CASE STUDY ON BISCUIT WRAPPERS

An example of weighing sustainability criteria for plastic flexible food packaging from a chemicals perspective

A Chemicals Perspective on Designing with Sustainable Plastics: Goals, Considerations and Trade-offs

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Foreword

This case study was developed to provide input to and inform the development of guidance on General Considerations for Design of Sustainable Plastics from a Chemical Perspective. Four case studies were developed as concrete examples to inform these considerations. Two in the plastic packaging sector: biscuit wrapping and detergent bottles; two in the construction sector: flooring and insulation. For this purpose, the case studies start from the premise that plastic material will be used and therefore alternative material selection is not considered. They focus on environmental sustainability aspects related to chemical selection, taking into account health protection across the product life cycle. They do not address cost, performance and chemical/material availability information, which would need to be considered in an application scenario. They also do not consider a discussion of social and environmental justice impacts.

The examples of material selection within the case studies are developed in the context of the information gathered for the case studies to exemplify the sustainable design process and to highlight key considerations. To make actual decisions about material selection other factors would also need to be considered (as outlined above) and the analysis could be further informed by elements such as life cycle assessment comparing alternatives and a full review of regulatory restrictions.

This document is based on a draft report developed by Partners for Innovation for this project and was reviewed by an OECD expert group supporting this project, which also provided a number of inputs. It was further reviewed by the OECD Working Parties on Risk Management and on Resource Productivity and Waste. Additionally the report was discussed at an OECD workshop on developing the general considerations for design of sustainable plastics from a chemical perspective held in March 2021.

This report is published under the responsibility of the OECD Chemicals and Biotechnology Committee in collaboration with the OECD Environmental Policy Committee.

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List of Acronyms

AlOx	Aluminium oxide
BioPE	PE made from bio-based feedstock
BOPET	Biaxially oriented polyethylene terephthalate
BOPP	Biaxially oriented polypropylene
BPA	Bisphenol A
Cd	Cadmium
ClVOCs	Chlorinated VOCs
CMR	Carcinogenic, mutagenic or toxic to reproduction
Cr	Chromium
Cu	Copper
EAA	Ethylene acrylic acid
EB curing	Electron beam curing
EDC	Endocrine disrupting chemical
EoU	End-of-Use
EVA	Ethylene-vinyl acetate
EVOH	Ethylene vinyl alcohol
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
Ni	Nickel
NIAS	Non-intentionally added substances
NIR	Near-infra red: used for detecting plastic types in sorting installations
OVOCs	Oxygenated VOCs
PA	Polyamide
PAAs	Primary aromatic amines
PLA	Polylactic acid
PO	Polyolefins

PP	Polypropylene
PUs	Polyurethanes
PVC	Polyvinyl chloride
PVdC	Polyvinylidene dichloride
PVOH	Polyvinyl alcohol
rHDPE	Recycled HDPE (High-density polyethylene)
rPET	Recycled PET (Polyethylene terephthalate)
rPP	Recycled PP (Polypropylene)
RSL	Restricted Substances List
SIN list	Substitute It Now list
SiOx	Silicon oxide
TiOx	Titanium (di)oxide
TPA	Terephtalic acid
UV	Ultraviolet radiation
VLDPE	Very low-density polyethylene
VOCs	Volatile organic compounds

Executive Summary

The OECD is conducting a project on the design of sustainable plastics from a chemical perspective, which aims to identify the key considerations regarding environmental sustainability and human health along the product life cycle that should be taken into account when chemicals are selected at the design stage, as well as the potential trade-off between these considerations. Case studies on particular sector/product combinations have been elaborated to inform the development of the general considerations.

In this case study, sustainability considerations regarding the chemical composition of plastic packaging film for biscuits are identified. It builds on the ‘Considerations and Criteria for Sustainable Plastics from a Chemicals Perspective’ report published by the OECD in 2018 (OECD, 2018a). The case study shows how the principles from the report can be put into practice. An approach is offered for designers of plastic food packaging film with examples of considerations and trade-offs in the specific case of biscuit packaging.

A life cycle approach is used to address all sustainability considerations and demonstrate the complexity of making a profound sustainable chemical selection for plastic packaging film. At each stage in the life cycle, different considerations regarding sustainability come into play, while decisions in one stage might also affect the impact at others. Considerations are divided into ‘polymer considerations’, which need to be taken into account to select the main polymer that makes up the film, and ‘chemical considerations’ regarding other chemical substances that might be incorporated into the plastic. In the approach used in this case study, a designer is provided with the information needed to make a preliminary selection for the polymer and to be aware of potential hazards from incorporated substances, so they can communicate with suppliers and make a final decision.

Polymer considerations

The most important polymer considerations revolve around optimising the properties of the film while using a minimal amount of sustainably sourced material that can be recycled at end-of-use.

Due to the small size of the packaging film, it is difficult and of low value to be sorted in a dedicated recycling stream. Therefore, it will not be recycled into high value plastic in current recycling systems but downcycled in lower grade applications. This means that preferably no primary fossil feedstock should be used. However, the availability of polymers from food-safe secondary feedstock is limited to rPET from bottle deposit schemes. Polymers from renewable feedstock are limited to a small number of options too, and unsustainable agricultural practices in the supply chain should be avoided.

To meet all functional requirements in the selection of a polymer, a balance needs to be found between increased material use and the combination of materials in a multilayer film. Multilayers decrease the recyclability of the film and increase the potential of incorporation of hazardous substances. The use of oriented film can also improve the film properties but requires the use of heat sealable layer or adhesive

to seal the packaging. This is another trade-off between material reduction and the drawbacks of a multilayer or use of adhesive.

The packaging should be designed to be suitable for either mechanical recycling or industrial composting at the end-of-use. For the highest possible grade of recycling with the least health and environmental hazards, a mono-material PE or PP film should be chosen, or a multilayer film with the highest possible share of polyolefins. For a compostable film, all components should biodegrade in an organic waste facility without leaving traces that decrease the quality of the compost. Conditions and process time vary among organic waste facilities. These should be verified per sales region of the packaging. Regardless of the chosen polymer, incineration and landfilling are considered unsustainable waste management options. Chemical recycling technology may become an option in the future but is at present not mature enough to base design decisions on it.

Chemical considerations

After a polymer is selected, the incorporation of a number of chemical substances in the plastic film needs to be considered. Potential hazards need to be investigated in collaboration with the supplier. Potential hazards from additives, production residues and non-intentionally added substances remain a point of attention for the supplier, regardless of the chosen polymer. Special attention should be paid to non-intentionally added substances (NIAS) in case of secondary feedstock due to the increased risk of contamination and degradation products.

For biscuit packaging film, heat and oxidation stabilisers are the most important production additives that need to be scrutinised, to avoid migration into the food and hazards in the end-of-use phase. Plasticisers are not commonly used in the production of plastic film for this application but should be investigated when a specific set of polymers is used.

When a multilayer film is used, the use of adhesives, primers and internal lubricants need to be investigated depending on the selected production method of the multilayer film. Concerns have been voiced mainly about constituents of adhesives, such as curing agents and solvents.

Inks consists of a wide range of possible chemical additives, and thus potential hazards. Due to their share and function in the ink, the pigment and solvent are the most scrutinised in this case study. Use as little ink as possible in your design, even when safe inks without associated human health hazards are chosen.

Policy considerations

The life cycle approach also leads to recommendations for further research and policy initiatives to address knowledge gaps and overcome systemic obstacles that inhibit truly sustainable use of plastic food packaging film.

The use of potentially hazardous substances should be discouraged with bans or financial instruments. Some substances with known or suspected hazards are still used while alternative safe substances exist, because the alternatives are not commercially attractive. Additionally, full transparency on material composition throughout the value chain must be encouraged.

To improve the availability of food-safe secondary feedstock, research should be conducted into forms of plastic packaging that are suited for uniform design agreements and separate collection. The combination of uniform design and separate collection makes PET bottles currently the only source of food-safe recycled plastic.

Where these are not already established, mandatory safety standards should be developed for plastic recyclers and waste incinerators based on available practices. To allow for the reliable design of compostable plastic packaging film, uniformity in the collection, processing time, and biodegradation conditions needs to be established in organic waste facilities and packaging needs to be recognisable as compostable.

Further research is required into the long-term environmental impacts of using recycled plastic in non-food applications.

Chapter 1. Introduction

Global plastics production has reached 368 million metric tons and is expected to continue to grow by around 4% annually for the foreseeable future (PlasticEurope, 2020). While plastics deliver many benefits to society, there is an increasing awareness of the potential impact of chemical components of plastics on human health and the environment.

The Organisation for Economic Co-operation and Development (OECD) organised a Global Forum on Environment focused on "Plastics in a Circular Economy: Design of Sustainable Plastics from a Chemicals Perspective" in 2018. The Forum sought to incentivise a shift in sustainable chemistry thinking at the product design stage by identifying good practices, including tools and approaches, as well as a policy framework to reduce the environmental and health impacts of plastics. This resulted in multiple reports on the sustainability of plastics from a chemical perspective.

An outcome to the Global Forum was to work further to develop general considerations for sustainable design of plastics from a chemicals perspective. To help inform the development of the considerations, case studies were developed for particular sector/product combinations. This case study focuses on sustainability considerations at a chemical level for plastic design of plastic film for biscuit packaging. A life cycle approach is taken for the development of the plastics packaging film. Sustainability aspects regarding human health and the environment are considered, resulting in sustainability considerations for professionals throughout the value chain who are involved in the design of plastic packaging film. This enables sustainable designs tailored to the specific life cycle scenario of a packaging film for biscuits.

1.1. Case Study Approach and Structure

1.1.1. Life cycle approach

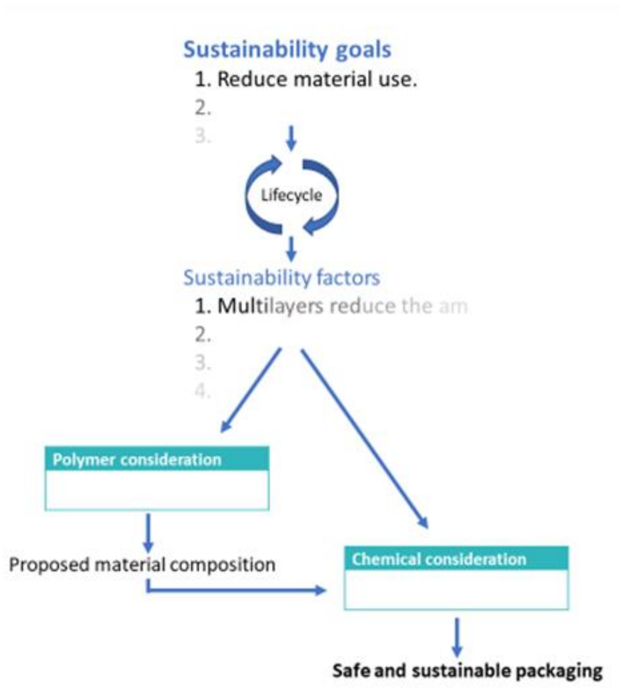
1. The sustainability aspects are assessed for the life cycle phases through which a plastic packaging film cycles: sourcing of the material, production and filling of the packaging, use of the packaging to preserve the biscuits and consumption of the biscuits, and end-of-use at which the plastic film is discarded and processed. At each phase in the life cycle, different considerations regarding sustainability come into play, while decisions in one phase might also affect the impact at other phases. From a designer's perspective, this journey starts with the use phase. The purpose of the product and the context in which it will be used, determine the basic set of technical requirements and constraints for a shortlist of possible materials. Therefore, this case study will consider the use phase first, after which the sourcing of the feedstock, the production of the packaging and its end-of-use are discussed. This approach is not to be confused with a Life Cycle Assessment (LCA), a method to determine the environmental impact of a specific packaging (or product) throughout its life cycle, while the current study aims to identify and address environment and health considerations in each phase of the life cycle.

1.1.2. Case study structure

The subsequent chapters discuss the different life cycle phases. A general overview of the life cycle phase is provided in each chapter, describing the different processes and relevant factors that influence sustainability of the packaging. The relevant sustainability factors are identified by keeping a list of Sustainable Design Goals in mind while working through the life cycle phases. Each sustainability factor leads to a polymer or chemical consideration; a decision that needs to be made to select a polymer or a chemical in the production of the plastic packaging film. Some of these considerations have a higher level of detail: the selection of a polymer or the combination of materials in the film. These are key considerations and need to be addressed first in the plastic selection process. Other considerations are on a much more detailed level: once a polymer or a group of materials has been chosen to form the packaging, the chemical additives that are used in production of the film need to be selected. These are chemical considerations; they are listed when the life cycle is analysed and an example is given for each.

Once all aspects of the life cycle have been considered, an overview of Key Considerations and Trade-offs is provided in Chapter 7. Subsequently, the key considerations regarding the polymer choice will be simultaneously assessed in an example of a choice matrix in Chapter 8. An overview of the chemical considerations that follow polymer selection is also given. This is intended as a reminder for further investigation into details that cannot all be considered in one step. Policy considerations based on the insights of the case study are discussed in Chapter 9.

Figure 1.1. Visual representation of case study structure



1.2. Scope

1.2.1. Description of biscuit packaging film

A flexible plastic packaging for biscuits, or a ‘wrapper’, consists of thin plastic film. Biscuits are collated in a stack, in a plastic tray, a corrugated cardboard sleeve, or are individually packed. The film can have the shape of a tube that is closed at both sides of the product with a heat seal, or the film is wrapped around the biscuits and folded and sealed shut.

For commercial reasons, the packaging is usually very colourful with images and product information directly printed on the packaging film. The use of additional labels or stickers is rare. The plastic film itself is generally a combination of materials, both plastics and non-plastics, to meet requirements like barrier properties, strength, printability and sealing.

Figure 1.2. Examples of biscuit packaging

Source: © Shutterstock

1.2.2. Scope: focus on plastic film

In the case study, it is assumed that the choice for a flexible plastic packaging has been made and the most sustainable plastic film now needs to be found. This includes polymeric barrier layers, attractive appearance and sealing of the film.

1.2.3. Out of scope

Some (sustainable) packaging options for biscuits will be left out of scope to prevent an almost unlimited range of comparisons and considerations. By focusing on the thin plastic film, the following aspects are not included in this case study:

- Reusable and returnable containers can be used to store and sell biscuits. Consumers who use biscuit tins or rigid plastic containers at home will still need to buy biscuits packed in single use packaging from the store. However, packaging that is returned to the food producer to be refilled, can replace plastic film as packaging solution. This case study aims to identify sustainability considerations regarding plastic film for biscuits, other packaging options are thus left out of scope.
- Alternative materials such as metallised film, plastic coated paper, or cardboard sleeves, can be used to replace plastic film or in combination with the plastic film. With the aim to focus on sustainability of plastics from a chemical perspective, other materials are left out of scope. Alternative materials would add much more considerations and trade-offs not directly related to the plastics.

1.2.4. Requirements for packaging

The over-arching requirements for all these different forms of flexible plastic packaging for biscuits are:

- Preserve the integrity and safety of the food;
- Maintain the taste, texture, and aroma of the biscuit;
- Display the biscuits in an attractive way at the point of sale;
- Display the required information about the ingredients, safety advice such as allergen warnings including, and the manufacturer of the biscuits;
- Make the biscuits easy to stack in transport and storage.

