity (Bonwick et al. 2019). Regarding sustainability, PLA is compostable and can be reused. Research has demonstrated that PLA is recyclable both chemically and mechanically (McKeown & Jones, 2020).

However, there are limiting factors when it comes to PLA’s sustainability. One is that it requires industrial conditions to decompose (Keynes, 2021). The temperature must be at least 50°C, which alongside the required high pressure and additives results in high energy costs and unwanted by-products. It’s inability to biodegrade naturally in terrestrial or marine environments means that it can contribute to the littering issue associated with traditional single-use plastics. Furthermore, current recycling infrastructure is not able to process PLA as it has a lower melting temperature than other plastics which causes complications. This leads to the material contaminating regular plastic recycling, being incinerated, sent to landfill or becoming waste which will not break down naturally (Plavec, 2020). Elsewhere, the case for using PLA as a single-use plastic alternative is hindered by its threat to compete with food markets for agricultural yields, as well as its significant use of fertilisers, pesticides and water in production (Gerassimidou, 2021).

5.2.1.5 Biopolymers produced by microorganisms

The third and final category for bioplastics is those produced by microorganisms. Bacteria can efficiently convert carbon and nitrogen sources into a range of cellular biopolymers such as polyamides, polyesters and polyphosphates (Moradali & Rehm, 2020) that have useful properties for food packaging.

Polyhydroxyalkanoates (PHA)

PHA is a polyester produced through bacterial fermentation. It is sealable (therefore extending food shelf life), offers strong physical protection from impact damage and can be produced to be transparent. The material is also hydrophobic (Sharma et al., 2021). PHA's perform relatively well when considering environmental impacts and circularity. Like PLA, PHA can also be made from waste/by-product of the food industry. They are able to biodegrade under natural conditions (Nilsen-Nygaard et al., 2021) and therefore require far less energy to break down compared to P LA. The biopolymer can also be recycled, but this is not yet done on a commercial scale (Vu, et al., 2020).

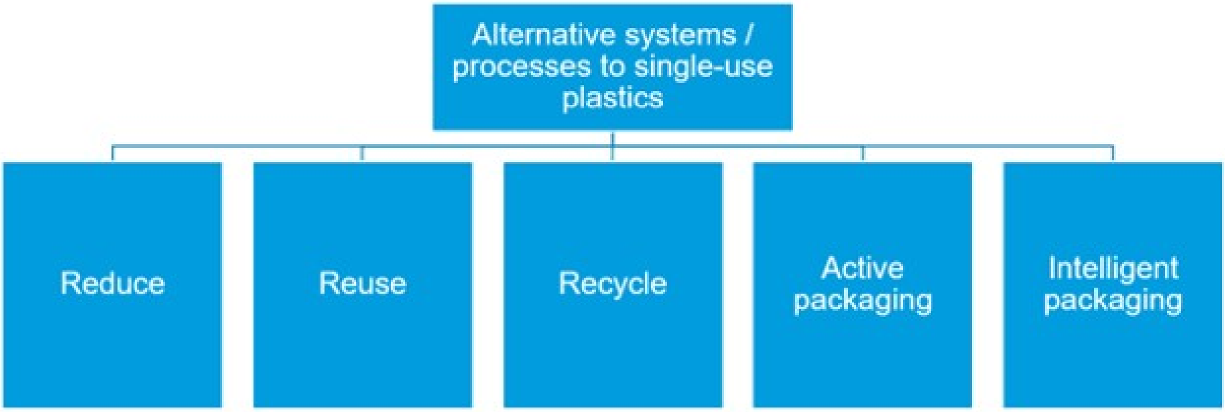
However, there is inconclusive evidence on the integrity of the material in the long term, which is important given that it biodegrades naturally. Furthermore, PHA production is currently expensive compared to traditional plastics (the evidence is inconclusive as to what extent). High costs associated with inputs for microorganism growth, such as carbon sources and the use of chemicals, has made PHA less competitive. Production technologies are also still inefficient as this is a developing industry. More research and funding will be needed to drive innovation which will bring the costs of production down so that PHA can be commercially competitive within the food packaging market (Kourmentza et al., 2017).

Currently, PHA production levels are far lower than PLA, but rapid growth has been predicted in this decade (European Bioplastics), albeit still slower than PLA growth. Markets and Markets (2022) have predicted a CAGR of 15.3% from 2022 to 2027 for the global PHA market as a whole.

5.2.2 Process and system alternatives

Alternative solutions to the problems generated by single-use plastics extend beyond new materials. A holistic approach which considers the entire food packaging lifecycle, including extraction, production, transportation, application, consumer use and disposal, helps to identify effective strategies to increase sustainability and circularity within our food packaging system. This could come in the form of a reduced carbon footprint, reduced natural resource extraction, reduced waste and reduced pollution.
Some of these process and system-based alternatives are illustrated in the schematic below.

Figure 3 Schematic illustrating the main categories of process and system-based alternatives to single-use plastics



5.2.2.1 Reducing single-use plastic in our food packaging system

Reducing non-essential single-use packaging is a direct way to reduce waste in many instances. Examples of packaging which could be deemed to have a low benefit-to-cost ratio are outlined below:

- single-use packaging for pre-sliced fruit and vegetables
- packaging within packaging
- individually wrapped hard sweets
- plastic wrapping for grouping multiple tins

Reducing the amount of plastic packaging used makes circularity in the wider food system easier to achieve. Research by WRAP (2022) has shown that food waste can be reduced by eliminating plastic packaging and selling loose produce, as it allows consumers to purchase the exact amount they will eat (see also Sand, 2020).

In contrast, the British Plastics Foundation (BPF) presented evidence that plastic packaging can extend shelf life, which is able to reduce food waste (Advisory Committee on Packaging, 2008). They also found that bananas sold in a flexible bag can have their shelf life extended by three days. For cucumbers, being wrapped in film delivers a 14-day extension.

These sources of conflicting evidence highlight how a consensus has yet to be reached regarding plastic's impact on waste of specific food items. This adds to the already complex task of determining which single-use plastic packaging products are non-essential.

Allergy concerns also exist, since reducing packaging increases the risk of cross contamination between different bulk foods, such as nuts.

The decision to reduce packaging for certain products will depend upon policy makers' relative preferences for consumer convenience, food safety and environmental considerations. Further research on reducing packaging will help to establish where trade-offs exist and where reduction will have minimal negative impact.

5.2.2.2 Reusing food packaging

One way to reduce the negative environmental impacts of food packaging waste is to transition towards reusable packaging (Accorsi et al., 2022). While some single-use plastics such as polyethylene may not function well for reusability, other products and materials which already exist within our economy are well suited for being reused and could eliminate the need for single-use plastics.

Reusable packaging can be classified into four distinct categories, as summarised by Coelho et al. (2020; as cited in Diprose et al., 2022). These are:

- refillable by bulk dispenser – consumers bring their own packaging to refill
- refillable Parent Packaging – a reusable parent packaging is reused and replenished by a refill packaging which is made of less material
- returnable Packaging – customers return used packaging to retailers who clean and reuse.
- transit Packaging – customers receive food delivery, and the packaging is returned by door delivery or pick up. This system can also apply to food retailers and their suppliers.

The benefits of reusing packaging are varied. In terms of carbon emissions, reuse of food packaging can be superior to recycling, as there are less added emissions with each additional reuse (Sheehan, 2017). Reusable food packaging is also a growing consumer trend (Food Navigator, 2021), which signals increasing levels of consumer acceptability. Furthermore, reusable packaging systems can reduce food waste, as it allows consumers to purchase only what they will eat (Sand, 2020).

However, some unintended consequences exist regarding the reuse of materials. In some instances, single-use plastics have been replaced by packaging materials with much higher upfront environmental costs. For example, reusable polypropylene containers need to be thicker for durability and have to be cleaned, which could increase raw material, water and energy use (Schmid et al., 2021).

On top of this, reuse systems will require investment into new infrastructure (Diprose et al., 2022) such as shop floor dispensers, washing services and/or reverse transport logistics.

5.2.2.3 Recycling food packaging

Compared to other alternatives, recycling is a well-established practice in the UK. The latest estimated figures are that 62% of all packaging waste is recycled. Traditional materials have some of the highest recycling rates like metal (79%), glass (74%) and paper/cardboard (69%), whilst the rate for plastic was 47% (Defra, 2022).

Recycling reduces waste by repurposing used packaging for new products, which also reduces the need for virgin material inputs in the food packaging system.

However, there are several significant limitations to recycling as an alternative to single-use plastics. The process is energy intensive, and therefore releases carbon emissions. Even if our electricity system becomes fully renewable, there is an opportunity cost of this energy which could be used for other economic activities. Furthermore, recycling often is not a closed loop system, since virgin materials are needed to supplement recycled materials if the resulting products are to be strong and durable (Don’t Waste Group, 2022). In addition, many food packaging products are multicoated with different plastics, metals and paper, such as crisp packets. These products are difficult to separate and present a technological challenge that current recycling infrastructure is unable to solve. More generally, sorting materials is a time-consuming process, which reduces the economic viability of closed loop recycling. In addition, significant amounts of household recycling, especially plastics, are not actually recycled. Often, they are exported to other countries, usually for incineration (Burgess, 2021). Recent evidence shows that 60% of UK plastic waste is exported, with Turkey being the main destination (UK Parliament, 2022).

One encompassing point about recycling is that it is an expensive process. For food packaging suppliers and retailers, it is currently cheaper to use virgin material (Herrmann et al., 2022). However, the plastic packaging tax introduced in 2022 may have reduced this price discrepancy between new and recycled plastic.