1.3. Notable regulations for this case study

Multiple national and international authorities have their own lists of substances that are prohibited or are limited in use for plastics and for food contact materials. When performing polymer and chemical selection, local regulations must be adhered to. For an overview of a subset of these regulations please refer to the OECD (2021) publication Guidance on Key Considerations for the Identification and Selection of Safer Chemical Alternatives, Exhibit 5 and to the Regulations and Restrictions page of the OECD Substitution and Alternatives Assessment Toolbox (OECD, 2020). To provide insight on the extent of such regulations the REACH and CLP regulations on chemicals of the European Union and the regulation on food contact plastics are briefly elaborated below.

1.3.1. EU: REACH and CLP Regulation

Regulation (EC) No 1907/2006 concerning Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and Regulation (EC) No 1272/2008 on classification, labelling and packaging of substances and mixtures (CLP), are regulations in place in Europe to control the health and environmental risks of chemicals. REACH establishes procedures for collecting information provided by industry on the properties and hazards of substances, their uses and exposure potential for human health and the environment, and eventually adopting regulatory measures to control their risks. Whenever a substance poses an unacceptable risk to human health or the environment, restrictions can be adopted to limit or ban the manufacture, placing on the market or use of a substance. For substances of very high concern, as defined in REACH, the use can be subject to authorisation. Currently polymers are not included in REACH, this may change in the future.

1.3.2. EU: Commission Regulation (EU) No 10/2011

This is a regulation on plastic materials and articles intended to come into contact with food, including the *Union list of authorised substances*. A ‘positive list’ of substances that can be used in the production of plastics that come into contact with food and the specific migration limits for some of these substances. It further requires and details compliance testing of materials, requires an assessment to be made of non-intentionally added substances, and requires each manufacturer in the supply chain to provide a declaration of compliance. This means that both the finished packaging and intermediate products need to comply with specific obligations. For the producer of the plastic resin or chemical additive this means that only allowed substances are used; for the manufacturer of the packaging it means that migration testing is performed and passed.

1.4. Overview of the life cycle of packaging film for biscuits

This section provides a general overview of the life cycle of packaging film for biscuits. The different stakeholders in the life cycle are visualised in Figure 1.3, with an indication of their primary activity and end product. Subsequently Table 1.1 provides an overview of the important factors influencing the sustainability of the biscuit wrapper for each life cycle phase.

Figure 1.3. Visual representation of the life cycle of a biscuit packaging film

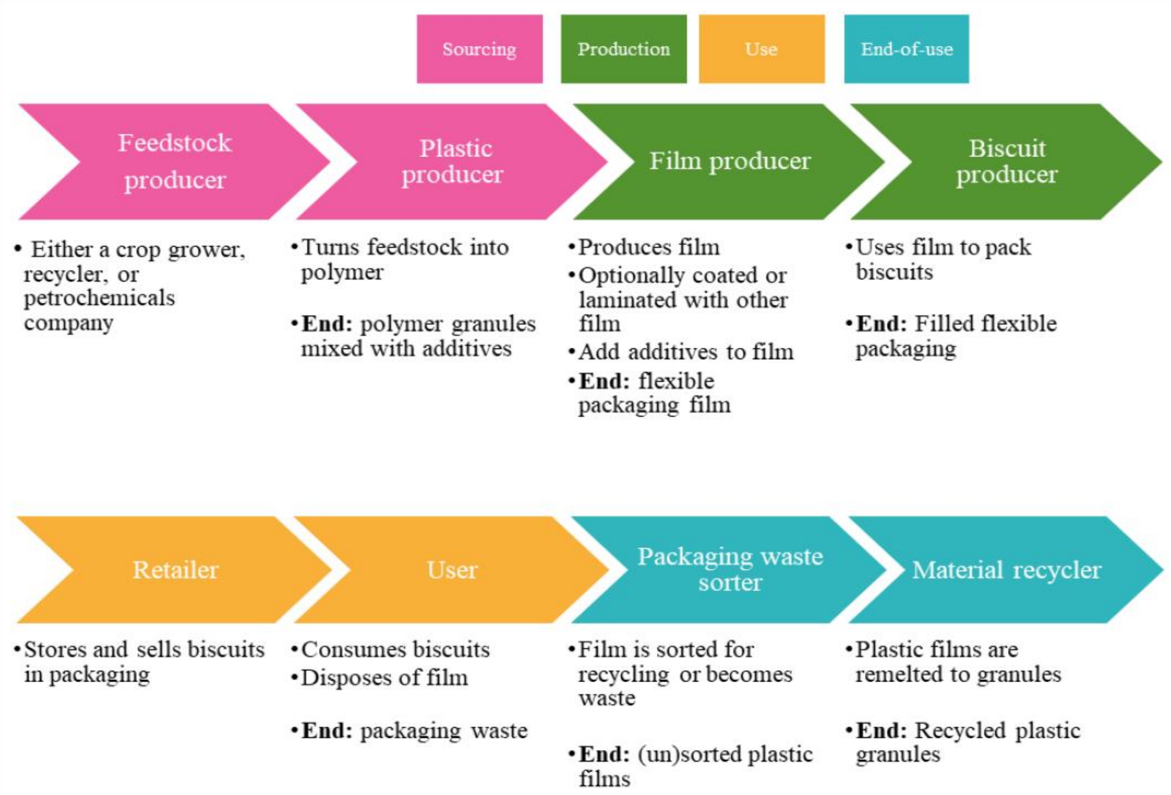


Table 1.1. Important sustainability factors per life cycle phase

	Sourcing of Materials	Sourcing of Materials	Use Phase	End-of-Use
	Production of polymer resin	Production, filling, and seal of packaging film	Transportation to user, preservation	Disposal, sorting and recycling of packaging film
Important sustainability factors	- Polymer options for packaging - Polymer feedstock and impact of sourcing - Residual substances from polymerisation - Additives used in plastic production - Contamination of secondary feedstock	- Additives required in production of film - Additional substances used in production of packaging from the film - Emissions to the environment during production	- Requirements for use (and transport) - Use of inks in packaging - Exposure of consumers to substances	- Recyclability or compostability of materials and packaging design - Emissions to the environment during end-of-use - Exposure of waste management staff to substances

Chapter 2. Methodology

2.1. Sustainable Design Goals

To guide the material and chemical selection, over-arching sustainability goals need to be set. Using secondary feedstock for the production of the film reduces dependency on fossil resources, but might lead to incorporation of hazardous substances in the film. A chemical additive might increase efficiency in the production of the packaging and thus reduce the overall CO_2 emissions in the process, but it could hinder the recycling of the material at the end-of-use. Establishing over-arching sustainability goals from the outset will enable the designer to ensure these kinds of benefits and drawbacks are taken into account when examining material alternatives. Furthermore, the goals will guide the designer in the selection of materials when trade-offs need to be made. The following five sustainable design goals are chosen for the case study of a plastic biscuit packaging. Examples of other goals are given at the end of the section.

1. **Prevent product spoilage**

   The packaging serves to protect the product. Usually the (environmental) impact of the production of the product is far higher than that of the packaging's total life cycle. Preventing the waste of the product before it reaches its intended goal is an important goal in the sustainable design of the packaging.

2. **Reduce material use**

   Packaging is a short-lived product but amounts to 40% of the world's total use of plastic (PlasticsEurope, 2019). Designers should strive to reduce the amount of used plastic to the absolute minimum to meet the packaging requirements.

3. **Close material loops**

   Due to the short-lived use of packaging, the used material should make multiple life cycles. The plastic should either be made from secondary feedstock or be able to be used a second time in another product. In an ideal situation, a combination of both is made.

4. **Preserve natural capital**

   Humans depend on natural capital for a wide range of ecosystem services. Poorly managed natural capital can destroy productivity and resilience, making it difficult for humans and other species to sustain themselves. Destruction of natural capital throughout the packaging life cycle can occur in the form of land use for mining and crop growing, biodiversity loss due to toxic emissions, exhaustion of feedstock, and climate impact through to greenhouse gas emissions.

5. **Safeguard the health of participants in life cycle**

   From feedstock extraction, through packaging manufacturing and product use, to the eventual end-of-use scenario, the packaging and its subcomponents will interact with humans. The direct negative effects of the packaging and its subcomponents on the health of these people needs to be minimised. The focus with regard to health in this case study will be in three phases of the life cycle:

i. The first is residential human health exposure: hazards for consumers in the use phase through migration of substances into the food or through skin contact with the packaging.

ii. The second is occupational human health exposure during waste management at end-of-use: the hazards for recycling facility employees who come into contact with the chemicals during treatment of the packaging waste.

iii. The third are hazards for the general population when substances spread into the environment due to emissions from production and waste treatment.

This focus is applied because it is assumed that the health risks at the plastic producing plants, film manufacturers, and product packaging facilities are known and adequate precautions can be taken. This is not the case for individual consumers, waste management employees, and the general public.

2.1.1. Examples of other sustainable design goals

The five goals listed above are chosen specifically for this case study. When working on a different packaging or product, other sustainable design goals might come into play, such as:

- Minimise waste
- Improve social conditions throughout the life cycle
- Decouple from fossil resources

2.2. Chemical selection process

During the design process, the listed five sustainable design goals must be considered to select the most sustainable plastic(s) to be used in the packaging. During the analysis of the life cycle, it will become apparent that trade-offs must be made. The selection of one material based on one sustainable design goal in one phase of the life cycle can counteract the realisation of another goal in another part of the life cycle. In addition to the selection of the most sustainable polymer for the packaging, the use of chemicals in the production of the polymer and the packaging and their consequences in later phases of the life cycle must be considered. This is especially important since the packaging is used for foodstuff and migration of known or potential hazardous substances to the biscuits must be taken into account.

To select a polymer or a combination of polymers from a list of options, the most important considerations and trade-offs need to be identified. It is not practicable to consider all possible chemical substances and their potential hazards for all the polymers simultaneously. The following selection process is therefore used in this case study and is proposed as a method for safe chemical selection.

1. Based on the over-arching sustainable design goals, identify the sustainability considerations for the packaging throughout the life cycle.
2. List and weigh the sustainability considerations; some will be regarded as key considerations while others have a minor impact on the overall sustainability of the packaging.
3. Collect data on the optional polymers for the plastic film.
4. Compare the polymers based on the identified key considerations.
5. Select the polymer that is identified as the best fit (i.e. having minimal or no impact on human health while maintaining the highest level of environmental sustainability) for the biscuit packaging.

Subsequently, for the selected polymer only, the relevant chemical considerations should be taken into account. Additives, residual production chemicals and potential non-intentionally added substances (NIAS) must be investigated on their consequences for environmental sustainability and human health.

6. Demand from all your suppliers that they comply with all applicable regulations on food contact materials.
7. Select a list of hazardous substances or substances of concern to review your packaging. The selection of the list can depend on the product, previous experience within the design team, or be mandated by company standards. The sources for this list will be discussed in the next section.
8. Check, in collaboration with your material supplier if necessary, whether they found chemical considerations involve any of the substances on the selected list with hazardous substances.
9. If substances on the list are part of a chemical consideration, reconsider the need for using this substance and try to find an alternative substance for the intended goal. Some lists provide overviews of alternative substances. Safe alternatives can be found with the help of 'positive lists' such as the Safer Chemical Ingredients List (US EPA, 2020). For guidance on the selection of alternatives, please refer to OECD (2021).
10. If step 8 cannot be passed, revisit step 5 and select another polymer or polymer combination.
11. If no polymer can be selected without the incorporation of hazardous chemicals, as identified on the list of hazardous substances: Innovate.
    a) Re-evaluate the functional requirements of the packaging (discussed in this case study in Section 3.1): do these enforce unsustainable decisions?
    b) Re-evaluate the shortlist of polymers: is innovation on a material level required?
    c) Re-evaluate the product-packaging combination, can another form of packaging be chosen? This might lead to reusable packaging, packaging-free concepts or non-plastic materials.

2.2.1. Lists to support the chemical selection process

Hazardous substances or substances of concern can be identified with the aid of lists of substances. Examples of these lists are the 'Proposition 65 list' from the State of California (OEHHA, 2021), the Substitute It Now (SIN) list developed by non-profit organisation ChemSec (ChemSec, 2021) and the Restricted Substances List (RSL) of the Cradle-to-Cradle Products Innovation Institute (Cradle-to-Cradle Products Innovation Institute, 2021).

The Californian list contains substances with known reproductive toxicity or carcinogenic properties. The SIN list consists of chemicals that have been identified by the NGO ChemSec as being Substances of Very High Concern. The SIN list provides information on REACH status, use and function, concerns, production and available alternatives for each chemical. The Restricted Substances List (RSL) is a checklist for materials that are not allowed to be used in Cradle-to-Cradle certified products. This is a certification for sustainable products and certifies them as safe, responsible, and fit for a circular economy. These lists differ in hazards that are included, how restrictive they are and whether alternatives are suggested. Besides these three examples, other lists can be used. More lists with hazardous substances are discussed in in the publication *Guidance on Key Considerations for the Identification and Selection of Safer Chemical Alternatives* (OECD, 2021), in the ECHA (2019) publication '*Substances of concern: Why and how to substitute?*', and in the OECD Substitution and Alternatives Assessment Toolbox (OECD, 2020).

Chapter 3. Use Phase

In the use phase, the packaging is used for its intended goal: transporting the biscuits from the producer to the consumer safely, providing information and attracting attention in the store. In Section 3.1, the main functional requirements to the plastic film in the use phase are discussed. A shortlist of possible polymers is introduced and compared based on these requirements. In Section 3.2, inks and the associated sustainability considerations are discussed. Inks are discussed in this phase because they are added to the packaging to fulfil a function in the use phase.

The use phase touches upon three of the over-arching sustainable design goals: (1) preserving the biscuits, (2) while using as little material as possible, and (3) without exposing humans to hazardous chemicals in the packaging.

3.1. Functional requirements to packaging film

The functions of the plastic biscuit packaging are collating the individual biscuits, labelling and advertising, and mechanical protection (i.e. to prevent breaking). However, these functions can also be performed by packaging made from other materials. The plastic packaging is usually chosen because it serves to protect the biscuits from spoilage. The quality of the biscuits can be spoiled by moisture. Moisture uptake will make the biscuits lose their crunch, this is the main requirement mentioned by industry experts and is taken into account in this case study. Oxidation of fats in the biscuit will change the taste and uptake of odours from the environment will change the taste and aroma of the biscuits. The oxygen barrier is listed in Table 3.1, but not regarded as one of the main requirements by industry experts. The three main requirements for biscuit film packaging are:

- **Water Vapour barrier** of the plastic to prevent moisture uptake. Biscuits are expected to be crisp and the loss of crunchiness poses the highest risk for deterioration in the journey between production and the consumer.
- **Toughness** of the film is an important factor since the barriers will only be effective as long as the packaging is intact. A thin plastic film minimises the amount of material used in the packaging. The more the thickness of the film is reduced, the greater the chance of damage to the packaging. A thin film with good barrier properties but low tensile strength may not survive the logistics channel of the biscuits from producer to consumer.
- **Heat-sealing** of the film on a fast filling line. On the fast paced, high volume packaging lines either a plastic film is wrapped around the biscuits, or the biscuits are placed in an opened bag. In both cases, the packaging needs to be closed which is commonly done through heat sealing. This will be discussed in further detail in Chapter 5 Production.

3.1.1. Commonly used polymers and barrier layers

Table 3.1 shows a shortlist of common polymers and plastic coatings for packaging and indicates how each performs as a film on the main three required properties, plus the oxygen barrier. This can be used to make a first selection of materials to consider in the biscuit packaging.

Table 3.1. Commonly used polymers and their properties. Ranking order: inadequate: red - excellent: dark green.

	Water vapour barrier	Oxygen barrier	Toughness	Heat sealing
LLDPE / LDPE	yellow	red	light green	dark green
HDPE	light green	red	light green	light green
PP	yellow	red	light green	light green
BOPP	light green	red	dark green	red
PET	yellow	yellow	dark green	red
BOPET	yellow	light green	dark green	red
PA	red	light green	dark green	red
PLA	red	red	red	yellow
Regenerated cellulose	red	light green	light green	red
Coatings and barrier layers				
Acrylics	red	red	red	light green
PVdC	dark green	dark green	red	light green
EVOH	red	dark green	red	yellow
EVA	red	red	light green	dark green

Note: Ranking order: inadequate: red - excellent: dark green
Source: Based on CEFLEX (2020), KIDV (2019), Dixon (2011) and Polymer database (2020).

3.1.2. Multilayer films

As can be concluded from Table 3.1 not one material scores perfect on all required properties. To improve the properties of the packaging film, multiple layers of polymers can be combined. A thin layer of a polymer with a good oxygen barrier can be combined with a thin layer of a polymer with a good vapour barrier. This can drastically reduce the amount of (mono-)material required to perform both functions. However, these multilayers do have consequences in other phases of the packaging's life cycle. This will be discussed in further detail in Section 5.3, *Multilayering*.

Box 3.1. Polymer considerations

In the use phase the barrier properties, strength and ease of sealing of the polymers are to be considered for the main polymer selection. As can be concluded from Table 3.1 not one material scores perfect on all requirements.

- Barrier properties can be improved by using thicker films, but this will increase material use.
- A combination of materials can be chosen in a multilayer film to combine beneficial properties, but this will have consequences in other phases of the life cycle.
- A designer can weigh and re-evaluate the functional requirements if no satisfactory decision can be made.

3.2. Printing and inks

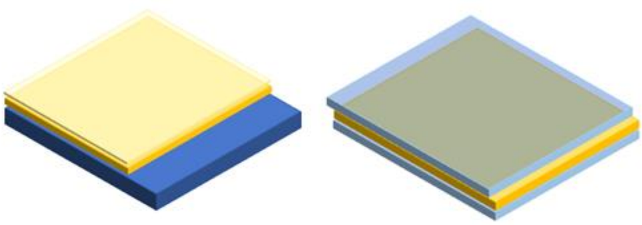
Biscuits are sold in attractive packaging to attract consumers with images and colours printed on transparent or evenly white coloured films. Food producers are required to print information about ingredients and nutritional value on the packaging. The inks that are used and their chemical constituents can have great impact on the overall sustainability. Potential hazardous substances from the ink can contaminate the consumers' hands and be absorbed through the skin or contaminate the biscuits with the consequence of being ingested by the consumer posing a potential threat to their health. Inks can also have negative effects when leached into the environment in a landfill, decrease the quality of the secondary material after recycling, and bring about both environmental and health risks when incinerated or heated during recycling.

3.2.1. Printing techniques

There are multiple methods to apply ink on a surface: flexographic printing, gravure printing, inkjet printing, and more. There are differences with respect to sustainability between these methods, but in the chemical selection for a flexible food packaging two other aspects are of much greater importance: the surface on which the ink is printed and the curing of the inks on the printed surface. Choices made in these aspects have impacts on the safety for human health.

Plastic films can either be surface printed, on the outside of the plastic film, or reverse printed, on the inside of one layer that is then laminated on a second layer of film.

Figure 3.1. A depiction of a surface printed plastic film with overcoating (L) and laminated film with reverse printing in between (R). The yellow layer represents the ink.



- **Surface printed inks** have the downside that they can be rubbed off and contaminate the consumer's fingers. Chemicals can be absorbed through the skin or form miniscule airborne particles that enter the respiratory system. In the production process, films are stacked as sheets or rolled as one piece on a reel. Surface printed inks on the outside can transfer off to the food contact layer on the other side. To prevent this, overprint coatings can be applied. This extra layer is applied over the surface-printed inks to protect the ink from rubbing off. Surface printed inks may come with health risks regarding contamination and spreading of the inks; this method should only be chosen if all constituents of the ink are deemed safe or when an overprint coating can be applied that is proven to be safe and not to negatively affect the recyclability of the film.
- **Reverse printed inks** are usually applied to the outermost plastic layer when multilayer films are used. They protect the inks from rubbing of and prevent direct migration to the food or skin. However, they require the lamination or coating of multiple plastic layers in the film, with the corresponding issues in recycling and health risks of migrating adhesives (see Section 5.4).

3.2.2. Ink types

- **Solvent-based inks** are cured by drying to the air. The solvent evaporates and leaves the pigments and binders on the film. The binders make up the largest part of the ink and can be bio-based resins such as nitrocellulose or rosin resin, or synthetic resins such as PVB, PA, or PU. For food-grade applications, bio-based resins are preferred due to the lower odour and migration risk (ILSI Europe, 2011). The evaporation of the solvents creates high risks for the release of volatile organic compounds (VOCs), which can be toxic and carcinogenic. The use of mineral oils in solvents for food-grade applications has been minimised (EuPIA, 2013), but contamination can happen. The migration of Mineral Oil Saturated Hydrocarbon (MOSH) and Mineral Oil Aromatic Hydrocarbons (MOAH) therefore need to be monitored when a solvent based ink is chosen. MOSH can bioaccumulate and have long-term toxicological effects. MOAH can be mutagenic and carcinogenic.
- **Water-borne inks** are not 'water-based' inks. The pigments and binders are still dissolved in a solvent (commonly an alcohol), but this is diluted with water. This decreases the amount of solvent that evaporates and reduces the emitted VOCs. Drawbacks of waterborne inks are that the ink cures more slowly on non-absorbent surfaces such as plastic film or that heat sources are used to decrease curing time. This might result in higher energy demand in production. Furthermore, it is important to control the evaporation process because retained solvent in the dried ink can act as a plasticiser, which increases the risk of migration of the ink to food and increases setoff in surface prints (ILSI Europe, 2011).
- **UV curing inks** do not use solvents, but rather a liquid binder of photo-initiators, monomers and oligomers mixed with the pigments (see Section 4.3 for an explanation of monomers and oligomers). In liquid form, they can be applied to a surface. When treated with UV light, the photo-initiators start the polymerisation of the monomers and oligomers, binding the pigments to the plastic film. For food-safe applications, it is essential that highly reactive oligomers and monomers be chosen so that all these are polymerised and migration of unreacted oligomers and monomers is minimised. Using highly reactive substances does add to the health risks in production and they could be more hazardous when incorporated in the packaging while unreacted. This is a trade-off that needs to be made between the additional hazard when the substance remains unreacted and decreasing the chance of having unreacted substances. For both UV and EB curing, it applies that curing time must be tightly controlled to make sure that no unreacted oligomers and monomers are present in partly cured inks. Photo-initiators that are demonstrated to be safe and having low migrating potential should be chosen, as they will remain fixed in the cured ink (ILSI Europe, 2011).

- **Electron beam (EB) curing inks** work in a similar way as UV curing inks, but do not require photo-initiators. Because the electron beams penetrate all the way into the inks, the reaction of monomers and oligomers is better controlled than that of UV curing inks. The binders and additives (with the exception of photo-initiators) are comparable to those used in UV-curing inks.

3.2.3. Biodegradation and recycling of inks

- **Biodegradability of inks** and varnishes is usually limited. Some bio-based pigments and binders exist, so that only natural occurring substances remain after composting. However, with current industrially used inks and their required application and curing speeds, minor traces of non-biodegradable additives will always remain even if the binders and pigments biodegraded. If biodegradability is intended, print should be done on as little surface as possible.
- **Plastic recycling** is intended to reclaim the polymers in the packaging. The addition of inks and varnishes will in any case contaminate the recycling products and should be used as little as possible. Surface printing of small surfaces with a thin overcoating are preferred since reverse printed inks will require an extra lamination layer, adding to the contamination. Light colours, irrespective of curing method are preferred. The pigment TiOx (white) is a known disturbance in the colouring of recyclate, while Carbon Black (black) is incompatible with near-infrared automatic sorting technology.

Box 3.2. Chemical considerations

- Carefully chosen EB curing inks seem to be the most sustainable choice when focusing on the ink alone.
- Surface-printed inks may come with health risks regarding contamination and spreading of the inks; this method should only be chosen if all constituents of the ink are demonstrated to be safe or when a safe and recyclable overprint coating is applied.
- Reverse printed inks require lamination, which has its own associated health risks and consequences in recycling and biodegradation.

3.2.4. Pigments

Pigments colour the ink colour and are the most important ingredients. Pigments are insoluble coloured chemical compounds with the ability to give colour to another material. “Pigments keep their original shape (as small crystals) over the complete life cycle, a consideration that must be taken into account during the material health assessment process” (Cradle to Cradle Products Innovation Institute, 2019).

“Several toxicity studies have been performed on pigments for select hazard endpoints including acute toxicity, mutagenicity and irritation potential. The results showed that very few pigments are hazardous. The main reason for this is that most pigments are poorly water soluble and predominantly chemically inert, and as a consequence are not bioavailable” (Cradle to Cradle Products Innovation Institute, 2019). However, some pigments, for instance those based on heavy metals, pose known hazards and should be excluded. The European Printing Ink Association (EuPIA) (2018) lists pigments with antimony, arsenic, cadmium, chromium (VI), lead, mercury and selenium as pigments to be excluded for use, together with the dye colourants, Auramine, Chrysoidine, Fuchsine, Induline, Cresylene Brown. For more information, please refer to the overview by the *Verband der Mineralfarbenindustrie* (2019) on national and international regulations regarding pigments and fillers in food contact materials.

3.2.5. Inks and safe chemical selection

Besides the previously discussed substances in inks, a wide range of additives can be used depending on the producer, the printing and curing techniques that are used, the solvents and the pigments. The International Life Sciences Institute (ILSI) lists antifoam agents, jellifying agents, adhesion promoters and twenty other possible types of additives in inks for food packaging (ILSI Europe, 2011).

Regardless of the choices made about the polymer and other required chemicals, inks should always be subjected to a critical review during the design of the packaging. Involvement of the ink producer in this process is crucial. The European Printing Ink Association has published a list of excluded substances in inks (EuPIA, 2018) and Guidelines for Good Manufacturing Practices including risk assessment and management (EuPIA, 2016). These documents can be adhered to in the chemical selection process, in addition to local chemical safety regulations, food contact regulations and screening with a list of hazardous substances as discussed in Section 2.2.

Box 3.3. Chemical considerations

- Inks consist of a wide range of possible chemical additives and thus potential hazards.
- Due to their relative proportions and function in the ink, the pigment and solvent are the most scrutinised. Sustainable, hazard free alternatives for these substances are available.
- Potential hazards of other constituents of the inks might be less well known. A designer should specifically inquire about other potential hazardous constituents when discussing inks with a supplier.
- Use as little ink as possible in your design, even when considered safe.

Chapter 4. Sourcing

In the sourcing phase of the life cycle, the plastic granules that will be used to make the packaging film are made. This includes the selection of the feedstock from which the plastic is derived. The overall considerations regarding the selection of the most sustainable feedstock are discussed in Section 4.1. The practical considerations regarding availability and origin of the feedstock are discussed in Section 4.2. In the production of the plastic from the feedstock, potentially hazardous substances are involved, either as residue from the production or additives to improve the plastic (Section 4.3) or as a non-intentionally added substance (Section 4.4).

Three of the over-arching sustainable design goals are of importance in the sourcing phase: preserving natural capital in the sourcing of the feedstock, closing of material loops, and protection from hazardous chemicals that are emitted during production or remain in the plastic.

4.1. General feedstock considerations

Depending on the polymer(s) chosen for the packaging film, there are three main sourcing routes: primary renewable resources, primary non-renewable feedstock, or secondary feedstock (or recycled material).

4.1.1. Renewable resources

A resource is considered renewable when the regeneration is able to keep up with the extraction and consumption of the material. Well-known examples are fast-growing crops such as corn, sugar cane, sugar beet and wheat. Rapidly renewable resources are selected to decouple feedstock extraction from fossil resources and to preserve natural capital. Using fast-growing crops will also reduce the emission of greenhouse gases (in comparison with fossil-based resources), as the growth of the plants requires them to capture CO_2 from the atmosphere. The carbon will be stored in the biomass, converted to a plastic and will eventually be released back into the atmosphere again as CO_2 or CH_4 (methane) when the plastic is incinerated or decomposes at end-of-use. A social benefit to the use of renewable resources is that, unlike reserves of fossil resources, their cultivation does not have to be concentrated in specific regions in the world. This means that bioplastics production can support local rural economies.

When selecting a renewable resource as feedstock for the plastic, several other sustainability criteria should be considered: land-use change, food scarcity and agricultural practices.

When crops are grown to serve as feedstock for plastic production, arable land is needed. The feedstock is not considered sustainable when it requires the destruction of natural capital, e.g. deforestation of rainforests to gain arable land. The cultivation of crops for plastic production should also not compete with food production in areas where arable land or water is scarce, or crop yields are unstable. By-products or residues of food production can be selected as feedstock in these cases. Furthermore, if the cultivation of the feedstock heavily depends on fossil-based energy, through petrol for tractors or on the use of fertilisers, use of hazardous substances such as pesticides, or large amounts of fresh water, the overall environmental impact of the feedstock might be higher than that of fossil-based alternatives.

Not all these factors can readily be taken into account in the selection of a polymer to produce a biscuit wrapper. When a polymer derived from a renewable resource (a “bioplastic”) is considered, potential suppliers and the origin of the feedstock should be checked against the criteria. In the packaging design process, this can be included by demanding credible certification of the materials by a third party, for instance the Bonsucro certification for sugar cane (Bonsucro, 2017) or the broader Roundtable on Sustainable Biomaterials (RSB, 2020).

Take care not to confuse plastics from renewable feedstock with biodegradable plastics. Renewability concerns the regeneration of the plastic feedstock. Biodegradation is the breakdown of plastic waste in naturally occurring substances through the biological action of microorganisms (Folino, Karageorgiou, Calabro and Komilis, 2020). Biodegradability of the plastics is discussed in Section 6.3.

4.1.2. Primary non-renewable feedstock

Intuitively, the fossil-based primary feedstock is regarded as the least sustainable. The extraction of the feedstock is polluting and requires the destruction of natural capital. The use of primary (or ‘virgin’) material means that the material cycles will not be fully closed and continual extraction of the feedstock is needed. However, the use of primary non-renewable feedstock might be required due to food safety concerns and unavailability or incompatibility of materials derived from renewable resources. In this case, a plastic must be selected that can readily be recycled and the biscuit film must be designed in a way that enables the highest possible recovery of the material in the existing recycling value chain. In this way, the plastic used in the biscuit wrapper can be reused in another product, replacing the need for virgin plastics.

A polymer from a primary non-renewable feedstock that cannot be readily recycled is an unsustainable material and should not be selected for use in a short-lived product such as biscuit packaging.