In the future, recycling may become much less resource intensive. New innovations into chemical and biochemical (using enzymes) plastic recycling could be a future solution to plastic waste. Plastic can be broken down into monomers, from which new polymers can be produced (Thiyagarajan et al. 2022). However, more research and innovation are required before this process is economically viable and fully scalable.

5.2.2.4 Active and intelligent packaging

Although not a direct alternative to single-use plastics, emerging active and intelligent packaging technologies are able to mitigate some issues concerning food waste. This is relevant, as they could be used alongside other alternatives to maintain key food packaging roles.

Active packaging

Packaging designed to deliberately interact with food and bring about change in their composition or characteristics (European Food Safety Authority, 2009). Active packaging can extend shelf life through its antioxidant and/or antimicrobial effects on food, which slows decomposition and prevents contamination. One example is an oxygen scavenger, which absorbs oxygen from within the packaging to extend shelf life.

Intelligent packaging

Packaging which monitors the condition of food (European Food Safety Authority, 2009). Technologies can be designed into the packaging to sense and indicate the freshness of the food using different variables. These variables include pH levels, time-temperatures and atmospheric composition within the packaging.

These technologies can help to reduce food waste, and they increase convenience for consumers. Research has shown that consumers are mildly positive towards this technology (Young et al., 2020). The global market for active and intelligent food packaging market is predicted to have a CAGR of 6.6% from 2022-2027 (Mordor Intelligence D).

Research is being conducted on the use of biodegradable biopolymers as active packaging (Jamróz and Kopel, 2020) since some materials, such as polysaccharides, have antioxidant and antimicrobial properties (Salgado, 2021).

However, no commercial breakthroughs have been made yet. Furthermore, many of these technologies are not biodegradable, compostable, reusable or recyclable within the current infrastructure. In this case, they fail to address one of the most significant negative impacts of single-use plastics: plastic waste.

5.2.3 Summary

The evidence reviewed in this study suggests that there is unlikely to be one single solution to the single-use plastics problem, and that all alternatives have significant limitations which must be considered. The solution will be a range of materials and systems depending on food type and context. For example, zero packaging may be the most sustainable solution for dry goods, edible films for fresh produce, and biopolymers such as PLA to replace single-use plastics in the take-away industry.

Table 3 below provides a summary of the performance of various alternatives discussed in this section, in terms of five broad categories. Conventional plastics are the benchmark which alternatives are scored against. For an expanded table which includes detailed notes on each alternative and category, please see Appendix A.

This rating system was designed through consultation with the FSA, expert advisors and desk research. In some instances, value judgements had to be made regarding what is more important in each category, so that we could determine a rating.

Table 3 Summary of the performance of alternatives compared to single-use plastics across five broad categories (details available in Appendix A)

Alternatives	Food safety	Convenience and acceptance	Circularity	Production and input costs	Market characteristics
Paper	Worse	Similar/mixed	Better	Similar/mixed	Similar/mixed
Glass	Similar/mixed	Worse	Better	Similar/mixed	Similar/mixed
Metal	Similar/mixed	Similar/mixed	Better	Worse	Similar/mixed
Natural fibrous material such as bamboo, cotton, jute	Significantly worse	Worse	Better	Better	Insufficient evidence
Synthesised from biomass: Seaweed polysaccharides	Similar/mixed	Worse	Significantly Better	Better	Similar/mixed
Synthesised from bioderived monomers: Polylactic acid (PLA)	Similar/mixed	Similar/mixed	Worse	Similar/mixed	Better
Produced by microorganisms: Polyhydroxyalkanoates (PHAs)	Similar/mixed	Similar/mixed	Better	Worse	Similar/mixed
Reducing packaging (either no packaging or less packaging)	Significantly worse	Worse	Significantly better	Better	Better
Reusing packaging	Worse	Similar/mixed	Significantly better	Better	Better
Recyclable packaging and systems	Similar/mixed	Similar/mixed	Better	Worse	Similar/mixed
Active packaging	Better	Better	Worse	Worse	Similar/mixed
Intelligent packaging	Better	Better	Worse	Worse	Similar/mixed

5.3 Research question 2: Extent to which alternatives are in use

This section aims to explore the extent to which alternatives to single-use plastics are already in use. However, market information available in the public domain is sparse and does not provide a comprehensive assessment for each alternative. Additionally, the information available is inconsistent (for example, while there is some information available for particular alternatives, no information was identified for others).

To address this research theme, an overview of the limited information available for each alternative has been provided, followed by case studies to demonstrate specific examples of how alternatives are currently used in food packaging applications.

5.3.1 Market information

Paper, glass and metal: The market for each of these alternatives to single-use plastics is mature, in 2019 they held a market share of 33.2%, 12.1% and 5.8% of packaging demand respectively (Statista, 2023). However, there is no information available to discern how much of this demand can be attributed to food packaging specifically.

Bioplastics: Globally, it is estimated that bioplastics (i.e., biopolymers that look and feel similar to conventional plastics but are made from natural materials rather than fossil fuels and are biodegradable or compostable) represent 1% of the total amount of plastics produced each year (more than 359 million tonnes). In 2022, 48% of the global bioplastics market could be attributed to packaging (an increase from 47% in 2020) (European Bioplastics, 2023). However, there is limited data available to suggest which proportion of the global bioplastics market is used for food packaging applications specifically.

Biopolymers: Innovative, new biopolymers such as PLA (synthesised from bioderived monomers) and PHAs (produced by microorganisms) show the highest growth rate in comparison to other alternatives. Bio-degradable plastics (including PLA and PHAs) account for more than 1 million tonnes of worldwide production capacities.

Reusable packaging: The global reusable food packaging market predicted to have a compound annual growth rate of 10.4% from 2019 to 2027 (Reports and data, 2020).

Active and intelligent packaging: The active and intelligent packaging market was valued at USD 18.84 billion in 2021, with an anticipated compound growth rate of 6.6% from 2022 to 2027 (Mordor Intelligence, 2023).

5.3.2 Case studies

In total, five case studies have been developed to provide examples of how alternatives are used in food packaging. Examples have been selected to showcase the variety of alternatives available and the range of contexts in which they can be applied. Most of the case studies were chosen as they were based in the UK, but we included one example from Europe as well. Selected examples include:

1. The London Marathon
2. The University of Cambridge Catering Services
3. Wagamama UK
4. McDonald's Europe
5. Loop trial in Tesco stores.

Case study 1: The London Marathon

Materials used: Seaweed (natural alternative).
Application: Pouches for water and sports drinks.
Key features: Edible and biodegradable.

Description:

- in 2018 the London Marathon used over 919,000 single-use plastic bottles.
- single-use plastic bottles have been described as "one of this generation's key environmental challenges" (footnote 4), placing pressure on high profile events such as the London Marathon to reduce their usage of these materials.
- race organisers attempted to cut down on the use of plastic bottles by trialling water and sports drinks in edible seaweed pouches at select drink stations across the marathon route.
- the pouches were also pitched as a way to hold alcoholic cocktails, juice and condiments like ketchup and salad dressing.

STEEPLE

Environmental considerations:

- no water or fertiliser is required to produce the seaweed.
- due to the introduction of seaweed pouches, marathon organisers were able to reduce the number of plastic bottles from 920,000 to 704,000.
- if the pouches are not consumed, the film breaks down in four to six weeks naturally, compared to the 450 years it takes for plastic bottles to decompose.

Economic considerations:

- the capsules were cheaper to produce than plastic bottles, and use "compact manufacturing technology", meaning they can be manufactured locally, minimizing the cost of shipping and the product's environmental impact.

Social considerations:

- pouches are vegan and gluten free.

Trade-offs: The pouches have a short shelf life and begin to shrivel and decompose quickly (four to six weeks). Their application is best suited to events such as marathons and festivals with limited opportunity to sell more widely. The capsules are single gulp, so more water is required by runners (making this application of the alternative to single-use plastic potentially less acceptable to this group of consumers). Plastic bottles were still in use during the marathon with organisers suggesting that they need to balance environmental needs with the welfare of runners.

Case Study 2: University of Cambridge Catering Services

Materials used: A variety of materials are used, including traditional materials (for example, paper, cardboard), biopolymers derived from biomass (starch composites) and polylactic acid (P LA).
Application: Food packaging products for café services. For example, recycled sugarcane fibre is used for microwave and freezer safe bowls and containers.
Key features: Compostable, can be disposed of alongside food waste in a single container or disposed of via anaerobic digestion (decomposition of materials by anaerobic microorganisms).

Description:

- the University of Cambridge's catering services adopted a zero-waste approach to food provision in 2015, in partnership with Vegware.
- the University has seven catering services, 6,500 sales transactions per day and 1,500 departmental events each year.
- provision of compost bins across all campuses to support the disposal of compostable packaging.
- the university have also stopped selling single-use plastic bottles and have installed water stations across campuses. The specifically designed Refill app directs students and staff members to water stations.

STEEPLE

Environmental considerations:

- since introducing the compostable packaging in 2015, the University has recorded 1.5 tonnes of carbon savings per month.
- the University has also recorded 710kg of virgin material savings (per month).

Trade-offs: Within the University of Cambridge Sustainable Food Policy (footnote 5), the university identified the need to continue to raise awareness of their move away from the use of single-use plastic in catering services. Without high levels of awareness, the university will be less likely to generate buy-in from students and staff members.

Case Study 3: Wagamama UK

Materials used: Recycled materials in combination with cardboard and Crystalline Polyethylene Terephthalate (cPET).
Application: Food bowls for takeaway options.
Key features: 100% recyclable, made from already recycled materials.

Description:

- Wagamama in the UK will implement 100% recyclable bowls for their takeaway and delivery services. However, it will take some time for the packaging to roll out (October 2023).
- in the meantime, Wagamama have introduced a ‘bowl bank’ scheme – in exchange for returning their clean plastic take-out bowls, Wagamama will provide customers with a free side dish, aiming to increase the circularity of food packaging (i.e. packaging is reused or recycled rather than disposed of). The restaurant team will ensure returned bowls are commercially recycled.

STEEPLE

Environmental considerations:

- the new packaging will replace up to 330 tonnes of virgin plastic each year, the equivalent of 8.1 million plastic bowls.
- Wagamama have observed a 33% reduction in carbon footprint.
- the staple Wagamama Katsu Curry is now 62% less carbon intensive.

Technological and social considerations:

- the packaging has excellent heat resistance and is an effective barrier against oxygen, carbon dioxide, water and nitrogen.
- as a result the packaging reduces the risk of food contamination, improves food quality and extends the shelf life during takeaway/delivery.

Trade-offs: Despite exploring bio-based and biodegradable materials, plastic remained necessary to preserve the taste and temperature of some dishes and ensure they make it to customers without leakages; “Reducing our use of virgin plastics is a complicated mission…sustainable progress doesn’t happen overnight” – Wagamama CEO (Creighton, 2022).

Case study 4: McDonald’s Europe

Materials used: Traditional alternatives (wood, paper), fibre and edible packaging.
Application: McFlurry® cups and lids, straws, drink cups and lids.
Key features: Recyclable and designed to mimic the functions of plastic packaging (for example, Fibre McFlurry® lid designed to prevent leakages).

Description:

- McDonald’s have launched a fibre McFlurry® cup, eliminating the need for plastic lids.
- new fibre lids made from 100% certified sustainable sources and recyclable materials are being introduced for cold drinks. The new lid allows customers to sip directly from the lid, removing the need for straws.
- edible packaging is being considered as an alternative to superfluous packaging currently used for sauces and sundaes.
- McDonald’s Germany is currently piloting a programme called ReCup, where customers can ask for a reusable coffee cup and return it at partnering McDonald’s restaurants to be cleaned and reused.

- UK customers can return used Happy Meal toys to a select number of restaurants so that they can be recycled in a new toy take-back trial.
- trials for both wooden and paper alternatives to McFlurry® spoons are also being conducted.

STEEPLE

Environmental considerations:

- 1,200 tonnes of plastic per year will be saved as a result of the McFlurry® packaging re-design.
- a further 1,200 tonnes of plastic will be saved following the implementation of new fibre drink lids.
- Social considerations:
- customers are unhappy with the functionality of some alternatives implemented by McDonald's.
- for example, customers have complained that new paper straws (which have replaced plastic straws) dissolve before a drink can be consumed, making them difficult to drink.

Trade-offs: The majority of McDonald's products are consumed away from restaurants, dependent on consumers and infrastructure to ensure recycling takes place. Regions with more robust infrastructure are showing greater progress. For example, around 78% of McDonald's restaurants in the largest European markets already provide recycling options for customer packaging.

Case Study 5: Loop

Materials used: Traditional alternatives (for example, glass) and stainless steel.
Application: Zero-waste, refillable packaging for a variety of products (for example, pasta, cereal).
Key features: Designed to be returned, cleaned and sold repeatedly.

Description:

- between September 2021 and June 2022, Loop launched a trial in 10 Tesco stores across the Midlands and East of England, as part of Tesco's 4Rs plan: Remove, Reduce, Reuse, Recycle (Tesco, 2023).
- the initiative allowed customers to buy a range of products in reusable packaging to be returned, cleaned, refilled and used again. Brands which took part in the trial included: BrewDog, TescoFinest, Coca-Cola, Radox, Naked Noodle, Heinz, Quaker and Persil.
- customers paid a deposit through the Loop Deposit App and returned their used packaging to the Loop Return Point in-store.
- at the return point, customers scan the QR code on their return bag using the Loop Deposit App. Their deposit was then refunded through the App.
- loop collected the empty packaging to be professionally cleaned, refilled and returned to stores for the next customer.

"We are determined to tackle plastic waste and one of the ways we can help is by improving reuse options available to customers…with 88 everyday products available, we're giving customers a wide range of options and we'll learn as much as we can from this to inform our future packaging plans" – Tesco CEO (Tesco, 2021).

STEEPLE

Environmental considerations:

- contributed to the elimination of waste in Tesco stores, including through a reduced number of food spillages encountered with in-store refill models.

Economic considerations:

- the cost of cleaning and prefilling reusable packaging cost more than the actual product inside.
- developing the scheme at scale would require significant investment from retailers to adopt new processes and manufacturers to adopt new production lines.

Social considerations:

- the scheme was easy for customers to use.
- pilot uptake was greatest amongst a small percentage of eco-conscious shoppers, but there needs to be a cultural shift amongst the general public for the scheme to be implemented at scale.
- for example, despite price matching, consumers still perceived refillable products to be more expensive and were less likely to purchase refillable products.

Trade-offs: The success of reuse is dependent on the customer returning the packaging to the store to be cleaned and re-filled. In addition, the Loop trial relied on more than 30 businesses, working together to supply and transport products in reusable packaging. Collaboration will need to be achieved on a large scale to make reuse a mainstream solution within the UK.

Tesco and Loop hope to use the learning from the pilot to improve their reuse offering in the future; "The consumer reaction to Loop in these first Tesco stores will prove pivotal in refining the Loop offering" – Loop CEO (Tesco, 2021).

5.4 Research question 3: Trajectory of alternatives

This section discusses the trajectory which alternatives to single-use plastics are likely to take, over the next 10 years, in terms of innovation, adoption, spread and becoming established in the industry. This section will also focus on the associated enablers and barriers impacting on the trajectory of alternatives, including regulatory approaches and policy initiatives.

5.4.1 Trajectory of alternatives

Increase in bioplastic production: Bioplastics are biopolymers such as PLA and PHA that look and feel similar to conventional plastics but are made from natural materials rather than fossil fuels and are biodegradable or compostable. Global production capacity of bioplastics in 2019 stood at 2.11 million tonnes, it is anticipated that this will increase to 6.3 million tonnes by 2027 (Renton, 2020). According to European Bioplastics, this increase will be driven by rising demand (8-10% growth per year; Naser et al. 2021), more sophisticated applications and improved physical properties (European Bioplastics, 2022b; Ronzano et al. 2021). The most prominent market driver is brands that want to offer their customers environmentally friendly solutions and critical consumers looking for alternatives to conventional plastic (Renewable Carbon News, 2021). The number of high-profile brands using bioplastics continues to increase. Companies such as Coca-Cola, Danone, Unilever, PepsiCo and Heinz have adopted some bioplastic packaging types, suggesting mainstream acceptance and market penetration (European Bioplastics, 2023).

The Centre for Economics and Business Research predicts that, with the right legislative, commercial and regulatory frameworks, UK production of bioplastics could increase to 120,000 tonnes. This would result in £1.29 billion of gross value added to the UK economy (Renton, 2020).

At present, to ensure suitability for food packaging applications, developing bioplastics requires more research and development than conventional plastics, resulting in higher costs. However, it is expected that the cost of bioplastics will fall in coming years due to:

- research advances leading to more efficient supply chains and refined production processes
- increased volume in the market as a result of rising demand for environmentally friendly alternatives (Ronzano et al. 2021).

Increase in PLA and PHA production: The production capacity of bio-degradable plastics (including PLA and PHAs) is expected to increase to 1.33 million tonnes by 2024, with the increase largely driven by the high growth rate of PHAs in particular (Naser et al. 2021). Production volumes of PLA are also expected to increase due to investment in new PLA production sites in Europe, the USA and China by companies such as TotalEnergies Corbion (European Bioplastics, 2020; Fera, 2019).

Focus on 3R's (reduce, reuse, recycle): In terms of trends, the 3Rs and the circular economy are likely to continue to be the focus of sustainable packaging in the future (Morashti et al. 2022). The European Union (EU) directives on circular waste and the packaging economy will ensure that producer responsibility schemes are established for all packaging by 2023. The directives have also raised requirements to ensure:

- recycling rates are increased
- landfill rates are reduced
- overall reduction in the disposal of packaging waste (for example, through reuse) (Tohme and Nemes, 2023).

Current targets set by the EU stipulate that the net climate impact of packaging waste must be zero by 2025. Specific targets have also been set for recycling, by 2030, 70% of all packaging should be recycled (European Commission, 2022).

Within the UK, organisations producing or using packaging or selling packaged goods may be classified as an obligated packaging producer and are legally required to:

- reduce the amount of packaging produced in the first place
- reduce how much packaging waste goes to landfill
- increase the amount of packaging waste that is recycled

This is in addition to the UK Government duty of care legislation for waste (UK Government, 2018) which requires all organisations to prevent, reuse, recycle or recover waste, with prevention being the first priority. By the end of 2023, the UK has set a target for all business to recycle 77% of all packaging and 61% of plastic packaging (UK Government, 2023b).

Other regions around the world are also introducing targets on the reuse of materials to encourage growth in the trend of reuse and refill business models. For example, the EU has called for an increase in the share of reused materials, to reach 10% by 2030 (Coelho et al. 2020). Additionally, draft EU regulations proposed at the end of 2022 stipulate that by 2040, all restaurants offering takeaway services will be required to serve 40% of their meals in reusable packaging and, all single-use coffee cups will be banned (Rankin, 2022). Other examples include:

- France – circular economy law which requires 10% of all packaging placed on the market to be reusable by 2027 (CMS, 2021). France also allocated €40 million for reuse investments as part of their circular economy fund in 2021/2022.
- Portugal - by 2030, 30% of all packaging on the market (of any material) must be reusable (Green Peace, 2021).