4.1.3. Secondary feedstock

Secondary feedstock, or recycled plastics, can be derived from both renewable and non-renewable resources. The benefit of the use of secondary feedstock is that recovery of the materials after their primary use generally has a lower environmental and health impact than the production of virgin plastics. Additionally, the use of recycled plastic means that this material has not been discarded as waste and the impact of incineration or landfilling has been prevented. The use of recycled plastic in a new product increases the demand for recycled plastics, which creates an incentive for collection and recycling of the plastic at end-of-use.

In food contact applications such as biscuit packaging, the application of plastics from secondary feedstock is limited, often due to the quality of the secondary material. In India for instance, the use of recycled plastic is prohibited in all food contact applications (Indian Ministry of Health and Family Welfare, 2018). In Canada, recycled plastics used in food packaging are subjected to the same regulations as virgin plastics in terms of their chemical safety (Health Canada, 2011). In the EU, recycled plastic in food contact applications can only be used when the primary plastic was food-grade, the collection system ensures no contamination with other material streams and the material is recovered through a process verified to be safe (EU Commission, 2008).

In practice, this means that only recycled PET collected through bottle deposit systems is widely adopted in food-grade applications, with the notable exception of regions where no recycled plastic is used at all. Depending on local policy and available facilities it is possible to obtain (small quantities of) other food-grade recycled plastics, for instance when a recycler can be supplied with separately collected food-grade plastics or through a chemical recycling process. Chemical recycling will be discussed in further detail in Chapter 6 *End-of-Use*.

Box 4.1. Polymer considerations

In the selection of a polymer, the availability of sustainable sources needs to be considered. Sourcing has a great influence on the overall sustainability, in particular on the chosen sustainable design goals 'Close material loops' and 'Preserve natural capital'.

- If a polymer can only be sourced from non-renewable primary feedstock, this might not fit the goals and can no longer be regarded as a viable option.
- Renewable feedstock might overall not be more sustainable when managed inappropriately. Credible third-party certification helps in the selection of sustainable renewable feedstock.
- Due to safety considerations, the availability of secondary feedstock is very limited.

4.2. Feedstock options

In this section, the feedstock options for the potential polymers on the shortlist compiled in the *Use Phase* chapter are discussed.

4.2.1. Renewable resources

From the shortlist of materials created in Chapter 3, *Use Phase*, the materials in Table 4.1 can be derived from a renewable resource.

Table 4.1. Polymers from renewable feedstock considered in this case study and their availability.

Polymer	Common Feedstock	Availability	Remarks
BioPE	Sugar cane and waste cooking oils	Commercially available	BioPE includes LLDPE, LDPE and HDPE.
BioPP	Waste cooking oils and palm oil	Scarce; R&D phase	Scarce at time of writing, availability is rapidly increasing
BioPET	Sugar cane and agricultural waste (from sugar cane)	Small scale	Bio-based feedstock is used in production, end product is ±30% bio-based
PLA	Corn and sugar cane	Commercially available	
Regenerated cellulose	Wood pulp	Large commercial availability	

Source: Based on Siracusa and Blanco (2020).

BioPE, BioPP and bioPET are so-called 'drop-in bioplastics'. They are chemically identical to PE, PP and PET derived from fossil feedstock, have the same material properties and can be processed and recycled just as their fossil counterparts.

Since biscuit wrappers are short-lived products, the selection of sustainable primary non-renewable feedstock for this purpose requires the polymer to be readily recyclable in the end-of-use phase. This means that the recycling system in the region in which the biscuits are consumed should be analysed. This will be further elaborated in Chapter 6, *End-of-Use*. However, plastic packaging film of this size is not well recycled and is typically ‘down-cycled’ in low-grade products made from mixed plastics.

4.2.2. Secondary feedstock

From the shortlist of polymers in Chapter 3, *Use Phase*, the polymers in Table 4.2 can be sourced as food-safe recycled plastics. Due to the current organisation of collection and sorting facilities, almost all recycled plastic will have the risk of contamination with organic pollutants or non-food-safe plastics. Only the separately collected PET bottles in deposit schemes are widely available for food-safe recycling. Chemically recycled feedstock might be a source of food-safe polymers in the future, but the availability is currently too low to act as the basis for design decisions. This will be discussed in further detail in Section 6.5 *Chemical recycling*.

Table 4.2. Polymers from secondary feedstock considered in this case study and their availability

Polymer	Food-Safe Mechanically Recycled; Availability	Chemically Recycled
LDPE	No	No; pilot scale
HDPE	No; pilot scale	No; pilot scale
(BO)PP	No; pilot scale	Yes; small commercial scale
(BO)PET	Yes; widely available	No; pilot scale
PA	No	No; pilot scale
PLA	No	No
Regenerated cellulose	No	No

Box 4.2. Polymer considerations

The use of primary non-renewable feedstock is not sustainable because currently it will not be recycled into high quality products. The currently available food-grade polymer from secondary feedstock is PET. Recycled PP is available in scarce quantities through chemical recycling. If renewable feedstock is preferred, currently the best options for the main polymer are BioPE, PLA or Regenerated cellulose, but only credibly certified renewable feedstock should be used.

Summarising, this narrows down the currently available sustainable options to:

- Mechanically recycled PET
- BioPE
- PLA
- Regenerated cellulose

4.3. Production residues and Production additives

Additives are used to aid in the production process. They can be added to renewable, non-renewable and secondary feedstock. Residual substances might be left in the plastic from production and other substances might remain as a contamination in the plastic after recycling. The health risks and sustainability of additives and production residues are discussed in this section. Only additives added by the plastic resin producer are discussed in this chapter. Additives that are added in the production of the film are discussed in Chapter 5, *Production*.

4.3.1. Production residues

- **Monomers** are the starting molecules used to form a polymer through polymerisation. Terephthalic acid (TPA) is a monomer used in the production of PET. Migration of residual TPA is regulated in the EU under Regulation (EU) 10/2011 on food contact materials with a migration limit of 7.5 mg/kg. Residual monomers are not expected in polyolefins (PE and PP in this case study), as these are very volatile substances which are released from the polymer pellets during production. A well-known restricted monomer is Bisphenol A (BPA); an endocrine disrupting chemical (EDC) for which a migration limit has been set in EU regulation since 2018. However, BPA is used in the production of polycarbonate (PC) and is therefore not relevant for this case study.
- **Oligomers** are partially reacted monomers or the result of degradation of polymers. They are mainly found in polyesters (PET and PLA) in food packaging applications. Oligomers can be present in polyolefins as waxes. For instance, in very low-density polyethylene (VLDPEs). It is assumed that oligomers tend to be less hazardous than the starting monomers, but that they are present in higher concentrations in the plastic (Barnes, Sinclair, and Watson, 2006).
- **Catalysts** are chemicals that start or accelerate a chemical reaction. In this case, the polymerisation from monomers to polymers. For example, in the production of PP catalysts can be added that are formed from a 'pre-catalyst mixture' containing, among other substances, phthalates. These form the catalyst in the reactor in which the polymerisation will take place. Ortho-phthalates such as bis(2-ethylhexyl) phthalate (DEHP) have endocrine disrupting properties. These phthalates are usually consumed in the reactions, but traces can be left in the final PP. Traces should be removed in the purification stage and tests must be performed to determine that concentrations are below specified limits so that the material can be used in food-grade substances.

Box 4.3. Chemical considerations

Screening for residual substances from the polymerisation in the plastic remains a point of attention for the supplier. The used substances in these processes are known, thus targeted analysis of plastic can be performed to determine whether residues are left in the material.

4.3.2. Additives

Additives are used to make plastics easier to process, enhance its mechanical properties (such as impact or stress crack resistance) or give it specific aesthetic qualities.

- **Flame retardants** reduce the flammability of plastics. They are not added to the resin for the application in food-grade plastic film. Many flame retardants have been banned due to reproductive toxicity, carcinogenicity and endocrine disruption.
- **Heat and oxidation stabilisers** are used in packaging film to prevent polymer degradation during extrusion. Butylated hydroxytoluene (BHT) is used as an antioxidant in multiple plastics for food contact materials, but its use is in decline due to high migration into fatty foods (Barnes, Sinclair,

and Watson, 2006). BHT is under assessment for endocrine disrupting properties and is very toxic to aquatic life (ECHA, 2020c).

- **Clarifying** agents or nucleating agents are added to improve the transparency of plastics, mainly to PP. As PP is semi-crystalline, these nucleating agents are the seeds to start crystallisation. This leads to a product with more and smaller crystals, resulting in improved optical clarity. No food safety or environmental risks are expected with this additive. Potassium benzoate is commonly used as a clarifying agent for this application, which is also used as a food preservative.
- **Biocides** prevent the degradation of plastics from microbiological attacks. They are not commonly used for this application. They might be used to slow down biodegradation of biodegradable plastics (Groh et al, 2019) but for a product with as short a lifespan as packaging, refrain from using these at all.
- **Pigments** are discussed in more detail in Section 3.2, as part of the considerations regarding inks. In plastics, pigments are dispersed within a binder matrix (masterbatch), which is then added during compounding of the granules to imbue it with colour. Coloured plastics pigments are embedded in a matrix and exposure is therefore limited (Cradle to Cradle Products Innovation Institute, 2019). Plastics films for biscuit packaging are usually left transparent (without added pigment) or titanium dioxide ($TiO2$) is added as a pigment to create white film for better printing results. Titanium dioxide has suspected carcinogenic properties in powder form (ECHA, 2020d). While it has been considered safe when used in plastic and used as a food colourant, concerns have recently been voiced over the safety of oral exposure to $TiO2$ (Brand et al, 2020); more insight in the potential carcinogenic properties of the substance is expected in 2021 (Braakhuis et al, 2020).

Box 4.4. Chemical considerations

Chemical additives are added to the plastic to serve specific purposes, but can have consequences for the sustainability of the plastic packaging, both in terms of hazard to human health and hindrance of recyclability.

- It should be considered whether the addition of the chemicals to the plastic is indispensable, and only confirmed unhazardous additives should be used.
- For the specific case of biscuit packaging film, heat and oxidation stabilisers remain the most important additives to be aware of, because of migration into the food and hazards in the end-of-use phase.
- Specifically, when biodegradable films are chosen, the use of biocides requires extra attention.

4.4. Non-intentionally added substances

Only taking production additives into account is not enough. Besides the intentionally added, registered and tested substances, both primary and secondary feedstock can contain NIAS. These are formed in the plastic through reaction of intentionally added substances or through contamination.

Side-products are unintended substances formed in the polymerisation. Side-products can also be formed later during reactions in the film production. Oligomers can be regarded as side-products, as these are unintended products of an intended polymerisation reaction (Peters, Undas and Van Leeuwen, 2020).

4.4.1. NIAS in secondary feedstock

Particularly in secondary feedstock, NIAS can be introduced in the recycling process through contaminants such as inks and adhesives and as breakdown products from the polymer itself. In the description below, the focus is on rPET for food applications. See Horodytska, Cabanes and Fullana (2020) for rHDPE and rLDPE.

- **Degradation products** are created due to thermal and mechanical degradation in the recycling process. Acetaldehyde is a thermal degradation product from PET (Barnes, Sinclair, and Watson, 2006). Acetaldehyde is suspected to be carcinogenic and mutagenic and is regulated in the EU with the overall migration limit set at 6 mg/kg. It is a potential hazard for staff at recycling facilities because it can cause serious eye irritation and is highly flammable (ECHA, 2020e).
- **Contamination of the recycling stream can add non-intentionally added substances to the secondary material**. Thoden van Velzen, Brouwer, Stärker and Welle (2019) found low quantities of benzene in rPET. They attributed the presence of benzene to accidental contamination of the PET recycling with PVC and found that an increase in recycled content increased the levels of benzene. The low concentration of benzene was considered of no concern. However, it was noted that no conclusion could be drawn on the effects of accumulation of the substance over multiple recycling cycles.

4.4.2. NIAS and safe chemical selection

Designers of plastic film packaging for food can only incorporate the risks of NIAS in their chemical selection by relying on information provided by the producers of the plastic and the film. The Food Packaging Forum (Geueke, 2018) writes, *"Many food contact materials have a high chemical complexity making a complete characterization of all NIAS unrealistic and the identification of those NIAS that may be of concern very challenging. NIAS may be predicted based on the knowledge of chemical processes, manufacturer's experience, and conditions of use. Such substances may then be identified and quantified rather easily by targeted chemical analyses. By using non-targeted screening methods, additional NIAS may be detected and at least some of them identified, while others remain completely unknown."*

Designers should therefore demand that their producers screen their products for NIAS that can be expected due to the production process, used substances or use conditions. For new products or products produced in a new process, a broader non-targeted screening should take place to identify new NIAS. Identified NIAS should be treated just as intentionally added substances in the safe chemical selection process. Incorporation of the NIAS in the material should be prevented, or methods should be sought to remove the NIAS from the material. If neither is possible, the use of the chosen polymers and additives should be re-evaluated.

Box 4.5. Chemical considerations

- Potential hazards from NIAS remain a point of attention, regardless of chosen polymer or feedstock.
- Special attention should be paid to NIAS in case of secondary feedstock due to the increased risk of contamination and degradation products.
- Designers cannot screen material themselves, but should demand that their producers or suppliers screen the material for reasonably expected NIAS. New material formulations should be screened extensively to identify potential additional NIAS.

Chapter 5. Production

This chapter discusses the sustainability considerations with respect to the production of the packaging film and the filling of packaging with biscuits. In Section 5.1, the substances used in the production of the film from the plastic are discussed. When multiple polymers or materials are used in the production of the packaging film, more additives and corresponding chemical considerations need to be taken into account; this is discussed in Section 5.2. When the film is produced and formed into biscuit packaging, it must be sealed. Considerations regarding this last production step are discussed in Section 5.3.

Many of the decisions in the production phase of the film and filling of the packaging are currently made based on efficiency and production speed, while remaining within the allowed boundaries for food safety. In this chapter, the main considerations revolve around three of the sustainable design goals.

Which chemical substances can be used to aid in efficient and fast production processes, and do not pose a hazard for (1) the consumer or waste management worker, or (2) the environment? In addition, how will it impact the recycling potential of the plastic film, to be able to (3) close materials loops?

5.1. Film production

Plastics films for this application are produced through casting or extrusion blowing, both of which have their own advantages, drawbacks and environmental footprint. To focus on the sustainability aspects and the influence of selected chemicals, only film production additives will be discussed in this chapter.

Plasticisers are used to improve the flexibility of plastics by reducing the forces between the molecules. They are mostly used in the production of flexible PVC, which is not included in the shortlist of polymers in this case study due to the high concentration of plasticisers, suspicion of other concerning additives, and known problems in recycling. PVdC coating is used in much smaller amounts but is under scrutiny for the same reasons. Notable uses of plasticisers for the polymers on the short list are in cellulose films (Hahladakis et al, 2018), PLA film (Darie-Niţă et al, 2016), and PVdC coatings (Wang et al, 2020). Common plasticisers are phthalates, including DEHP, benzylbutyl phthalate (BBP) and dibutyl phthalate (DBP), which have endocrine disrupting and reproductive toxicity properties. For these phthalates, specific migration limits are set in the EU regulation on plastic materials and articles intended to come into contact with food (Commission Regulation (EU) 10/2011). Safe and sustainable plasticisers do exist, such as polyethylene glycol (Darie-Niţă et al, 2016). Plasticisers can also be used in inks and adhesives. This is one of the reasons to use inks and adhesives sparingly in and on the packaging.