5.4.2 Enablers

In Table 4 below, we summarise the main enablers that are likely to influence the trajectory of alternatives to single-use plastics, as found in the reviewed literature.

Table 4 Summary of factors enabling the adoption of alternatives to single-use plastics

Enablers	Description
Increased consumer awareness of environmental issues	Consumer awareness of single-use plastics and plastic pollution has increased in recent years, in particular following COVID-19 (Renton, 2020). Increased consumer awareness has placed pressure on companies to reduce detrimental effects of packaging by adopting sustainable alternatives or focusing on the 3Rs and circularity (Renton, 2020).
Existing legislation and regulation	• the UK has established legislation and policy in place to decrease plastic waste, increase recycling and encourage reuse (Renton, 2020). • for example, in 2022 the UK introduced a plastic packaging tax (£200 per tonne) produced in or imported into the UK if it is not composed from at least 30% recycled content. • the UK has also introduced other interventions such as an extended producer responsibility (EPR) scheme (likely to be introduced in 2024) that would require businesses to take on the costs of the end-of-life processes for their product. The objective of the scheme is to encourage producers to shift their packaging strategies. • although updates may be required as new materials come to prominence, there are existing regulations in place to ensure food safety and limit health risks posed by packaging. These regulations can serve as a basis for the regulation of new materials.

5.4.3 Barriers

In Table 5 below, we summarise the main barriers that are likely to influence the trajectory of alternatives to single-use plastics, as found in the reviewed literature.

Table 5 Summary of factors posing a barrier to the adoption of alternatives to single-use plastics

Barrier	Description
Established industry regimes	• Dissemination of sustainable materials is limited by existing technologies, production processes and business models in place which would be costly to adapt. In contrast, the plastics/petro-chemical industry has vast economies of scale relative to alternative packaging solutions at present. The oil industry may also increase pressure to diversify further into plastics production, as demand for fossil fuels declines. • previous investments into machinery, manufacturing know-how, and relationships might also decrease the likelihood of established industry actors investing in sustainable packaging. • there are several large, well-known producers of plastic packaging. These organisations have the power to resist making investments in new technology or materials if the economic costs outweigh the benefits (Kernanen et al. 2021).
Consumer practices, perceptions and awareness	• Consumer awareness of environmental issues associated with single-use plastics has increased. However, consumers are often unaware of appropriate recycling or disposal methods for alternatives such as bioplastics (Keranen et al. 2021). • Consumer perceptions of plastics may lead to companies adopting packaging materials which are not necessarily more sustainable than plastic. Companies may engage in ‘greenwashing’ (footnote 6) i.e. the tactic used to make a product or company appear environmentally friendly without meaningfully reducing its environmental impact or indeed deliberately obscuring its poor sustainability credentials through marketing strategies. • despite shifting consumer attitudes, consumers don't buy packaging per se, they buy the food product - as such packaging forms only a small part of the purchasing decision. Moreover, despite consumer's attitudes and awareness of the need for alternative packaging, they are price sensitive and given the option most will not pay more for more sustainable packaging options (Sifted, 2023).

Barrier	Description
High production costs of bioplastics	• the investment required to produce bioplastics may act as a barrier to the adoption/commercialisation of materials. • producers often lack the know-how required to produce packaging at a low unit cost which directly impacts on demand. • slow-growing market demand and acceptance by consumers can also further increase production costs (Chaudhary et al. 2022).
Lack of waste management guidance available	• lack of clear guidelines from government for industry (for example, inconsistencies regarding recycling practices and waste treatment) can act as a deterrent for organisations investing in sustainable packaging as improper waste management processes are subject to fines (Morashti et al. 2022). • there is a lack of recycling and industrial composting infrastructure (Kearney, 2023). The high costs and lack of clear policy directives discourage private-sector investment in the needed capacity (ibid.).

5.5 Research question 4: Adapting UK Food Regulation

This section discusses the changes required to the current food regulation in the UK, in the context of the emerging alternatives, in terms of legislation, governance, training and enforcement. It also discusses the challenges that may be encountered while making adaptations in regulations. The content in this section is primarily derived from a workshop discussion with members of the expert panel recruited for this project, including colleagues from the FSA as well as representatives from academia, industry and government representatives. This is because there were very few findings from the literature review to address this topic. Where possible, we have also supplemented findings from the literature review – where this is the case, they are clearly cited below.

5.5.1 Changes in legislation or guidance

Recent developments have taken place in the UK to reduce the production and circulation of single-use plastics, such as the Plastic Packaging Tax (enforced in April 2022), restrictions on use of single-use plastic drink stirrers, straws and cotton-buds (enforced in October 2020), and the upcoming ban on single-use plastics in the take-away and eating out industry (to be enforced in October 2023). There is a potential for further legislation to ban certain single-use packaging, following the example of France banning single-use plastics packaging for fruit and vegetables (Government of France, 2021) and evolving EU legislation, for instance the EU Green Deal Industrial Plan (footnote 7). It would also be useful for the UK government to monitor developments in EU packaging regulations, as there will be a need for coordination around evolving standards for imports and exports with the EU.

However, the application of the existing legislation to novel materials that serve as alternatives to single-use plastics is unclear and could be improved, as detailed below.

A key point highlighted in the workshop discussion was related to definitions and language around packaging, particularly with alternatives to conventional plastics emerging. As summarised in a publication by WRAP (2020), alternative packaging materials may be produced from biomass sources but may not be biodegradable or compostable (for example, polyethylene). Similarly, there may be materials that are biodegradable under certain conditions but may be derived from fossil-based sources rather than from bio-based sources (for example, polycaprolactone). This is particularly true when material composites are developed that combine different properties of base polymers, such as adding plasticizers to starch-based polymers. With this complexity in mind, there needs to be further clarity and classification in the regulation to allow all stakeholders to better understand the appropriate treatment and disposal of novel packaging. The workshop attendees suggested updating definitions or classification of what is a plastic and what is not, as well as simplifying how these are presented to consumers to avoid confusion. The literature additionally suggested the need to legislate clear end-destinations for new materials (for example, landfill, recycling, industrial composting or home composting; WRAP, 2020) and developing clear labelling standards for the products that use novel packaging as well as accessible guidance available for both the public and industry (DESNZ & Defra, 2021).

Fera (2019; see also WRAP, 2020) also found that there were no internationally accepted standards for the process of biodegradation of bio-based polymers, which often release carbon dioxide, water and residual biomass due to microbial metabolism (i.e. the process of digestion by microbes such as bacteria) and other organic mechanisms. In their report, Fera (2019) thus suggested that it may be useful to develop, where they do not exist, UK-based standards for acceptable residue levels and processes for decomposition and biodegradation of biopolymers, as well as coordinate this with international regulation (for example, from the EU and other major developers and exporters of biopolymers). This will also support the manufacturers to test, be certified and demonstrate compliance with standards of existing and new biopolymers, particularly if the manufacturers operate internationally.

In terms of safety of food contact materials, England has an existing Framework Regulation in place, i.e. Materials and Articles in Contact with Food (England) Regulations 2012, as well as equivalent regulations for Wales (2012) and Northern Ireland (2012). However, there is a lack of clarity amongst industry partners attending the workshop regarding the interpretation of the regulation for alternatives to single-use conventional plastics. While there is extensive guidance in place for manufacturers to demonstrate safety for plastic packaging, the same does not exist for new materials. For instance, alternatives currently have to comply with regulation aimed at mitigating the risks of conventional plastics. However, these rules may not apply across alternatives or additional regulation may be required to address the unique risks that alternatives may bring. This gap is particularly pertinent in terms of the technical requirements to demonstrate compliance which is a crucial barrier for manufacturers to overcome to get materials approved for use.

5.5.2 Potential challenges or barriers to adapting regulation

The following issues may pose challenges to implementing changes to the legislation or guidance based on the evidence gathered form the workshop discussion as well as from the literature:

- the lack of sufficient evidence on single-use plastic alternatives is a major barrier for the development of any legislation or policy decisions (Kearney, 2023). This includes an absence of evaluations of economic (for example, conducting sensitivities on key assumptions), environmental (for example, conducting cradle to end of life analysis both in terms of biogenic carbon material and carbon used for processing and disposal) and consumer outcomes (for example, investigating acceptability and behavioural change). The workshop attendees suggested that this may be partly because many new materials are in early stages of development, and where they are being implemented with real-world applications, there may be commercial interests against publishing evidence.
- according to our experts, there are barriers from a strong lobby that may create political resistance to regulatory change. For instance, there may be push-back from the industry lobby, particularly from the petrochemical/plastic packaging sector, but also from food producers and retailers. There may also be push-back from consumers because of the reduced convenience, increased hassle for recycling, potentially higher costs (directly or indirectly as higher community taxes for recycling systems, etc) and related considerations over food accessibility for lower-income groups.
- the Industrial Biotechnology Innovation Centre reported in 2018 that there were no facilities to test biodegradability of newly developed materials, and we are not aware of any being put in place since then. As such, industry partners have to outsource this testing in order to obtain appropriate data. Further, the cost of testing facilities can be a major disincentive, particularly the absence of equipment to test digestion by microorganisms such as bacteria.
- similarly, new materials may need new processing capabilities to be developed before packaging and treatment at disposal and end of life. These requirements may not be met

by the infrastructural capabilities that are currently available. For instance, new sorting infrastructure may be required to separate different types of bio-based polymers that have different end-destinations (Kearney, 2023). Sheehan (2017) reported that most compost facilities in the United States did not accept PLA despite it being compostable, with the vast majority being landfilled instead. The reasons underlying this practice are unclear, but Sheehan reported that almost 80% of compost facilities only accept yard trimmings or food scraps. As such, new systems may be necessary to accommodate these materials, but these may be resource-intensive, requiring investment, legislation and guidance, as well as training.