Box 5.1. Polymer considerations

- Regenerated cellulose film, PLA film, or PVdC coatings or other materials containing phthalate or other plasticisers or additives with a similar migration tendency should not be used in sustainable biscuit packaging.
- When one of these polymers is chosen, the hazards of the plasticisers should be investigated.
- Replace hazardous plasticisers for non-hazardous alternatives or reconsider the use of the polymer.

Lubricants are used to reduce the friction between processing machinery and the plastic. They improve production efficiency and reduce energy use and machine wear. Lubricants are used in very small quantities. Commonly used lubricants are paraffin waxes and glycerol stearates. Currently these are no cause of concern during production, use or reprocessing at end-of-life. However, little research has been done into the impurities (Central Science Laboratory, Bradley, and Coulier, 2007) or migration (Wagner, 2012) of these substances.

Anti-block and slipping agents are used to prevent films from sticking together. They are mainly used in LDPE and PP films and to a lesser extent in PVC and PET (Zilles, 2014). A distinction can be made between inorganic agents, which can be compared with finely distributed mineral particles on the surface and organic agents, which can be compared to lubricants that migrate to the surface of the film. Organic anti-block agents have high migration potential since they form a release layer on the outside of the film (Zilles, 2014). They are commonly derived from vegetable oil or other natural fats and no risks are associated with their use. Crystalline silica is used as an inorganic anti-block agent. Prolonged or repeated exposure to crystalline silica in powder form has long-term toxicological effects. This exposure will not occur when the substance is embedded in the plastic film, so occupational exposure during film production and in the supply chain of film producers is the main concern in this context.

Antistatics are not commonly used in biscuit packaging. Film on a fast-moving filling line will build up static energy in the packaging. This is mainly a problem with the packaging of electronics and powdered goods. They might be added to biscuit packaging film when the production of the bakery and packaging are carried out as one continuous operation in the same facility. Dust from flour, sugar and grain particles can cause problems when they are attracted to static packaging. An electrostatic discharge could even lead to ignition of the dust. Among others, ethoxylated amines are used as antistatic agents in food packaging (Central Science Laboratory, Bradley, and Coulier, 2007 & Barnes, Sinclair, and Watson, 2006). These can be very toxic to aquatic life and harmful to humans when swallowed or touched (ECHA, 2020b). A specific migration limit of 1.2 mg/kg is set in EU regulation (Commission Regulation (EU) 10/2011).

Box 5.2. Chemical considerations

- Refrain from using an antistatic agent where possible. When used, potential hazards should be reviewed.
- More research is needed into migration and leaching of production additives from the film throughout the entire life cycle.

5.2. Multilayering

Currently, most biscuit wrappers and other flexible plastic packaging do not consist of a single polymer film. More common is the use of a multilayer film that combines the properties of two or more materials. Generally speaking, materials can be bonded together in three ways:

1. **Co-extrusion**, in which two or more polymers are melted and extruded as thin layers on top of each other.
2. **Coating**, in which a liquid part is applied on an existing film to be bonded together.
3. **Lamination**, in which two existing films are bound together with the aid of another (liquid) material.

5.2.1. Co-extrusion

Regarding sustainability of the plastic film from a chemical perspective, co-extrusion is likely to be preferred over lamination. Section 5.4 elaborates on lamination and the use of adhesives, and the involved sustainability aspects. In co-extrusion, the use of adhesives can be prevented, and these aspects do not thus need to be considered. However, the following aspects need to be taken into account when a multilayer film is co-extruded.

Tie layers: Co-extrusion can require the extrusion of a 'tie layer' between two materials to enable two polymers to be extruded together. For example, ethylene-vinyl acetate (EVA) is used in the co-extrusion of PA and PE. A drawback from the use of tie layers is that they require substantially more material to bond the layers than with the use of an adhesive. Extra polymer layers reduce the recycling potential of the film because there are more polymers with (slightly) different properties present in the eventual recycled product. More polymers also mean more additional chemicals that need to be checked on potential hazards.

Lubricants: In co-extrusion, the flow behaviour of the different materials needs to be similar to prevent shear stresses between the layers (Ten Klooster, 2008). Internal lubricants can be used to fine-tune the compatibility of the materials. The same applies here as for the external lubricants mentioned in Section 5.1.

Printing: As described in Section 3.2 on printing and inks, reverse-printed films require lamination or coating in production. When reverse printing is chosen for a multilayer with two material layers, co-extrusion is not an option, because there is no 'inside' of the film to print on when the two layers are extruded on top of each other.

Box 5.3. Polymer considerations

Multilayers that can be co-extruded are likely to be preferred over adhesive laminated multilayers due to the absence of adhesives. But consider:

- In some cases, the use of a tie layer needs to be considered, with its subsequent effect on material use, recycling and potential hazards at all phases of the life cycle.
- Internal lubricants are used more often and in higher amounts in co-extruded multilayers.
- Reverse printing requires lamination or coating.

5.2.2. Coating

In the application of a food packaging film, the coating methods of dispersion coating, extrusion coating and vapour deposition coating are relevant.

- **Vapour deposition coating**, or vacuum coating, is used to coat thin layers of metals and oxides on plastic film. It is an energy intensive process but can reduce the amount of material used and improve barrier properties. However, combining metals and plastics is detrimental for recycling.
- In **extrusion coating** one layer is extruded on top of an existing film. This is most commonly done with PE, EVA and PP coatings.
- With **dispersion coating**, the coating is applied on the film in a liquid form, either waterborne or in a solvent. The use of **curing agents** and **solvents** as discussed in section 5.2.3 should also be taken into account for dispersion coating.

Primers: For correct application of an extrusion or dispersion coating, an additional primer layer might be required. Primers are commonly used when a PE layer is extruded and for coating or extrusion lamination on PP or PET (or BOPP or BOPET) film (Qenos, 2015). It is also used for lamination of paper and metalised film and can be used with all other polymer combinations as an insurance against delamination on fast production lines to increase output. The most common primers are polyethyleneimines (PEIs), polyurethanes (PUs), and PVdC (Lyondellbasell, 2005; Dixon, 2011; Qenos, 2015). PEIs have long lasting toxic effects to aquatic life, have skin sensitising properties and are potentially carcinogenic and mutagenic (ECHA, 2020a). PU primers and the corresponding issues are similar to those of the PU adhesives described below under *Adhesion Lamination*, although the primers are applied in much smaller amounts. PVdC is discussed in this case study as a polymer coating, with drawbacks such as the use of plasticisers and occurrence of hazardous thermal degradation products.

Box 5.4. Chemical considerations

- The use of coatings greatly reduces the material use, with the associated benefits in sourcing, recycling and the risk of contamination.
- However, primers might be required. Primers are associated with potential hazards and should be thoroughly investigated.
- Extrusion coating is preferred over dispersion coating to eliminate the use of curing agents and primers and their associated hazards.

5.2.3. Adhesion Lamination

Whereas co-extrusion is the simultaneous creation of multiple films on top of each other, lamination is a process in which multilayer film is created from two or more existing films. This requires some kind of binder to keep these two films together. This is done for materials that cannot be simultaneously extruded. For instance, because of the incorporation of a non-thermoplastic layer, a reverse-printed film, or oriented films (such as BOPP and BOPET in this case study).

Distinctions can be made between lamination processes. In this case study, the following methods will not be discussed in detail:

- **Extrusion lamination,** in which a third polymer layer is extruded between two winding rolls with film layers. With regard to sustainability from a chemical perspective, this is very similar to co-extrusion, discussed in Section 5.2.1.

- **Wax or hot melt lamination**, which is used to bind paper to aluminium foil and thus is out of scope for this case study.

The focus described here is adhesive lamination. This can be further divided into different methods of applying and curing the adhesives. For more details on this, see the work of Dixon (2011), Aznar et al. (2011) and Mieth, Hoekstra and Simoneau (2016).

The most common adhesives for flexible food packaging are ‘reactive’ polyurethanes (PU) for plastic-to-plastic lamination and to a lesser extent ‘dry’ solvent-borne acrylics and vinyl-based adhesives. The polyurethane adhesives are liquids coated on one film. After application, a second film layer is applied and a chemical reaction starts to form a three-dimensional solid web, serving as an adhesive between the layers. The solvent-borne adhesives are also applied to one layer first, dried in an oven to evaporate the solvent, after which the second layer is applied.

Due to these processes and the required chemicals, two main concerns are raised, namely, curing agents and solvents.

Curing agents are chemical agents that cause a reaction that turns a liquid resin into a solid adhesive. Isocyanates are used to form PU adhesives. Concerns have been raised over the effects of isocyanates on workers, mainly as a cause of asthma when inhaled (Lockey et al, 2015).

Other concerns are voiced over food safety. Unreacted aromatic isocyanates might migrate into food and react with water to primary aromatic amines (PAAs), which are potential carcinogens (Dixon, 2011).

Solvents are used to apply adhesives in a liquid state to one of the film layers. This is used in acrylic and vinyl adhesives, in some polyurethane dispersion adhesives, and besides adhesion lamination, solvents are used in dispersion coating lamination as well.

On production lines, the solvents need to evaporate quickly after application. This is why volatile organic compounds (VOCs) are used as solvents. VOCs emitted from the production location to the outside air can cause smog (Barry et al, 2017). Ethyl acetate, used for example as a solvent for PU dispersion adhesive, is an example of a VOC that contributes to smog formation (NPI, 2014).

If the production location is not properly ventilated, these VOCs can be hazardous to the workers. For instance, for cyclic methyl siloxanes which are commonly used as solvents (Aznar et al, 2011), there are concerns about respiratory toxicity, potential carcinogenicity (Pieri et al, 2013) and endocrine disrupting properties (Bergman et al, 2013).

Not fully evaporated solvents are a food safety risk too. Because residual solvents are small molecules with a low boiling point, they can migrate rapidly through the packaging layers into the food (Hahladakis et al, 2018). Besides a potential food safety concern, they can cause an unpleasant odour in the food (Dow, 2017).

Furthermore, lamination adhesives contain small amounts of plasticisers (discussed in Section 5.1) and antioxidants (discussed in Section 4.3.2).

Box 5.5. Polymer considerations

Adhesive use increases the potential of migration of hazardous substances to food, increases the emissions of substances to air and soil and decreases recycling potential. The selection of a combination of polymers that do not require adhesive lamination is preferred.

Box 5.6. Chemical considerations

Concerns have been raised about multiple constituents of all the discussed adhesives. When weighing the sustainability aspects for adhesive selection, priority should be given to the health concerns and migration of curing agents and solvents to the food.

5.2.4. Multilayers and End-of-Use

Combining materials in multilayer films decreases the options of suitable sustainable end-of-use processes. To arrive at a truly sustainable packaging film, it should either be recycled or composted at end-of-use to retrieve the materials or nutrients. As will be discussed in Section 6.2, combining materials hinders mechanical recycling of plastic films and all non-polyolefin layers will be a contamination to the recycling stream. In case recycling is the intended EoU scenario, select a multilayer combination of PE and PP, with as few other substances as possible. When composting is the intended scenario, all components of the multilayer film should be compostable in the biodegradation conditions of organic waste facilities, as will be discussed in Section 6.3. Coatings that do biodegrade over time might still prevent moisture, oxygen, and/or organisms to reach other layers long enough to not be accepted in organic waste facilities.

Box 5.7. Polymer consideration

- In a multilayer film, a combination of polyolefin layers is preferred, due to the recyclability and the absence of plasticisers. Slipping agents are commonly used in polyolefins. These are of little concern but should be reviewed when incorporated in the film.
- Extrusion coating generally seem to be the most sustainable method, with regard to the required use of extra additives and amounts of material used. The use of primers before a coating can be of concern and should be thoroughly investigated.

5.3. Sealing

For the sealing of the packaging, one main choice has to be made: whether cold sealing or heat sealing is to be used.

Heat sealing is usually chosen in the application of a biscuit packaging because of the fast-paced filling lines. Heat sealing requires the selection of an easily heat sealable film (such as PE), or a heat sealable layer on the outside (and sometimes inside) of a multilayer. A heat-sealable coating can also be used. PVdC layers or coatings or EAA or EVA coatings are commonly used for this application (Mieth, Hoekstra and Simoneau, 2016). EAA or EVA coatings are preferred since there are no known associated health or environmental hazards. In the selection of a heat seal layer, it is important that the melting temperature of the heat seal is lower than that of the 'web', the main polymeric layer. The seal layers should melt together, while the web remains intact.

A possible drawback of the use of heat sealing is the creation of thermal degradation products of all substances embedded in the film. No study has been identified that has examined the occurrence and hazards of degradation products of polymer films due to heat sealing.

Cold sealing is the sealing of the packaging with an adhesive. This is uncommon in biscuit packaging but can be chosen when the requirements for heat sealing cannot be met. The selection of adhesives has been discussed in Section 5.2, under *Adhesion lamination*. Adhesives for cold sealing will be applied selectively to allow for 'peeling' when the consumer needs to open the packaging. In the case of cold sealing, the evaporation of the solvent and the emission of by-products from the chemicals setting need to be investigated more critically. Cold seals that are applied in an extrusion process before the packaging is filled are preferred to prevent the uptake of the odour of the adhesive by the biscuits.

5.3.1. Oriented films

Oriented films are made by stretching casted films in one direction (oriented, usually indicated with 'O' (e.g. OPP)) or two directions (bi-oriented, usually indicated with 'BO' (e.g. BOPP)). This will orient the molecules of the polymer in the direction of the stretching and consequently make the film thinner, reduce elasticity, and improve the gas and water vapour barrier (Ten Klooster, 2008). A benefit of this is that thinner film can be used while maintaining the barrier properties. A drawback is that the film is not as easily heat-sealed. This can be observed for BOPP and BOPET in Table 3.1 with material properties. To close a packaging with this material on a fast filling line requires a sealable coating. This can be done either by adhesively laminating a sealant layer to the BOPP or BOPET or by coating a layer that is sealable directly onto the oriented film.

Box 5.8. Polymer considerations

The use of oriented film can reduce the material use in the packaging but often requires a heat sealable layer or the use of an adhesive. A designer should consider the trade-off between the drawbacks of an extra component to the film and the benefits of reduced material use.

Box 5.9. Chemical considerations

- The use of heat sealing is preferred over cold sealing with an adhesive.
- The creation of thermal degradation products during heat sealing should investigated.
- In the selection of an adhesive for cold sealing, attention must be paid to the release of odour and hazardous substances in the curing to not spoil the biscuits.

Chapter 6. End-of-use

In this phase of the life cycle, the biscuit packaging is discarded by the consumer. In the polymer and chemical selection for a plastic packaging, it should be considered how the packaging will most likely be processed after being discarded. The available waste infrastructure will determine the choices that need to be made: the design of the packaging must fit the most sustainable option for processing at end-of-use. This includes collection and sorting of the packaging (discussed in Section 6.1). There are five end-of-use (EoU) scenarios that can be considered:

- Mechanical recycling (Section 6.2)
- Composting (Section 6.3)
- Incineration (Section 6.4)
- Landfilling (Section 6.4)
- Chemical (Section 6.5)

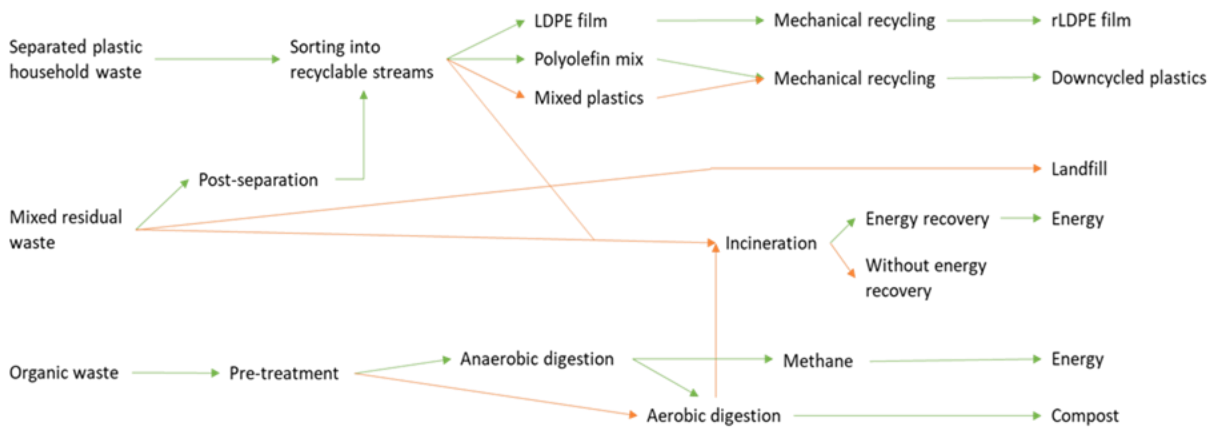
Although chemical recycling is discussed in Section 6.5, this is included to discuss potential future possibilities and restrictions. Currently, chemical recycling is not a viable EoU scenario to base design decisions on.

Three of the over-arching sustainable design goals are of importance in the end-of-use phase. The decisions to be made in the design of the packaging to (1) enable the closing of material loops; (2) how can the right chemical selection prevent exposure of waste management workers to hazardous substances; and (3) emissions of hazardous substances to the environment.

Littering of plastic packaging has detrimental effects on the environment but is not considered as an EoU scenario in this case study. Small plastic films for single serving food items such as candy bars are among the most littered plastic items. However, multi-packaging for collated biscuits is rarely littered, since it is usually eaten at home and not ‘on-the-go’. Littering can be considered for flexible packaging of other foods. When littering is a likely scenario, the use of plastic film should be reconsidered to prevent plastic pollution in the environment and the degradation of the film into microplastics. Biodegradable plastics cannot be regarded as a solution to littering. Each biodegradable plastic has its own specific degradation conditions. Whether it biodegrades depends on environmental factors such as the presence of the right microbes, levels of oxygen, moisture, acidity, UV, and temperature (Folino, Karageorgiou, Calabro and Komilis, 2020). The rate of the degradation is also influenced by these factors and the thickness of the plastic film. Littered packaging film can end up in different environments, such as on or in the soil, in moist or dry environments, in small fresh waterways or in the ocean, in animals, or in the urban environment. This means that there cannot be one single design of a biodegradable plastic to mitigate the problems of plastic littering. Alternatively, if the use of a plastic film cannot be prevented, the problems of littering can be addressed with policy interventions such as deposit refund schemes or extended producer responsibility legislation.

Figure 6.1 shows the possible EoU scenarios for plastic packaging film. Green arrows show the most sustainable routes, the possibilities are however determined by the availability of processing facilities and design of the packaging.

Figure 6.1. The different End-of-Use scenarios. The green arrows depict the most sustainable route per step in the scenario, depending on the available facilities and design choices made.



6.1. Waste collection & Sorting

When discarded properly by the consumer, packaging film can be collected via four main routes. Which one applies depends mostly on local availability of the collection system and on the composition of the plastic film. Note that in some countries informal waste collection methods provide input for recycling.

6.1.1. Collection

Residual waste

Currently, the most common route of collection is the municipal waste collection of residual household waste. The plastic film is mixed with food scraps and other unsorted materials. It might be sorted for recycling at a 'post-separation plant', sometimes also known as a 'post-collection separation plant' (see post-separation section below). Unsorted residual waste is either incinerated or landfilled.

Post-separation

Recent technological developments allow for separation of plastic packaging waste from mixed residual waste in post-(collection-)separation facilities. Availability of these sorting facilities is not widespread at the time of writing (late 2020). After sorting, the separated plastic will be transferred to plastic recycling plants or might be sorted a second time at plastic sorting facilities into different polymer streams.

Separated plastic packaging waste

If available, the packaging film can be discarded by the consumer through the separate collection of plastic packaging waste, pre-sorted from the residual waste by the consumer at home. Plastic packaging film is not collected in these systems in all countries. Multi-material plastic films such as combinations of plastic and aluminium or plastic and paper are not (yet) collected or sorted in these systems. After collection, it needs to be sorted in one of the material streams for further recycling. It is highly recommended that recyclability be indicated on the packaging. If the packaging is recyclable, the consumer should be reminded to properly discard it with recyclable plastic waste. If the packaging cannot be recycled using the facilities available, the consumer should be informed accordingly to prevent improper disposal and contamination of the recycling stream.

Organic waste collection

If separate collection of organic waste is available and the plastic film is (industrially) compostable, the film can be collected through this service. This should again be indicated on the packaging, preferably in a very noticeable way. If composting is the intended EoU scenario, verify that organic waste is separately collected in the region in which the biscuits will be sold.

Box 6.1. Design considerations

- Early on in the design process, an analysis of the available waste infrastructure in the intended sales market should be made on which to base design decisions.
- If available, an EoU scenario should be chosen and designed for that allows for the closing of material loops; either through recycling or composting.

6.1.2. Sorting

Sorting for mechanical recycling

Plastics that are either pre-separated in households or separated from the residual waste after collection are sorted in a few main polymer 'streams' before they are fit for recycling. The sorted and recycled streams vary per country. Usually rigid PET, HPDE and sometimes PP are sorted as individual streams. Plastic films are separated from the rest with a wind shifter and are either sorted as one residual stream of mixed films, or further sorted with near-infrared spectroscopy. LLDPE and LDPE are the main polymers used to make plastic films; PP is also very common. As can be seen in Figure 6.1, when films are further sorted, a mono-stream of LDPE / LLDPE can be sorted to be recycled into LDPE films again. This does currently require the film to have a surface area large than A4 paper size. It is assumed that the biscuit packaging film in this case study has a smaller surface area than A4. A mixed fraction of polyolefins (PE and PP) can also be sorted from the other films, after which the other films are diverted to incineration. Both the polyolefin and unsorted mix streams of plastic film are recycled into thick-walled low-grade products. All non-polyolefin substances in the material mix are contaminations to the stream and will decrease the quality of the recycled material, consequently increasing the required material use and production waste.

Box 6.2. Polymer considerations

Due to its size, the film will in any case be sorted in the fraction of mixed films or mixed plastic and be down-cycled in a low-grade plastic. All non-polyolefin substances in the material mix will be regarded as contaminants to the recycled plastic.

Sorting for organic waste treatment

Organic waste treatment and the sorting of collected organic waste are not standardised. Sorting methods, biodegradation conditions and processing times vary between organic waste facilities. This can cause problems for brand owners who want to use one kind of packaging for large sales regions in which multiple organic waste facilities are responsible for the processing of the compostable waste. Design teams are recommended to consult organic waste facilities in the intended sales region on the sorting methods and degradation conditions at their facilities.

Two separate methods can be distinguished based on the time the waste is sorted.

1. In some processes, collected waste is not sorted until after the biodegradation process. It is shredded into smaller pieces to increase the total surface area, mixed and processed by micro-organisms into methane and/or compost. It is then sieved to decontaminate the compost from metals, plastics, stones and other contaminants that decrease the quality of the compost.
2. In other processes, the collected waste will be checked for contaminants beforehand. This is mainly done in larger automated processes with sieves and wind shifters. Plastic film will in this case be sorted from the organic waste and diverted to incineration. In some cases, the sorting relies on human observation and manual sorting. In those cases, the compostable plastic film should be clearly recognisable as (industrially) compostable by the facility staff. This can be achieved by printing multiple large markings for compostable material such as the 'OK Compost' or 'seedling' logos on the packaging (note: these both require a certification process).

Biodegradable plastic packaging might still be sorted out by a composter. It generally does not add nutrients to the compost but does increase the throughput and thus decreases the efficiency of the process (KIDV, 2020). When anaerobic digestion is used, favourable amounts of methane can be produced from biodegradable plastics, which can be used to generate energy (Thoden van Velzen, de Weert and Molenveld, 2020).

6.1.3. Recycling rates

Plastic films are not well recycled. There are no reliable global statistics or specific statistics per polymer type. A World Wildlife Fund (June 2020) publication from 2020 estimated that globally only 2% of flexible packaging is recycled, while 22% is littered. This is based on information of five large industry partners. For Europe, statistics from Eunomia (2020b) can be used as indication, although only PE films are recorded. From the PE film used in household applications, 17% was recycled in 2018. In 2018 in the USA, about 10% of all plastic packaging film was collected for recycling (U.S. Environmental Protection Agency, December 2020). This included bags, sacks and wraps, and only LDPE, LLDPE and HDPE films were counted as 'recycled'. LDPE and LLDPE films contributed to 80% all recycled plastic film.

6.2. Mechanical recycling

As discussed above in the section on sorting, in the mechanical recycling scenario, sorting facilities for plastic packaging currently sort the biscuit packaging film in a fraction of mixed plastics or in a fraction of mixed polyolefin (PO) films. This is due to the size of the film, regardless of the chemical composition. To allow for the highest possible recycling quality of these streams, the film should:

- Be minimally 90% mono-PP, mono-PE layers, or mixed PO layers by mass (CEFLEX, 2020);
- Not contain PVC, PVdC, PET, biodegradable material, or foamed polymers other than POs (CEFLEX, 2020);
- Not contain aluminium, PA, oxo-degradable plastics or paper (KIDV, 2019).

If these requirements are not met, the packaging film contaminates the fraction, decreasing the efficiency of the recycling process and quality of the end product. This could for instance lead to blockage in the melt filters when the shredded material is re-melted to pellets, which in turn leads to the wasting of other recyclable material. When it ends up in recycled material, it will decrease the quality of the plastic, which increases production waste and required material for new products made with recycled plastics.

Box 6.3. Chemical considerations

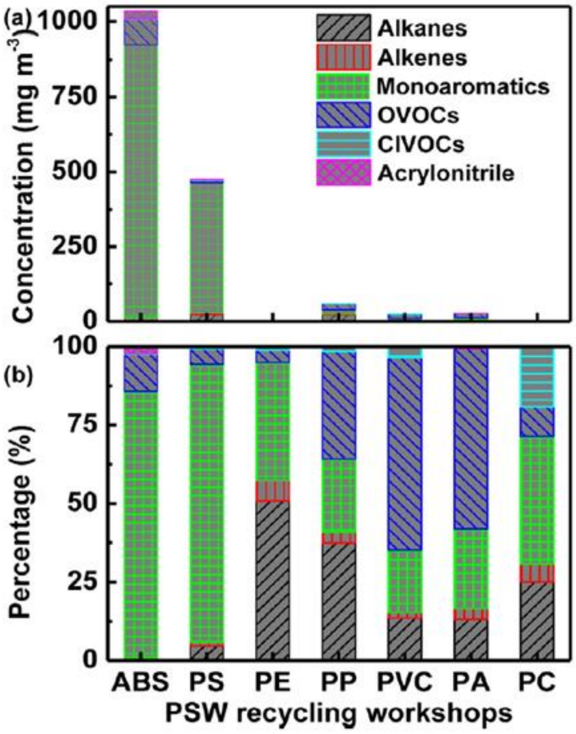
- To enable efficient mechanical recycling, the film should be made from mono-PE or PP layers or at least a multilayer containing 90% of polyolefins.
- It should not contain PVC, PVdC, PET, oxo-degradable plastics, biodegradable plastics, foamed non-polyolefin plastics, aluminium or paper.
- Other barrier layers or chemical additives are contaminants to the recycled plastic and, when combined, should not exceed 10% of the film’s mass.

6.2.1. Safety issues in plastic recycling

The melting of plastic creates fumes, also called Volatile Organic Compounds (VOCs). VOCs are often polymer degradation products. Other causes are additives or food residues attached to the plastic waste (Yamashita et al., 2007).

VOCs pose a serious threat to human health: the immediate effects are severe irritation to the eyes, nose and lungs. Prolonged exposure to fumes of any synthetic plastic with no safety precautions can lead to cancer, birth defects and illnesses (He et al., 2015). Examples of VOCs caused by the melting extrusion procedure in recycling are alkanes, alkenes, monoaromatics, oxygenated VOCs (OVOCs), chlorinated VOCs (ClVOCs) and acrylonitrile. Different polymers release different amounts and types of VOCs. Figure 6.2 provides an overview of the VOCs emitted per polymer type.

Figure 6.2. Concentrations (a) and contributions (b) of six groups of VOCs emitted in seven plastic solid waste recycling workshops during extrusion processes



Source: He et al., 2015.

Health risks for workers

As can be seen in Figure 6.2, PE and PP release relatively few VOCs (He et al., 2015). The pyrolytic temperature of PE and PP is 350°C, whereas the melt temperature in mechanical recycling is typically between 150 and 250°C. This explains the relatively low amounts of VOCs. Alkanes are the most emitted VOC for these polymers. Table 6.1 shows the most common VOCs emitted for the polymers.

In general, monoaromatic VOCs pose the biggest health risk. According to He et al. (2015) VOCs that are the major contributors to chronic health effects are benzene, toluene, ethylbenzene, styrene, methylene chloride and trichloroethylene. Inhalation of the monoaromatic VOC toluene, for example, can lead to severe neurological damage. Substances emitted with a major cancer risk (such as causing tumours in the lungs, liver, kidneys and brain via inhalation) are acrylonitrile, styrene, ethylbenzene and 1,2-dichloromethane (He et al., 2015).

Based on the research of He et al. (2015), it can be concluded that PVC and PA release the most harmful VOCs when melted, with PE the safest polymer in the comparison. For mechanical recycling of PET, less information is available concerning health issues. However, it is known that when melting PET, VOCs are emitted (Liu et al., 2018), which is thus expected to have negative environmental effects. How this compares to other polymers is unknown.

Additionally, the research of He et al. (2015) expects that residents living close to plastic recycling plants with limited safety measures, have a potential cancer risk due to the processing of PS, PA, ABS and PVC. For PE and PP, the VOCs of particular concern are acrylonitrile, 1,2-dicloroethane, styrene and benzene.

Table 6.1. The three most emitted VOCs for PE, PP, PA, PVC and PET

	PE	PP	PA	PVC	PET
1	i-pentane (20.4%)	Cyclopentanone (20.6%)	Cyclopentanone (25.1%)	Cyclopentanone (33.1%)	acetaldehyde
2	n-undecane (13.5%)	3-hexanone (10.2%)	2-ethyl-cyclopentanone (10.8%)	n-butanol (22.1%)	benzene
3	Toluene (10.3%)	Styrene (11.2%)	methyl methacrylate (7.2%)	methyl methacrylate (4.8%)	benzaldehyde

Sources: He et al., 2015 and Liu et al., 2018.

Box 6.4. Polymer considerations

When polymers are melted in an extruder during mechanical recycling, VOCs are formed as degradation products. Exposure to fumes of any synthetic plastic with no safety precautions can lead to cancer, birth defects and illnesses.