- these add to the scale-up costs of materials that are already associated with high development costs, making them expensive options to conventional plastics and likely to become a barrier to adoption as equal competitors in the market.

1. Production_of_quick_scoping_reviews_and_rapid_evidence_assessments.pdf (publishing.service.gov.uk)

2. Apeel Sciences was found in 2012 and developed the product called 'Apeel' which is an edible fresh food coating made from edible plant oils and composed of mono and diglycerides. More information can be found on their website.

3. Notpla is a sustainable packaging start-up founded in 2014 that developed an edible package called 'Ooho' that could hold liquids like water, made from seaweed. More information can be found on their website.

4. Quoted from an academic journal publication in Nature Geoscience by Allen et al. (2019) entitled Atmospheric transport and deposition of microplastics in a remote mountain catchment.

5. University of Cambridge (2015) Sustainable Food Policy.

6. The Greenpeace UK website describes what greenwash is and how to avoid it.

7. The EU website provides more detail on the EU Green Deal Industrial Plan.

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Alternatives to single-use plastics: Discussion and areas for further consideration

6.1 Strengths of the research

Systematic process guiding the literature review: Clear protocols were developed with the FSA and our academic advisor to guide the search for relevant literature in two databases (Appendix B). These were further adapted as appropriate based on feedback from the expert panel. The revised approach was validated by the FSA before proceeding with the search, to ensure agreement from each involved party. The two databases used for the search were Web of Science and SCOPUS, which have extensive, international records both from sciences and social sciences. We followed a systematic process for the literature review, guided by PRISMA style of reporting to monitor the number of records included/ excluded at each stage of the screening with clear reasons for exclusion as set out in the search and screening protocol (see methodology for details). Finally, we used the framework developed and recommended by Defra (footnote 1) to undertake critical assessment of the evidence by rating the quality of the articles in terms of robustness and relevance.

Coverage of research questions: The findings from the literature review showed that the search and screening process resulted in a high volume of articles, in particular related to research theme two on current adoption of single-use plastics in the UK food industry. These were also supplemented wherever possible with insights gained from our expert panel.

Expert panel membership: Uptake for expert panel membership was high in comparison to the number of experts invited. This meant that there was representation from experts across a variety of sectors (for example, academia, industry and policy) and a diverse range of views have been incorporated into this research.

Peer-review by FSA and academic advisor: All outputs from this project, from the development of the search protocols, draft and final reports and presentation slides, were peer-reviewed by our academic advisor, Dr Samuel Short, who is an Industrial Associate from the Institute of Manufacturing (IfM) at the University of Cambridge. All outputs have also been peer-reviewed by the FSA project team.

6.2 Limitations of the research

Research gaps in literature: There were relatively few results related to research theme three on forecasted trajectory of alternative packaging development and use or research theme four on adapting UK food regulation. Gaps were followed up through expert panel workshops and one-to-one consultation with the panel. Where literature was available to support these findings, it has been cited within the text.

Intellectual property: To fulfil opportunities within the market for alternatives to single-use plastics, innovation is required. However, to protect their organisation against competitors, it is likely that developers of new materials will be unwilling to release information on their innovations until intellectual property rights have been granted (for example, patents). As a result, it is unlikely that all potential alternatives to single-use plastics could be captured by this research.

Publication time scales and availability of reports: Due to the fast pace of innovation within the industry, there is a gap between the pace at which innovations are introduced and the pace at which research relating to these innovations can be published. Also, much research and commercialisation are being done outside universities and so falls outside the academic journal knowledge base.

Tight timescales for the project: An additional barrier came from the fact that the project had tight timescales (as a rapid evidence review). As a result, some experts were unable to engage in the expert panel within the specified timeframes which meant that their views could not be incorporated.

6.3 Conclusions

Research question 1 - What are the emerging alternatives to single-use plastics in food production and packaging?

Two broad groups of alternatives were established: material/product alternatives (traditional materials, natural fibres, biopolymers synthesised from biomass, biopolymers synthesised from bioderived monomers, biopolymers produced by microorganisms) and, and system/process alternatives (reducing, reusing and recycling food packaging and, active and intelligent packaging).

Research question 2 - To what extent are the alternatives already in use within the UK?

There was insufficient data available to get a clear picture of the extent of usage in the UK. However, five case studies were selected purposively for this work, to capture a variety of different products that are currently in within the UK and Europe. These included: The London Marathon (seaweed), The University of Cambridge Library Services (traditional alternatives, biopolymers and PLA), Wagamama UK (recycled materials, cardboard and cPET), McDonald's Europe (traditional alternatives, fibre, edible packaging) and, Loop/ Tesco Trial (reusable packaging made from traditional alternatives such as glass and aluminium).

Alternatives brought a number of benefits in each case. However, companies typically encountered a number of trade-offs when introducing alternatives. For example, the majority of McDonalds products are consumed off-site meaning they are dependent on consumers and adequate infrastructure for their recyclable packaging to be of maximum benefit.

Research question 3 - What trajectory are the alternatives likely to take, over the next ten years, in terms of innovation, adoption, spread, and becoming established in the UK food industry?

Global production capacity of bioplastics is anticipated to increase from 2.1 million tonnes in 2019 to 6.3 million tonnes by 2027 (1% of current plastic packaging market, increasing to about 3% by 2027). This will largely be driven by growth in production of PLA and PHAs. Current and upcoming legislation in the UK and Europe will encourage a continued focus on the 3R's (reduce, reuse, recycle) and the circular economy.

Enablers for the growth of alternatives to single-use plastics include increased consumer awareness of environmental issues and, existing regulation and legislation. Barriers that may pose a challenge to the growth of this industry include established industry regimes, consumer practices, perceptions and awareness, high production cost of bio-plastics and a lack of available waste management guidance.

Research question 4 - Are there any changes required to UK food regulation in the context of the alternatives, and if so, what are the potential changes at the legislative, governance, training and enforcement levels?

The application of existing legislation to novel materials which serve as an alternative to single-use plastics is unclear. Clarity is needed with regards to the following factors for new materials: appropriate treatment and disposal of packaging, labelling standards and guidance on how to demonstrate safety of new materials.

Overall, fossil-based plastics are a very cheap, versatile material compared with the alternatives currently being developed and tested. Conventional plastics will probably remain the preferred choice for certain applications for the foreseeable future, while the alternatives are optimised and scaled into commercial products for application in real world industries. As such, there is a need for caution in driving the transition to more sustainable solutions.

Based on the reviewed evidence, a sustainable food packaging system is likely to involve multiple levers and a combination of different materials/products and processes, rather than a singular system solution (Kearney, 2023). This could include circularity in terms of harvesting waste and by-products from the food industry to form the raw materials for the production of alternative packaging, incentivising and innovating within the food supply chain to reduce, reuse and recycle plastics as well as alternatives, and improving the industrial composting of packaging mixed with domestic organic waste.

1. The Defra website provides more information on the production of quick scoping reviews and rapid evidence assessments, including critical assessment of evidence, Production of quick scoping reviews and rapid risk assessments (PDF)

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Alternatives to single-use plastics: Appendix A Alternatives to single-use plastics matrix

Alternative to plastic	Food safety (including; contamination, physical damage, shelf life, traceability and allergen concerns)	Convenience and acceptance (including labelling, branding, consumer perceptions and acceptance)	Circularity (including biodegradability, recyclability, reusability)	Production and input costs (including; material, labour, energy, infrastructure/investment requirements)	Market characteristics (including; price, market size and growth predictions)
Paper	Slightly worse: not sealable/airtight, moderate physical protection, regular shelf life, traceable, no allergen concerns, permeable.	Mixed or similar performance: suitable for labelling and branding, not transparent, perceived as sustainable by consumers, well known.	Slightly better: Biodegradable (can release methane, a strong green-house gas, if buried in a landfill)[ii], recyclable, but not if contaminated with food, crease or plastic coating [iii], limited reusability.	Mixed or similar performance: water, chemicals, printing inks and energy intensive production[iv], deforestation risks, infrastructure scaled and available.	Mixed or similar performance: cheap, mature market, compound annual growth rate of 3.9% from 2023 to 2028[v].
Glass	Mixed or similar performance: sealable, strong physical protection, extended shelf life (oxygen, moisture and UV light barrier), traceable, no allergen concerns, impermeable	Slightly worse: stickers required for labelling and branding, transparent, well known by consumers, heavier than alternatives and risk of shattering[vii].	Slightly better: non-biodegradable, recyclable, food and grease contaminations and not preventative, [viii] indefinite reusability.	Mixed or similar performance: energy intensive production and recycling, abundant raw materials[x], infrastructure scaled and available.	Mixed or similar performance: higher price than plastic and more expensive to transport, mature market, compound annual growth rate 3.5% from 2023 to 2028[xi].
Metal	Mixed or similar performance: sealable for packaging, strong physical protection, extend shelf life, traceable, no allergen concerns, impermeable.	Mixed or similar performance: stickers required for labelling and branding, not transparent, well known by consumers, light and convenient (aluminium foil).	Slightly better: non-biodegradable, cost effective recycling compared to new production [xii], long term reusability.	Slightly worse: energy intensive production[xiii], harder to obtain raw materials compared to other alternatives, infrastructure scaled and available.	Mixed or similar performance: more expensive than plastic, mature market, compound annual growth rate 3.4% from 2023 to 2028[xiv].
Natural fibrous material such as bamboo, cotton, jute	Significantly worse: not sealable, moderate physical protection, shortened shelf life, tracing difficulties, allergen concerns from source material and permeable.	Slightly worse: stickers required for labelling and branding, not transparent, no evidence found on acceptance.	Slightly better: biodegrades in natural conditions, non-recyclable, medium term reusability,	Slightly better: low energy production, abundant raw material, high water and land requirements for certain materials such as cotton[xv], competes with food agriculture.	No evidence on price, market size and growth.