- PE and PP emit relatively low amounts of VOCs during recycling and are therefore preferred.
- If rPET is selected as a polymer, it should be sourced from a certified recycler that has taken all necessary safety precautions.

6.2.2. Risk reduction

There is a broad difference between recycling facilities in safety measures taken regarding VOC emissions. In many facilities in developing countries, these VOCs are discharged directly into the air without any ventilation or treatment (He et al., 2015). Workers in these areas are thus at high risk of health issues. In modern facilities, ventilation and air treatment are present that reduce the risks for workers and residents in the area. See the article by Khan & Kr Ghoshal (2000) for the various options for removal of VOCs from the air.

According to Yamashita et al., (2007), fewer VOCs are emitted at lower temperatures, based on the melting of LDPE. When the melting temperature was reduced from 250°C to 200°C, VOC emissions drastically decreased (by over 80%). Lowering temperatures to 150°C resulted in a further reduction of VOCs. Additionally, it was found that lower oxygen levels also reduce the VOCs emitted during the plastic melting process.

6.2.3. Risks associated with mechanically recycled plastic

Mechanically recycled plastic packaging film will most likely be ‘downcycled’ plastic products: public benches, roadside marker posts and riverbed bulkhead, for instance. With improved sorting technology and the use of mono-material films, biscuit packaging might in the future be recycled into non-food contact consumer products. However, little is known about the long-term risks of the use of recycled plastic in these applications. Studies have been done into the leaching of substances from recycled plastic in food-grade applications, although mainly focused on PET bottles (Geueke, Groh and Muncke, 2018). An unknown mix of chemical substances can be hazardous in non-food applications too, but this has not been properly studied.

This report highlights the complex chemical composition of biscuit packaging film. The substances and their degradation products will be incorporated in the recycled plastic. When it is applied in outdoor products, heating, abrasion and other external influences will increase the risk of leaching of chemicals to the environment and the release of microplastics. One study on the subject concludes that there is low risk of chemical leaching from recycled plastic (Xie et al, 1997), while another study concludes that there is a significant impact (Weis, Weis, Greenberg, and Nosker, 1992). These studies are respectively 23 and 28 years old, thus a new study with present-day recycled plastics is desirable.

When recycled plastic is used in consumer products, more factors should be taken into account: shedding of micro particles in an indoor environment, inhalation and skin contact by humans.

Designers can consider these issues in the packaging design by understanding that all additions to the film that are non-polyolefin plastics will add contaminants to the recycled plastic. This will decrease the quality of the recyclate, which in turn increases the risks of shedding of microplastics, increases the amount of plastic required to perform the intended function, and increases the number and quantity of contaminants that might leach from the plastic.

Box 6.5. Polymer considerations

For the safety of the created recycled plastic, keep the proportion of polyolefins in the plastic as high as possible and minimise the incorporation of additives and other contaminants.

6.3. Composting

Industrial composting of film in an organic waste facility is possible for two of the shortlisted polymers in this case study: PLA and regenerated cellulose. For more information on possible biodegradable and compostable plastics, please refer to EUBP (2020), Eunomia (2020b), Folino, Karageorgiou, Calabro and Komilis (2020), and Van den Oever, Molenveld, van der Zee and Bos (2017).

To regard composting as a sustainable EoU solution, the plastic film must break down into water, CO2, and other natural occurring substances without negative effects on the quality of the compost. It should not contain or create substances in the composting process that are harmful to living organisms. The composting process should be completed in a timespan and in biodegradation conditions that are normally achieved in industrial composting installations. Multiple standards (TÜV Austria, 2019) and certificates (EUBP, 2017) are created to confirm that compostable packaging is indeed compostable. However, conditions vary per organic waste facility. Therefore, it is prudent to verify with local composters in the intended sales market that the designed packaging is suitable for their specific process in terms of processing time and biodegradation conditions.

For complete composting, all components of the packaging film should adhere to the compostability requirements, including adhesives, barrier layers and inks. To do so, it is suggested that as little complexity is added to the packaging as possible. Aluminium oxide (AlOx) and silicon oxide (SiOx) can be used as barrier layers in compostable plastic film (Thoden van Velzen, de Weert, and Molenveld, 2020), because SiOx is a naturally occurring substance and small amounts of aluminium can be considered a trace element that is necessary for biological activity. Inks are usually not compostable, but inks with compostable binders and only small residues of harmless pigments and inorganic fillers exist (EuPIA, 2020). Biocides are added to biodegradable plastics to slowdown the degradation of the plastic during the use phase. These can however have a negative effect on the quality of the compost.

Box 6.6. Polymer and chemical considerations

- If composting is chosen as the desired EoU scenario, the main polymer and the barrier layers should be compostable in industrial composting processes available in the intended sales market.
- Biodegradability of the additives should also be considered. Substances such as inks and adhesives require extra attention because of the amounts in which they are used.
- The use of biocides should be excluded.

6.4. Incineration and Landfilling

6.4.1. Incineration

A huge amount of plastic is still incinerated today, usually for energy recovery. In Europe alone, 42.6% of all post-consumer plastics are incinerated (PlasticsEurope, 2019). However, incineration of plastics is not without risks. Besides the emission of greenhouse gases, there is growing concern about the potential atmospheric release of hazardous substances during incineration. Substances can be released as gases, soot and residue solid ash (Okunola A et al., 2019; Valavanidis et al., 2008). Substances include halogenated additives, furans, dioxins, polychlorinated biphenyls (PCBs), volatile and semi-volatile organics, polycyclic aromatic hydrocarbon (PAHs) and toxic metals.

- **Gases are produced** with the pyrolysis or combustion of even a simple synthetic polymer (Nkwachukwu et al., 2013), such as hydrogen chloride and hydrogen cyanide. Most of these gases are self-toxic, i.e. interfering with the normal biochemical processes of the body. The type and concentration of gases differ per polymer.
- **Halogenated additives** can be found in some pigments. During combustion, small amounts of volatile organohalogen compounds will be formed. These combustion products are likely to be persistent, bio-accumulative, and toxic (Cradle to Cradle Products Innovation Institute, 2019). Furthermore, burning of PVC produces halogens that may pollute the air (Verma et al., 2016).
- **Dioxins, furans and polychlorinated biphenyls (PCBs)** are produced during the manufacture of materials containing chlorine, such as PVC (Nkwachukwu et al., 2013). Burning these plastics can release dioxins. Open burning of such plastics must be avoided. Controlled incineration drastically reduces dioxin release, by controlling the incineration process, cooling of post-combustion gases and reducing the presence of specific metals such as copper (Lali, 2018). Dioxins, furans and PCBs have a high carcinogenic potential for humans.
- **Polycyclic aromatic hydrocarbon (PAHs)** are chemical compounds containing only carbon and hydrogen, composed of multiple aromatic rings. Some PAHs are carcinogenic and mutagenic. PAHs have been detected in soot at relatively high concentrations (Valavanidis et al., 2008), including PAHs known for their carcinogenic potential (e.g. Benz[a]anthracene, Benzo[a]pyrene, Indeno[1,2,3-cd]pyrene and Benzo[k]fluoranthene with fused rings).
- **Toxic metals** such as Pb, Cd, Cr, Cu, Ni are found in soot and residue ashes (Valavanidis et al., 2008), although their concentrations are very low. The highest levels of toxic metals were found when burning PVC.

Health effects

Without suitable safety measures, release of these substances during incineration poses a threat to human health, in both workers and residents living nearby, and to the environment. Substances are released that are highly toxic and can cause cancer. Soot can end up in the surrounding environments and thus end up in the soil or water. Additionally, the ash created in combustion are toxic. When these are not disposed of safely, they can contaminate the environment.

According to Nkwachukwu et al. (2013) "*a few of these pollutants, such as mercury, PCBs and dioxins, persist for long periods of time in the environment and have a tendency to bio-accumulate. … In wildlife, the range of effects associated with these pollutants includes cancer, deformed offspring, reproductive failure, immune diseases and subtle neurobehavioral effects. Humans can be exposed indirectly just like wildlife, especially through consumption of contaminated fish, meat and dairy products*."

Safety measures

According to Nkwachukwu et al. (2013), plants compliant with the EU Waste Incineration Directive are not thought to have any significant environmental impact. To prevent pollution of the atmosphere, soil and groundwater, all incinerators must have a suitable filter system for toxic substances. Additionally, the disposal of ashes and slag have an environmental impact. For example, flue gas cleaning residues must often be disposed of as hazardous waste due to the toxicity of the compounds they absorb.

Due to the risks involved in plastic incineration and loss of valuable materials, incineration is an unsustainable and highly undesirable EoU scenario for plastic packaging film.

6.4.2. Landfilling of plastics

This section describes the chemical considerations related to landfilling of plastics. It must be noted that landfilling is not a preferred disposal route and should be avoided. However, globally 80% of plastics was accumulated in landfills between 1950 and 2015 (Geyer, Jambeck and Law, 2017). The capacity of landfills is finite: the disposal of plastics in landfill is not an activity that can be sustained over time (Scott & Hannan, 2006). Plastics degradation is extremely slow and thus the material will not quickly decrease in volume. As other types of waste degrade, plastic remains. This means that the volume of plastic in landfills accumulates over time.

Additionally, landfills are an unsafe method for disposing of plastics. Leakage of additive chemicals to the soil and marine environment occurs, transferring these chemicals to animals and humans. In addition, wildlife ingests or is entangled in plastic waste and microplastics are created (Scott & Hannan, 2006). Because research on the effects of plastics in landfills, and the environment in general, is still relatively new, there remains much uncertainty. The long-term effects in particular are difficult to gauge. However, there is a consensus that plastic in the environment has negative effects and must be avoided.

Microplastics

Over time, plastic in landfills degrades and decomposes over hundreds or thousands of years, gradually fragmenting into microplastics and nanoplastics. Microplastics can migrate beyond the landfill, e.g. through the air or the aquatic environment, enter the food chain and pose risks for human health for example through:

- Microplastics ingested by fish and shellfish (Thompson, 2015).
- Microplastics can be absorbed by roots of crops (Li, L et al., 2020).
- Microplastics found in tap water (Kosuth, et al., 2018) and bottled water.

Much is still unknown about the effects of microplastics and nanoplastics. Large quantities of plastics have only been present in the environment for a relatively short period of time. It is therefore difficult to gauge its consequences.

A type of plastics that causes particular risk for creation of microplastics are degradable, as opposed to biodegradable, polymers (known as oxo-(bio)degradable). According to Thompson (2015) "Oxo-degradable polymers are designed to break down under UV exposure and/or dry heat and mechanical stress, leaving small particles of plastic They do not degrade effectively in landfills and little is known about the timescale, extent or consequences of their degradation in natural environments." Oxo-degradable plastic should not be used in plastic film. Use of oxo-biodegradable plastics is prohibited by the EU starting 2021, as part of the SUP directive[1].

Leakage of additive chemicals into the environment

Additive chemicals in plastic in landfills can leak into the environment. This results in a polluted environment around the landfills and can end up in aquatic environments. Additives of particular concern are phthalate plasticisers that might be used in inks, adhesives, and have in the past been used in cellulose film and PVdC coatings, and anti-microbial agents that can be used in biodegradable films to delay the degradation process (Thompson, 2015).

Phthalate plasticisers can leach out of products because they are not chemically bound to the plastic matrix. Phthalates are endocrine disruptors that interfere with the normal hormonal mechanisms that allow a biological organism to interact with its environment (Diamanti-Kandarakis et al., 2009). Not all plasticisers are phthalates, although phthalate plasticisers are common.

Both ethoxylated amines and polyethyleneimines have long lasting toxic effects on aquatic life. Ethoxylated amines are used as anti-statics and polyethyleneimines can be used as primer for coated multilayer films or as primer for adhesive laminated films.

Box 6.7. Design consideration

Incineration of plastics is unsustainable and the use of landfill is highly undesirable. Adhere to design for recyclability guidelines to increase chances that the packaging will end up in a recycling stream.

Box 6.8. Chemical considerations

- Prevent use of oxo-degradable plastics: degradability of these plastics is not achieved in the landfill environment. These types of plastics also have negative effects when they end up in the recycling stream.
- Prevent additives that can leak into the environment: phthalate plasticisers, anti-microbial agents, ethoxylated amines and polyethyleneimines.

6.5. Chemical recycling

Chemical recycling of the packaging film is included in this case study to refer to the possible future options and restrictions. The current availability of chemically recycled plastics comes from pilot plants and carefully selected and sorted waste. The environmental benefits of the technologies are not yet proven. Chemical recycling promises to be a solution for hard-to-recycle plastic waste such as mixed plastic film that varies in composition or is too contaminated for mechanical recycling. However, it is currently not available on a scale that it should be taken into consideration in packaging design or has been developed far enough to be regarded as the sustainable solution for the future.

Chemical recycling is an umbrella term for a range of different processes that break down polymers to monomers or other chemicals that can be used to make new plastics or other useful products. Summarising from WRAP (2019), Thoden van Velzen, de Weert, and Molenveld (2020), Eunomia (2020a) and Solis and Silveira (2020):

- **Solvolysis:** A process still in development, with a few companies operating pilot plants. PET, PLA or PA are converted to monomers and oligomers for plastic production. For an efficient process, it requires carefully sorted waste from the targeted polymer as input.
- **Selective dissolution:** A process in which a specific polymer is dissolved from mixed waste, laminates, or from sorted but contaminated plastic waste. The specific polymer can be recovered for plastic production after an elaborate filtration and precipitating process, the rest is still waste. This is also still in the pilot phase.
- **Pyrolysis and gasification:** Mixed plastic waste is broken down into char and gas or oils of smaller hydrocarbons, which can be used as fuel, as a product such as lubricating grease, or can be further refined into monomer building blocks for polymer production. For efficient processes, sorted plastic containing predominantly polyolefins is required.

It should be noted that the processes with fuel as output or chemical downcycling should not be regarded as solutions to close material loops. Only processes that result in a secondary raw material that can be used in the production of plastic products should be regarded as truly circular recycling methods.

In theory, all processes are able to process a mix of plastics. However, for efficiency and an environmental benefit, the waste should be pre-sorted and the films should contain as much of one of the targeted polymers as possible. All other contaminants in the throughput reduce the efficiency of the process.

Box 6.9. Design considerations

Chemical recycling is currently not a plausible EoU scenario and should not be taken into consideration in the packaging design. When chemical recycling becomes a serious sustainable option, the packaging should contain as much of the specific targeted polymers as possible. In the current technology, those polymers are PET, PA or polyolefins.

Note

[1] More information on the SUP Directive can be found here: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52018DC0035&from=EN

Chapter 7. Key considerations and Trade-offs

7.1. Key considerations

Key considerations are the most important sustainability aspects on which polymer selection should be based. For biscuit packaging film, the following hotspots are identified per life cycle phase.

7.1.1. Sourcing

- In the selection of the main polymer for the film, the overall sustainability of the feedstock must be considered. This includes potential hazards in secondary feedstock and unsustainable agricultural practice for renewable feedstock.
- Availability of polymers from renewable or secondary feedstock is limited to rPET, BioPE, PLA and regenerated cellulose.
- Polymers from primary non-renewable feedstock should be readily recyclable to be considered sustainable, but plastic films of this size are currently only ‘downcycled’ to low-grade applications.