Alternative to plastic	Food safety (including; contamination, physical damage, shelf life, traceability and allergen concerns)	Convenience and acceptance (including labelling, branding, consumer perceptions and acceptance)	Circularity (including biodegradability, recyclability, reusability)	Production and input costs (including; material, labour, energy, infrastructure/investment requirements)	Market characteristics (including; price, market size and growth predictions)
Synthesised from biomass; Seaweed polysacchardies	Mixed or similar performance: sealable, weak physical protection, extended shelf life (antimicrobial and antioxidant properties), traceable, allergen concerns from source material	Slightly worse: stickers required for labelling and branding, transparent, no evidence found on acceptance	Significantly better: biodegrades quickly in natural conditions, non-recyclable, limited reusability, limited knowledge on the ecological impacts of seaweed farms [xvi].	Slightly better: abundant, fast growing raw material source which combats ocean acidification[xvii], high production costs, continued investment needed for scale up	Mixed or similar performance: infant industry price is high which reflects current costs[xviii], global compound annual growth rate of 16.50% from 2022 to 2029 (valuation of $181 million in 2021)[xix].
Synthesised from bioderived monomers: Polylactic acid (PLA)	Mixed or similar performance: sealable, strong physical protection, regular shelf life, traceable, allergen concerns (dependent on source material), impermeable.	Mixed or similar performance: stickers required for labelling and branding, transparent, some evidence of bioplastics perceived as unsustainable[xx], consumers unlikely to be able to differentiate between bio-based and petroleum plastics[xxi].	Slightly worse: biodegradable only in industrial conditions at temperatures of at least 55 degrees [xxii], waste P LA can contribute to plastic litter in terrestrial and marine environments [xxiii], recyclable, but not currently at scale[xxivxxvxxvi], risks contaminating current plastic recycling systems[xxvii], reusable, P LA can derive from fossil-based sources or food waste/by-product[xxviii].	Mixed or similar performance: abundant material sources, significant water input[xxix], opportunity cost for food crop production, small negative impact on food security, environmental costs of using pesticides and fertilisers[xxx].	Slightly better: readily available in filament and pellets, production growth predicted[xxxixxxii].
Produced by microorganisms: Polyhydroxyalkanoates (PHAs)	Mixed or similar performance: sealable, strong physical protection, extended shelf life, traceable, allergen concerns (dependent on source material)	Mixed or similar performance: stickers required for labelling and branding, transparent, some evidence of bioplastics perceived as unsustainable[xxxiii], consumers unlikely to be able to differentiate between biodegradable PHA and non-biodegradable plastics[xxxiv].	Slightly better: Biodegradable under natural conditions[xxxv], recyclable but not widely recycled[xxxvi], can be made from fossil-based sources or food waste/by-product[xxxvii], no evidence on reusability of material.	Slightly worse: high production costs associated with feedstock and carbon sources[xxxviiixxxix], use of chemicals[xl], more research required to identify cost-reducing innovations[xli].	Mixed or similar performance: less available than PLA, low total production levels currently, but significant growth predicted[xlii].
Reducing packaging (either no packaging or less packaging)	Significantly worse: contamination risk, physical damage risk, reduced shelf life, some tracing difficulties, allergen concerns from cross contamination of exposed foods such as nuts.	Slightly worse: labelling and branding limitations, product visibility, growing consumer trend[xliii], less convenient, especially for wet foods and liquids. Consumers may have to bring their own packaging.	Significantly better: less materials and resources used, less waste, requires bulk packaging products for example, dispensers.	Slightly better: reduced inputs, requires initial infrastructure investment.	Slightly better: packaging free shops are opening at an increasing rate in the whole of Europe[xliv].
Reusing packaging	Slightly worse: potentially sealable, strong physical protection, regular shelf life, some tracing difficulties, allergen concerns depend on packaging type	Mixed or similar performance: stickers required for labelling and branding, can be transparent, growing consumer trend[xlv], less convenient[xlvi].	Significantly better: reuse circularity, requires bulk packaging products for example, dispensers.	Slightly better: reduced input requirements, investment required for in-store infrastructure for example, dispensers, washing services, reverse transport logistics[xlviixlviii].	Slightly better: trials on reusable packaging systems occurring in large supermarkets such as Tesco and Waitrose, global reusable food packaging market predicted to have a compound annual growth rate of 10.4% from 2019 to 2027[xlix].
Recyclable packaging and systems	Mixed or similar performance: sealable, strong physical protection, extended shelf life, traceable, no allergen concerns	Mixed or similar performance: stickers required for labelling and branding, can be transparent, accepted by consumers[l].	Slightly better: recycling circularity, process inefficiencies and energy costs, not feasible for some materials for example, multicoated wrappers, thin plastics.	Slightly worse: reduced input requirements but virgin material needed to sustain durability of material[li], inefficiencies with current waste separation and infrastructure[lii].	Mixed or similar performance: more expensive than virgin material[liii], long running system, growth is highly dependent on government policy.
Active packaging	Slightly better: antimicrobial and/or antioxidant, extended shelf life, traceable, allergen concerns from source material	Novel to consumers, convenience from extended shelf life, consumers are unfamiliar with a mild to slightly positive attitude to this technology[liv].	Slightly worse: biodegradability varies per product, not recyclable, not reusable.	Slightly worse: high research costs[lv], inputs and productions costs vary significantly per product.	Mixed or similar performance: compound growth rate of 6.6% from 2022 to 2027[lvi].
Intelligent packaging	Slightly better: potential to extend shelf life, increased visibility of food data throughout supply chain[lvii].	Slightly better: Add on for labelling and branding, convenient for suppliers, retailers and consumers, consumers are unfamiliar with a mild to slightly positive attitude to this technology[lviii].	Slightly worse: Biodegradability varies per product, not recyclable, no evidence on reusability.	Slightly worse: high research costs[lix], inputs and production costs vary significantly per product.	Mixed or similar performance: compound growth rate of 6.6% from 2022 to 2027[lx].

Note: Alternatives are rated by category, with conventional plastics as the benchmark. Dark red means that the alternative performs significantly worse than plastics in that category, orange is slightly worse, beige is similar or mixed performance, light green is slightly better, and dark green is significantly better.

This rating system was designed through consultation with the FSA, expert advisors and desk research. In some instances, value judgements had to be made regarding what is more important in each category, so that we could determine a rating.

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Alternatives to single-use plastics: Appendix B Search Protocol

Review of evidence base for alternatives to single-use plastics in food packaging and production

Evidence review protocol overview

Research aims

The core focus of this research will be to search, gather, review, synthesise and report literature which provides evidence on the growing market of alternatives to single-use plastics within the food industry. More specifically, literature that provides insight into the types of alternatives and their current use, emerging trends in innovation, consumer preferences and the changing policy environment for the FSA will be key. Through the process, the quality and quantity of the evidence will be considered, identifying gaps where they exist.

Priority research questions

Themes	Primary research questions	Secondary research questions

1 Emerging single-use plastic alternatives	1.1 What are the emerging alternatives to single-use plastics in food production and packaging?	1.2 What benefits/risks do single-use plastics offer? 1.3 What unique benefits/opportunities do specific alternatives offer? 1.4 What risks come with the development and adoption of these technologies? Consider 1.2, 1.3 and 1.4 with regards to STEEPLE themes: **Social**, for example, food safety for the general public and specific consumer groups (allergens, pathogens, toxicity, cross-contamination); food availability, nutrition, choice; consumer acceptability; food fraud/crime and traceability; **Technological**, for example, materials, functionality, durability; **Economic**, for example, cost-effectiveness, market maturity, business model innovation (egg, circular business model, retail model), adoption and spread of innovation/solution both currently and in the future (next 5-10 years); **Environmental**, for example, sustainability including carbon footprint, resource use, waste and pollution in production, transport, storage, disposal; **Political**, for example, legislation, advocacy; **Legal**, for example, regulatory and enforcement; and **Ethical**, for example, accountability, responsibility.
2 Current adoption of alternatives to single-use plastics in the UK food industry	2.1 To what extend are the alternatives already in use within the UK?	2.2 Where do alternatives already have significant presence, both within the UK and similar developed economices? 2.3 Which businesses, food industries and demographic consumer groups are most involved?
3 Forecasted trend of alternative development and use	3.1 What trajectory are the alternatives likely to take, over the next ten years, in terms of innovation, adoption spread and becoming established in the UK food industry?	3.2 What are the associated enablers of this change? 3.3 What are the associated barriers? 3.4 What level of unpredictability exists in possible trajectories?
4 Adapting UK Food Regulation	4.1 Are there any changes required to UK food regulation in the context of the alternatives, and if so, what are the potential changes at the legislative, governance and training and enforcement levels?	4.2 What challenges are likely to exist in making these adaptations in regulation?
5 Role of the FSA	5.1 What is the role that the FSA could play in advocating for food safety, promoting awareness and supporting innovation and consumer acceptance?	5.2 What trade-offs are present and likely to emerge between protecting different stakeholder groups? 5.3 How can the FSA appropriately balance the needs of protecting consumers, businesses, and the environment?