7.1.2. Production

- Plasticisers are used in the production of plastic film from regenerated cellulose and PLA and in PVdC coatings. Plasticisers are associated with multiple hazards. Either the used plasticisers should be thoroughly investigated, or these polymers should be excluded from further consideration.
- If a multilayer is selected, extrusion coating generally seems to be the most sustainable method, with regard to the required use of additives and amounts of material used. PEs, PP and EVA are commonly used as extrusion coating. The use of primers before coating can be of concern and should be thoroughly investigated.
- The use of oriented film can reduce the material use in the packaging but requires a heat sealable layer or the use of an adhesive to seal the packaging. A designer should consider the trade-off between the drawbacks of an extra component to the film and the benefits of reduced material use.

7.1.3. Use phase

- To satisfy all functional requirements in the selection of a polymer, a trade-off needs to be made between increased material use (i.e. thicker film) and the combination of materials in a multilayer film. Multilayering will have consequences such as increased hazards from additives and decreased recyclability.

7.1.4. End-of-Use

- The available waste infrastructure in the intended sales market determines the end-of-use scenario that can be designed.
- Mechanical recycling of the plastic film will result in downcycled plastics due to the size of the packaging. For the best possible recycling, a mono-material PE or PP film should be chosen, or alternatively a multilayer film with at least 90% polyolefins and minimal incorporation of additives.
- All components of a compostable film should compost in the biodegradation conditions of an organic waste facility. PLA and regenerated cellulose are the only polymers on the shortlist that (can) meet this requirement.
- Incineration and landfill cannot be deemed as sustainable scenarios, and chemical recycling technology is not mature and widespread enough to act as a basis for design decisions.

7.2. Trade-offs

The decisions or constraints in one phase of the life cycle influence the possibilities in the other phases. The table below indicates how constraints set in the top row of the table influence the phases in the leftmost column.1.1.2Scope: focus on plastic film

Table 7.1. Dependencies between decisions and constraints in one life cycle stage to the other stages.

How → Influences ↓	Sourcing	Production	Use	End-of-Use
Sourcing		The selected method of film production can require the use of specific additives.	Requirements on food safety and barrier properties limits sourcing options.	A preferred EoU scenario limits the number of possible materials.
Production	Available materials might require specific production methods and additives.		Barrier properties require bonding of multiple materials.	Recycling or composting preference limits the use of laminated films and additives.
Use	Properties of the available materials might not meet requirements.	The production method requires additives that might migrate to the food.		Preferred EoU scenario limits the use of combined materials with optimal properties.
Enf-of-Use	Selected polymers and their required additives might limit the EoU options.	Lamination of the materials decreases the recyclability and compostability.	Required barrier properties lead to materials with low recycling potential.	

Food safety and safety of the staff in waste management facilities is a constraint that should not be compromised. The main trade-offs that need to be made are choices regarding the material properties and the shelf life of the product versus the sustainable sourcing of the material and the recycling potential. Below, the main trade-offs are listed, along with their corresponding sustainable design goals. As such, a trade-off between the goals can be made, and the implications on the design of the packaging can be weighed.

Close material loops & Guard health of participants in the life cycle	*vs*	*Prevent product spoilage*
A monolayer film is used. This improves recyclability and decreases the number of different substances used in the film, decreasing potential hazards, although this also decreases the barrier properties of the film.	**or**	A multilayer film is used. The biscuits are preserved longer but the recycling potential of the packaging is decreased, and more layers mean more potential hazardous substances.

Close material loops	*vs*	*Reduce material use*
The same barrier requirements are met with a monolayer film, but more material is needed.	**or**	Materials are combined and less material is used, but the recycling potential of the packaging decreases.

Preserve natural capital & Close material loops	*vs*	*Prevent product spoilage*
Renewable or secondary feedstock is selected, but the barrier properties decrease, and the biscuits have a shorter lifespan.	**or**	The biscuits are preserved longer, but a non-renewable primary feedstock is selected.

For the last trade-off, it should be noted that only bioPE is both renewable and recyclable. PLA and regenerated cellulose are both renewable but not compostable in all organic waste facilities. '*Guard health of participants in the life cycle*' is not mentioned in this trade-off, but potentially hazardous plasticisers can be used in PLA and cellulose film, and rPET has increased risks for NIAS. These issues can be resolved by thorough screening.

Chapter 8. Material Assessment

8.1. Material choice matrix

In this chapter, an example of a material choice matrix is given. The matrix can be used by a designer to select the most sustainable polymer. Once a polymer is selected, an in-depth chemical safety analysis follows for the selected polymer only. This method is explained in Section 2.2.

The material choice matrix on the next page is an example, with criteria and information gathered within the limits of this case study. It is not to be regarded as an all-encompassing advice on the most sustainable plastic packaging film for food.

To create the material choice matrix, the shortlist of material options is checked with the sustainability considerations regarding the polymer selection. Each material is ranked with colours for each criterion, with dark green being an excellent score and red being a very low score. A designer can choose a large range of colours if more distinction between materials needs to be made. The colour coding facilitates a quick overview of the differences between the materials. More important criteria are printed in bold to indicate their importance. The top row of the table lists the polymers and coatings. As such, combinations of materials can also be assessed. Two conflicting criteria can be incorporated in the matrix, compostable and recyclable in this case study, for example.

Based on the results of the table in the example, in this case study a combination of BOPP, for its barrier properties and strength, and an LDPE coating (for heat sealing) seems the most sustainable option. LDPE can be applied on the BOPP film through an extrusion coating process (Lyondellbasell, 2005). Both polymers are polyolefins that will not contaminate the recycling stream. In the future, the best option might be a PP film sourced from chemically recycled PP and an LDPE coating derived from renewable feedstock.

Table 8.1. Example of material choice matrix with criteria and information gathered within the limits of this case study. It is not to be regarded as an all-encompassing advice on the most sustainable plastic packaging film for food. Each material is ranked with colours for each criterion, with dark green being an excellent score and red being a very low score.

	LDPE / LLDPE	HDPE	PP	BOPP	PET	BOPET	PA	PLA	Regenerated cellulose	Acrylics	PVdC	EVOH	EVA
Vapour barrier													
Heat sealable													
Toughness													
Renewable feedstock													
Secondary feedstock													
Little risk of hazardous prod. additives													
Compostable													
Recyclable													
Limited risks in recycling													

8.2. Chemical considerations

Once a polymer is selected, relevant chemical considerations need to be revisited to make decisions in the production process and for a safe and sustainable chemical selection. This section provides a summary of all the chemical considerations encountered during the analysis of the life cycle.

8.2.1. Sourcing

- Regarding screening by the supplier:
    - Screening for residual substances in the plastic from the polymerisation process remains a point of attention for the supplier. The substances used in these processes are known, thus targeted analysis of plastic can be performed to determine whether residues are left in the material.
    - Potential hazards from NIAS remain a point of attention, regardless of chosen polymer or feedstock.
    - Special attention should be paid to NIAS in case of secondary feedstock due to the increased risk of contamination and degradation products.
    - Designers cannot screen material themselves but should demand from their producers or suppliers that the material is screened for reasonably expected NIAS. New material formulations should be screened extensively to identify potential additional NIAS.
- Regarding functional additives:
    - It should be considered whether the addition of the chemicals to the plastic is indispensable and only tested confirmed unhazardous additives should be used.
    - For the specific case of biscuit packaging film, heat and oxidation stabilisers remain the most important additives to look out for. Both because of migration into the food and hazards in the end-of-use phase.
    - Specifically, when biodegradable films are chosen, the use of biocides requires extra attention.

8.2.2. Production

- Regarding production additives:
    - Refrain from the use of an antistatic agent where possible. When used, potential hazards should be reviewed.
    - Other production additives are of lower concern, although impurities and migration from lubricants should be further investigated.
- Regarding multilayer film production:
    - The use of coatings greatly reduces the material use, with the associated benefits in sourcing, recycling and the risk of contamination.
    - Primers might be required in the case of extrusion lamination and adhesion lamination. Primers are associated with potential hazards and should be thoroughly investigated.
    - Extrusion coating is preferred over dispersion coating to eliminate the use of curing agents and primers and their associated hazards.
    - Concerns have been voiced about multiple constituents of adhesives. When weighing up the sustainability aspects for adhesive selection, priority should be given to the health concerns and migration of curing agents and solvents to the food.

- Regarding sealing
  - The use of heat sealing is preferred over cold sealing with an adhesive.
  - In the selection of an adhesive for cold sealing, attention must be paid to the release of odour and hazardous substances in the curing to not spoil the biscuits.

8.2.3. Use phase

- Chemical considerations in this phase focus on the use of inks, since other considerations have been discussed for the polymer selection.
  - Inks consists of a wide range of possible chemical additives, and thus potential hazards.
  - Due to their share and function in the ink, the pigment and solvent are the most scrutinised. Sustainable, hazard free alternatives for these substances are available.
  - Potential hazards of other constituents of the inks might be less well known. Specifically, inquire about other potential hazardous constituents when discussing inks with a supplier.
  - Use as little ink as possible in your design, even when safe inks without associated human health hazard are chosen.
  - Carefully chosen EB curing inks seem to be the most sustainable choice when focusing on the ink alone. However, these inks can only be surface printed and require the right machinery.
  - Surface printed inks come with health risks regarding contamination and spreading of the inks, this method should only be chosen if all constituents of the ink are deemed safe.
  - Reverse-printed inks require lamination, which has its own associated health risks and consequences in recycling and biodegradation.

8.2.4. End-of-use

- For mechanically recycled plastic film:
  - To enable efficient mechanical recycling, the film should be made from mono-PE or PP layers or at least a multilayer containing 90% polyolefins.
  - It should not contain PVC, PVdC, PET, oxo-degradable plastics, biodegradable plastics, foamed non-polyolefin plastics, aluminium, or paper.
  - Other barrier layers or chemical additives are contaminants to the recycled plastic and should when combined not exceed 10% of the film's mass.
  - For the safety of the created recycled plastic, keep the proportion of polyolefins in the plastic as high as possible and minimise other additives.
- For compostable film:
  - If composting is chosen as the desired EoU scenario, the main polymer and the barrier layers should be compostable in biodegradation
  - Biodegradability of the additives should also be considered. Substances such as inks and adhesives require extra attention because of the amounts in which they are used.
  - The use of biocides should be excluded.
- In case of landfill or incineration:
  - Prevent use oxo-degradable plastics: degradability of these plastics is not achieved in the landfill environment. These types of plastics also have negative when they end up in the recycling stream.
  - Prevent additives that can leak into the environment: phthalate plasticisers, BPA, brominated flame retardants, anti-microbial agents.

Chapter 9. Policy considerations

This case study leads to insights about current practices that inhibit genuinely sustainable use of plastic food packaging film. Six considerations for policy development and research by regulatory bodies are proposed.

Note that these considerations mainly concern the safe and circular application of plastic packaging. However, it should be kept in mind that the circular economy is a means to an end of a sustainable future, not a goal in itself. The ambition should focus on minimising resource use and overall environmental impact.

Discourage the use of potential hazardous substances

Some substances with known or suspected hazards are used to perform functions in food packaging film, despite the existence of alternative substances. These alternatives commonly have as a drawback that they are not commercially attractive due to higher costs, lower process efficiency or incompatibility with currently installed machinery. Policies should be developed to discourage or in some cases ban the use of potential hazardous substances, either through financial instruments such as taxes, through extended producer responsibility, or by prohibiting the use of the substance in certain applications, depending on the nature of the hazard and the exposure risk unless it is demonstrated that the substance causes no harm.

Deposit refund schemes for large flows of plastic packaging to increase availability of recycled food-grade plastic

The availability of recycled food-grade plastic is too limited. This is partly due to strict regulations on the use of recycled plastic in food contact applications. This report provides an overview of the (potential) hazardous substances that an uncontrolled or loosely controlled stream of recycled plastic can contain. The current regulations are not overly strict but are required to maintain safe food contact materials. The recycling stream of food-safe PET originates from separately collected bottles in deposit refund schemes. In Europe, a voluntary industry initiative exists that provides guidelines on PET bottles for all producers to adhere to. This results in a somewhat uniform recycling stream that improves the recyclability and safety of the recycled plastic. Deposit refund schemes and uniformity among producers could also be used to improve and collect other large flows of plastic packaging: for example, HDPE milk bottles and PP jars for different food applications. Packaging films are too light and too complex to design uniformly and to be collected separately. An investigation should be conducted into the types of plastic packaging that are suited for this kind of uniform design and collection.

Mandatory safety standards for plastic recyclers and waste incinerators

Poor recycling and waste management practices can lead to the emission of hazardous substances. This poses risks both through occupational exposure of workers as well as through emissions to the environment and to close-by residential areas. The risks can be reduced with solutions such as vacuum extrusion, strict control of extrusion temperatures, proper ventilation and air treatment. Regulatory bodies should create mandatory standards for recyclers and waste incinerators based on best available practices.

Develop End-of-Use scenario for compostable plastic film

Compostable plastic packaging film is currently not a viable sustainable option. If it is discarded improperly, it will have no benefits when incinerated, can cause problems when it enters the plastic recycling stream and is not a solution to littering of plastic packaging. Biodegradation conditions and processing time vary between organic waste facilities, meaning that no design decisions can be made that are valid for a broad range of sales areas. In addition, the compostable packaging does not contribute to the quality or nutrients of the compost when it degrades. Organic waste facilities regard the packaging as an inefficiency that adds to the throughput but not to the final product. To make compostable plastic film an option, collection and processing of compostable organic waste needs to be uniform in large regions. Certified compostable packaging needs to be readily distinguishable by both consumers and staff at the organic waste facility. Financial schemes must be set up to reward composters for processing the material. If these barriers cannot be overcome, it is preferable to focus on a good recyclable film as when recyclable and compostable film exist side by side it is not clear to the consumer and there is contamination of either the recyclable flow or the compostable flow.

Research long-term environmental impacts of using recycled plastic in non-food applications

To the best of our knowledge, no extensive research has been done into the long-term effects of the use of recycled plastics in non-food contact applications. How do different environmental conditions affect the creation of micro-plastics and leaching of (potential) hazardous substances from different kind of recycled plastics? What are the hazards of the leached substances in different environments? These questions should be addressed in dedicated studies.

Encourage transparency within the supply chain

Encourage full disclosure of information on material composition and additive substances used in the packaging within the supply chain. As such, purchasers would gain more insight into the current use of substances in their packaging film (or other packaging) and could steer towards more sustainable and recyclable material compositions. Another benefit of transparency could be in the certification of recycled plastics. Prices of recycled materials are sometimes higher than those of virgin counterparts, which is especially the case for PET. In the market, virgin PET is sometimes sold as recycled PET. To prevent such practices, it is recommended to promote development of certificates for recycled plastics with chain-of-custody traceability.

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This case study on biscuit wrappers was developed to provide input to and inform the development of general considerations for design of sustainable plastics from a chemical perspective. Four case studies were developed as concrete examples and included two in the plastic packaging sector (biscuit wrappers and detergent bottles) and two in the construction sector (flooring and insulation). For this purpose, the case studies start from the premise that plastic material will be used and therefore alternative material selection is not considered. They identify the key considerations regarding environmental/health sustainability that should be examined along the product life cycle when chemicals are selected at the design stage, as well as the potential trade-offs between these considerations.

The examples of material selection within the case studies are developed in the context of the information gathered for the case studies to exemplify the sustainable design process and to highlight key considerations. To make actual decisions about material selection other factors would also need to be considered and the analysis could be further informed by elements such as life cycle assessment comparing alternatives and a full review of regulatory restrictions.

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