Protocol for searching, screening and reviewing the literature

Stage 1: Database searches

We will be reviewing relevant literature from two sources. The first source is academic literature which has been published in scientific journals. The second is grey literature which originates from the UK government and its public agencies, international public agencies, non-governmental organisations, market reports and patents. Rachael Posaner (University of Birmingham, Knowledge, and Evidence Services (KES)) will conduct the search for published/academic literature via the University of Birmingham Library Services based on agreed search terms, whilst RSM will conduct the search for grey literature and manage the wider call for evidence. We will use the PRESS checklist (footnote 1) to structure our search strategy and fully optimise the time available for the search.

Our advisor Dr Samuel Short will be asked to contribute any key sources, including those not yet published, available to them given their academic knowledge and network. RSM will also issue a call for evidence and ask the FSA expert panel, and our advisor to disseminate this call for evidence.

We propose the following search criteria and databases. Parameters may need to be refined depending on the scarcity of available and relevant sources.

Search terms and inclusion criteria

Criteria	Details
Language	English or accredited translations
Time period	January 2017 to present
Search strings	The search terms will be a variation of: [Terms for:] alternatives OR innovation OR technology OR technologies OR developments OR novel OR horizon scanning OR opportunity OR spread OR innovative OR emerging OR future AND [Terms for:] non-plastic OR active packaging OR biopolymers OR bioactive OR biodegradable OR edible film OR reusable OR recyclable OR renewable OR zero packaging OR sustainability OR sustainable OR single-use packaging OR refillable OR circular packaging OR eco-friendly OR compostable OR dissolvable OR plastic replacement OR plastic substitute OR plastic-free OR plastic free OR biobased OR bio-based OR composite OR smart packaging OR intelligent packaging OR loose produce OR glass OR paper OR silicone OR metal OR synthetic materials OR beeswax OR circular economy OR circularity OR refillable OR bring your own OR BYO AND [Terms for:] food safety OR food packaging OR food production OR food system OR food risk OR food hygiene OR food distribution OR food waste
Database/sources	Published academic literature: Two databases out of the following, depending on scoping search results: Web of Science, SCOPUS, ScienceDirect (Elsevier), JSTOR, SAGE, Taylor and Francis, Wiley Online Library Grey literature: Government sources (for example, Gov.uk, the Food Standards Agency, the Health and Safety Executive) Websites of national and international (specifically the UK, the USA, Canada, the EU, Germany and Australia) organisations, related to food safety/health (for example, International Association for Food Protection, the World Health Organisation, the Food and Agriculture Organisation), AgriTech, consumer groups and/or environment advocates (for example, United Nations Environment Programme, Greenpeace) Academic advisor: Sources identified by Dr Samuel Short Call for evidence amongst panel of experts: Sources identified by the expert panel who will also highlight areas of key interest

Stage 2: Screening of titles and abstracts

Using our various sources of literature, we will review a longlist of a maximum 600 titles of published and unpublished studies, articles and reports (‘grey literature’) pertaining to the research questions on single-use plastic alternatives as specified above.

The table below sets out the first level inclusion/ exclusion criteria which we will apply to each title. We anticipate excluding 25% to 50% of titles at this point either because they are not of central relevance to single-use plastic alternatives, or they are duplicate studies in our sample.

1st level criteria	Inclusion criteria	Exclusion criteria
Topic	Key details about the alternative/s (covering at least one of the STEEPLE themes) and/or related to implications for the FSA	Does not offer any information on single use plastics alternatives, does not cover any STEEPLE themes.
Language	English	All other languages
Quality	Pee reviewed for academic sources, perceived credibility for grey literature	Non-peer reviewed work for academic literature, unknown or perceived as non-impartial for grey literature.
Other	-	Duplicates

We will then review around 300 abstracts and executive summaries at the second stage of screening, having already excluded irrelevant titles and duplicates. The second level criteria are listed below and relate to the detailed research questions. These may need to be refined depending on the number of studies retrieved. Abstracts which do not meet any second level inclusion criteria will be discarded and the remaining abstracts will form the shortlist of relevant literature for further screening and quality assessment.

Second level criteria	Inclusion criteria	Exclusion criteria
Topics based on research questions	Related to one or more of these topics: Emerging alternative technologies to single-use plastic in food production and packaging Current market size and characteristics of alternatives Trajectory of alternatives and future developments (next 5 to 10 years) in the sector Changing policy context given the development of the plastic alternatives market and the possible net social benefit associated.	Not related to any of the topics related to the research questions.

Stage 3: Quality assessment of full texts

After removing irrelevant abstracts, we expect to shortlist about 60 full texts. They will be examined and screened to identify the final list of the most relevant, informative and useful studies to undergo full review. The selection will be based on tighter inclusion criteria, including quality measures i.e. the extent to which methodologies/ evidence bases are robust following DEFRA guidance (footnote 2) using the following steps:

a) Score the relevance of the evidence for each research theme on a 3-point scale, (from 1=low to 3=high), considering:
• To what extent does this text help to provide an evidence-based answer to the research question/s that come under this theme?
b) Score the robustness of the evidence on a 3-point scale (from 1=low to 3=high) where the following rating system would apply:

Scale rating	Description
1	Significant methodological limitations which must be taken into account when comprehending key findings and conclusions.
2	Some of the methodological approach is appropriate for the research and limitations are thought unlikely to alter the conclusions of the study (risk of bias)
3	All or most of the methodological approach appropriate for the research (low risk of bias)

c) Combine the two scores from a) and b) into one final measure of quality, i.e. scored from 1 (1*1) up to 9 (3*3) and coded to result in a red-amber-green rating.
d) Present the process and results clearly to ensure transparency and replicability.

Throughout the search process, a log will be kept on a spreadsheet which will eventually be developed into the full literature review log in the next stage of the search protocol.

Stage 4: Full review and data extraction

We will complete a full review of a maximum of 60 papers or reports, and extract information from the review literature into a spreadsheet which can be filtered for each research theme. The suggested headings for the spreadsheet are below. If after reviewing all full texts significant gaps in the literature remain, it may be required that we conduct a purposive second round search to gather new information to conduct a complete STEEPLE analysis.

To keep our approach structured, we will follow the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) reporting items (footnote 3) to allow for a transparent, encompassing and comparable collection of article records included in our final review list.

Headings for the full literature review log:

- document title
- author(s)
- date of publication
- organisation/owner
- study type
- aims
- methodology
- summary of findings
- strengths
- limitations
- evidence gaps
- quality appraisal - relevance
- quality appraisal - robustness
- research questions

Quality appraisals will be completed concurrently with the extraction process. We will ensure that our work meets quality ratings according to AMSTAR (A Measurement Tool to Assess Systematic Reviews) (footnote 4).

Findings across the evidence base will be synthesised following ESRC guidance on conducting narrative synthesis (footnote 5). The synthesis will be grouped by research question and will provide single-sentence evidence statements for each. Within this synthesis, information on the volume and quality of evidence per research question will be included, highlighting gaps where they exist.

1. PRESS 2015: checklist for search strategies | Karolinska Institute University Library (ki.se)

2. The Production of Quick Scoping Reviews and Rapid Evidence Assessments: How to guide (PDF)

3. PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews | The BMJ

4. AMSTAR - Assessing the Methodological Quality of Systematic Reviews

5. Popay et al. (2006) Guidance on the Conduct of Narrative Synthesis in Systematic Reviews. Institute for Health Research, Lancaster University

Alternatives to single-use plastics: Appendix C Literature review framework

Additional details about each article, such as level of robustness and relevance, and mapping on to research themes and questions can be available on request.

Author (s)	Document Title	Date of publication
Ahari, H. and Soufiani, S. P	'Smart and Active Food Packaging: Insights in Novel Food Packaging	2021
Carina, D. et al.	Seaweeds polysaccharides in active food packaging. A review of recent progress.	2021
Defra	A Green Future: Our 25 year plan to improve the environment	2018
Environment and Climate Change Canada	Guidance for Selecting Alternatives to the Single-Use Plastics	2021
EPECOM	Report of the Expert Panel on Environmental Charging and Other Measures: Recommendations on Single-use Disposable Beverage Cups.	2019
EU Parliament and Council of the EU	DIRECTIVE (EU) 2019/904 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 June 2019 on the reduction of the impact of certain plastic products on the environment.	2019
European Bioplastics	Bioplastics market data	2022
Food Standards Agency	Bio-Based Materials for Use in Food Contact Applications	2022
Fortunati, E., Mazzaglia, A. and Balestra, G. M.	Sustainable control strategies for plant protection and food packaging sectors by natural substances and novel nanotechnological approaches	2019
Gerassimidou, S., Martin, O. V., Chapman, S. P., Hahladakis, J. N. and Iacovidou, E.	Development of an integrated sustainability matrix to depict challenges and trade-offs of introducing bio-based plastics in the food packaging value chain	2021
Giacovelli	Single-use plastics: A roadmap for sustainability.	2018
Gradon Diprose, Louise Lee, Hannah Blumhardt, Sara Walton & Alison Greenaway	Reducing single use packaging and moving up the waste hierarchy	2022
Herrmann, C., Rhein, S. and Strater, K. F.	Consumers' sustainability-related perception of and willingness-to-pay for food packaging alternatives	2012
HM Treasury.	Tackling the plastics problem summary of responses to the call for evidence.	2018
HM Treasury.	Tackling the plastic problem Using the tax system or charges to address single-use plastic waste.	2018
HM Treasury	Budget 2018 Single-use Plastics	2018
Holley, P	The London Marathon's method for reducing plastic bottles. Edible seaweed pouches.	2019
Jia-Wei Han, Luis Ruiz-Garcia, Jian-Ping Qian, and Xin-Ting Yang.	Food Packaging: A Comprehensive Review and Future Trends	2018
Jonathan Asher Morashti, Youra An and Hyunmi Jang.	A Systematic Literature Review of Sustainable Packaging in Supply Chain Management	2022
Keranen, O., Komulainen, H., Lehtimaki, T. and Ulkuniemi, P.	Restructuring existing value networks to diffuse sustainable innovations in food packaging	2021
Lamontagne, N. D.	Food Packaging Innovations Balance Convenience with Sustainability: Whether they	2018
Logomasini, A.	Five Reasons Banning Plastics May Harm the Environment and Consumers.	2018
M. K. Verma, S. Shakya, P. Kumar, J. Madhavi, J. Murugaiyan.	Trends in packaging material for food products: historical background, current scenario, and future prospects	2021
McCarthy, J and Sanchez, E.	5 Plastic Alternatives Doing More Harm Than Good — and What to Use Instead.	2019
Miller, B.	17 Biggest Advantages and Disadvantages of Plastics.	2020
Photopoulos, J.	Seaweed coffee cups could help ditch single-use plastics.	2018

Author (s)	Document Title	Date of publication
Rana, K.	This is how to ensure sustainable alternatives to plastic.	2022
Renton, M	Market and safety analysis of alternatives to plastic food packaging	2020
Ronzano, A., Stefanini, R., Borghesi, G. and Vignali, G.	Agricultural waste as a source of innovative and compostable composite biopolymers for food packaging: a scientific review	2021
Springle, N., Li, B. L. D., Soma, T. and Shulman, T.	The complex role of single-use compostable bioplastic food packaging and foodservice ware in a circular economy: Findings from a social innovation lab	2022
UNEP	Single-use supermarket food packaging and its alternatives: Recommendations from life cycle Assessments.	2022
Werner, B. G., Koontz, J. L. and Goddard, J. M.	Hurdles to commercial translation of next generation active food packaging technologies	2017
Ahmad, A., Qurashi, A. and Sheehan, D.	Nano packaging – Progress and future perspectives for food safety, and sustainability	2023
Ataei, S., Azari, P., Hassan, A., Pingguan-Murphy, B., Yahya, R. and Muhamad, F.	Essential Oils-Loaded Electrospun Biopolymers: A Future Perspective for Active Food Packaging	2020
Cao, C., Xiao, Z., Ge, C. and Wu, Y.	Animal by-products collagen and derived peptide, as important components of innovative sustainable food systems—a comprehensive review	2022
Chaudhary, V., Bangar, S. P., Thaku, N. and Trif, M.	Recent Advancements in Smart Biogenic Packaging: Reshaping the Future of the Food Packaging Industry	2022
Hosseini, S. A., Abbasi, A., Sabahi, S. and Khani, N.	Application of Postbiotics Produced by Lactic Acid Bacteria in the Development of Active Food Packaging	2022
Ludwicka, K., Kaczmarek, M. and Bialkowska, A.	Bacterial Nanocellulose-A Biobased Polymer for Active and Intelligent Food Packaging Applications: Recent Advances and Developments	2020
Mahmud, J., Sarmast, E., Shankar, S. and Lacroix, M.	Advantages of nanotechnology developments in active food packaging	2022
Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R. and Beas, I. N.	Environmental impact of food packaging materials: A review of contemporary development from conventional plastics to polylactic acid based materials	2020
Nilsen-Nygaard, J., Fernandez, E. N., Radusin, T., Rotabakk, B. T., Sarfraz, J., Sharmin, N., Sivertsvik, M., Sone, I. and Pettersen, M. K.	Current Status of biobased and biodegradable food packaging materials: Impact on food quality and effect of innovative processing technologies	2021
Petkoska, A. T., Daniloski, D., D'Cunha, N. M., Naumovski, N. and Broach, A. T.	Edible packaging: Sustainable solutions and novel trends in food packaging	2021
Salgado, P. R., Di Giorgio, L., Musso, Y. S. and Mauri, A. N.	Recent Developments in Smart Food Packaging Focused on Biobased and Biodegradable Polymers	2021
Yan, M. R., Hsieh, S. and Ricacho, N.	Innovative Food Packaging, Food Quality and Safety, and Consumer Perspectives	2022
Peter Kershaw	Exploring the potential for adopting alternative materials to reduce marine plastic litter	2018

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Alternatives to single-use plastics: Appendix D Workshop topic guides

Introduction

Purpose of the guide: This topic guide has been developed for use in workshops with expert panel members. Workshops are expected to last around 1 hour depending on the depth of responses.

Overview: Hello, my name is [insert name] and I am an [insert role] at RSM. Thank you for finding the time to speak with me today.

RSM UK Consulting LLP (RSM) are delighted to have been commissioned by Food Standards Agency (FSA) to carry out a rapid evidence assessment to develop an understanding of the alternatives to single-use plastics in the production and packaging of food.

The primary purpose of the assignment is to carry out an assessment and establish a baseline understanding of the risk and opportunities associated with use of plastics in the food system in terms of sustainability and food safety; to identify the main alternatives to single-use plastics in terms of materials and their functions; and to understand potential future developments in this area.

The outcomes of the assessment have the potential to inform future policy and regulation decisions as well as guide the development of further research. As part of this research, we have developed a search protocol setting out the scope and plan for the literature search.

You have been recommended by the Food Standards Agency to participate in this research, as an expert in the area of alternatives to single-use plastics. We are particularly interested in your views on this research as an [academic/ retailer/ FMCG representative/ industry representative]. The purpose of this discussion is to gather your thoughts on this topic area and your recommendations for any key materials that we should be asking about or looking at.

This discussion should last 1 hour but may be a little shorter or longer depending on your responses. Participation is completely voluntary, and you can choose not to answer a question or to stop the discussion at any time. The findings from this discussion will be used to ensure the robustness of our search protocol. We will take notes on the discussion for internal purposes. They will not be provided to anyone outside of the research team.

- do we have your permission to take notes on this discussion?

[Record of verbal consent]

Record of each participant:

- name/s
- organisation/s
- country (if applicable)
- date

Topic Guide

Introduction [talk through intro slides and aims]

1. Please could you describe to us:

- your role
- your experience of working with/knowledge of alternatives to single-use plastics

Research Questions: [talk through slide 2]

2. From your perspective, are the research questions appropriate?

a) Why/why not?

b) [If no] how could we improve the relevance of these questions?

3. Are there any other questions we should be asking?

Elicitation

4. With these broad questions in mind, what are the key developments and priorities in this field that we should be capturing?

5. In terms of gathering relevant information, we are keen to get your recommendations in terms of the key materials or sources we should be looking at. Can you suggest:

a. Specific academic articles, or research labs or universities that are conducting relevant research? (Within the UK and internationally)
b. Similarly, organisations or institutions outside of the academic space that are currently leading the movement and innovating in this field? (Within the UK and internationally)
c. Countries where this research/innovation work is particularly well developed?
d. Any government reports or briefing papers or media articles that might be useful to incorporate?

6. As we have mentioned in the introduction, with this project we aim to inform the FSA's policy and regulation decisions as well as guide the development of further research carried out or commissioned by the FSA. In your opinion, how can we make sure that the results of this research are of value from a policy or regulatory perspective?

7. Are there any research or knowledge gaps you are aware of that may be useful to address with this or future research?

Closing questions

8. Are there any other considerations which would be helpful to note?

9. In terms of the next steps on the project [go through the research process and brief overview of timeline in slide 2], we would like to bring you all back together to discuss the findings from the research and work collectively with you to shape recommendations based on the findings? For this, we'd like to facilitate a workshop in [mention week]. Can everyone make XX date in that week? [suggest a few alternative dates and reach a final date that meets the majority's needs]

10. If there are any other thoughts or comments you may have on this work, please do reach out. Our emails will be copied in the calendar invite and also in the chat [copy email into chat].

Thanks and close

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Alternatives to single-use plastics: Appendix E Expert panel

Below is a list of all experts and/or stakeholders of the food packaging and production sector who we consulted for guidance on the search protocol, research topic and/or research findings and recommendations. It should be recognised that the findings of the report may not necessarily reflect the views of individuals within the expert panel.

Name	Role	Organisation
Dr Sam Short	Industrial Associate	University of Cambridge, Institute for Manufacturing
Dr Claire Barlow	Industrial Sustainability Specialist	University of Cambridge, Institute for Manufacturing
Vincent Greenwood	Policy Advisor	Food Standards Agency
Allan Shivembe	Senior Policy Advisor	Food Standards Agency
Timothy Chandler	Senior Policy Advisor	Food Standards Agency
Mackey Geoff	UK Head	Plastics Europe
Alan Boobis	Emeritus Professor of Toxicology	Imperial College London
Emma Bradley	Head of Food Quality and Safety	Food and Environment Research Agency (Fera Science)
Sally Beken	Knowledge Transfer Manage Polymers	Innovate UK Knowledge Transfer Network
Paul Davidson	Challenge Director - Smart Sustainable Plastics Packaging	UK Research and Innovation (UKRI)

In addition to those named in the table, there was also one additional representative in the expert panel who has chosen to remain anonymous.