Science Advice for Policy by European Academies

BIODEGRADABILITY OF PLASTICS
IN THE OPEN ENVIRONMENT

SAPEA

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Biodegradability of plastics in the open environment

Informs the Scientific Opinion of the European Commission's Group of Chief Scientific Advisors

About the cover artwork

By conducting our daily activities blinded by routine, we forget to take a moment to look and see what is surrounding us. *Freathy*, taken from a collagraph series titled *Re(f)use*, has been created using littered plastics, packaging and fishing net collected from its titled location. It captures the natural beauty that we as consumers may overlook or take for granted. The work's purpose is to challenge the destructive behaviours of our society on the environment and initiate positive and effective steps towards ecological sustainability.

About the artist

Heather Nunn studied BA (Hons) Fine Art at Plymouth University in the UK, where she discovered a love for printmaking. Through her work, she expressed her passion for the environment whilst challenging the imbalances between modern society and nature, comparing the beauty to the ugliness of our existence. She spent her time at Plymouth University working alongside the Sustainable Earth institute and was awarded the Sustainability Prize 2016 for her works *Re(f)use* and *(Ex)change*.
Instagram: @heather.ln
Facebook: Heather Nunn Printmaker

Version history

Version	Date	Summary of changes
1.0	14 December 2020	First published version
1.1	18 December 2020	Fixed typos; fixed referencing errors; updated table of contents

About SAPEA

SAPEA (Science Advice for Policy by European Academies) brings together outstanding expertise in engineering, humanities, medicine, natural and social sciences from over 100 academies, young academies and learned societies across Europe.

SAPEA is part of the European Commission's Scientific Advice Mechanism. Together with the Group of Chief Scientific Advisors, we provide independent scientific advice to European Commissioners to support their decision-making. We also work to strengthen connections between Europe's academies and Academy Networks, and to stimulate debate in Europe about the role of evidence in policymaking.

The Evidence Review Report informs the Scientific Opinion of the Group of Chief Scientific Advisors.

Funded through the EU's Horizon 2020 programme, the SAPEA consortium comprises five Academy Networks: Academia Europaea (AE), All European Academies (ALLEA), the European Academies' Science Advisory Council (EASAC), the European Council of Academies of Applied Sciences, Technologies and Engineering (Euro-CASE), and the Federation of European Academies of Medicine (FEAM).

For further information about SAPEA, visit www.sapea.info.
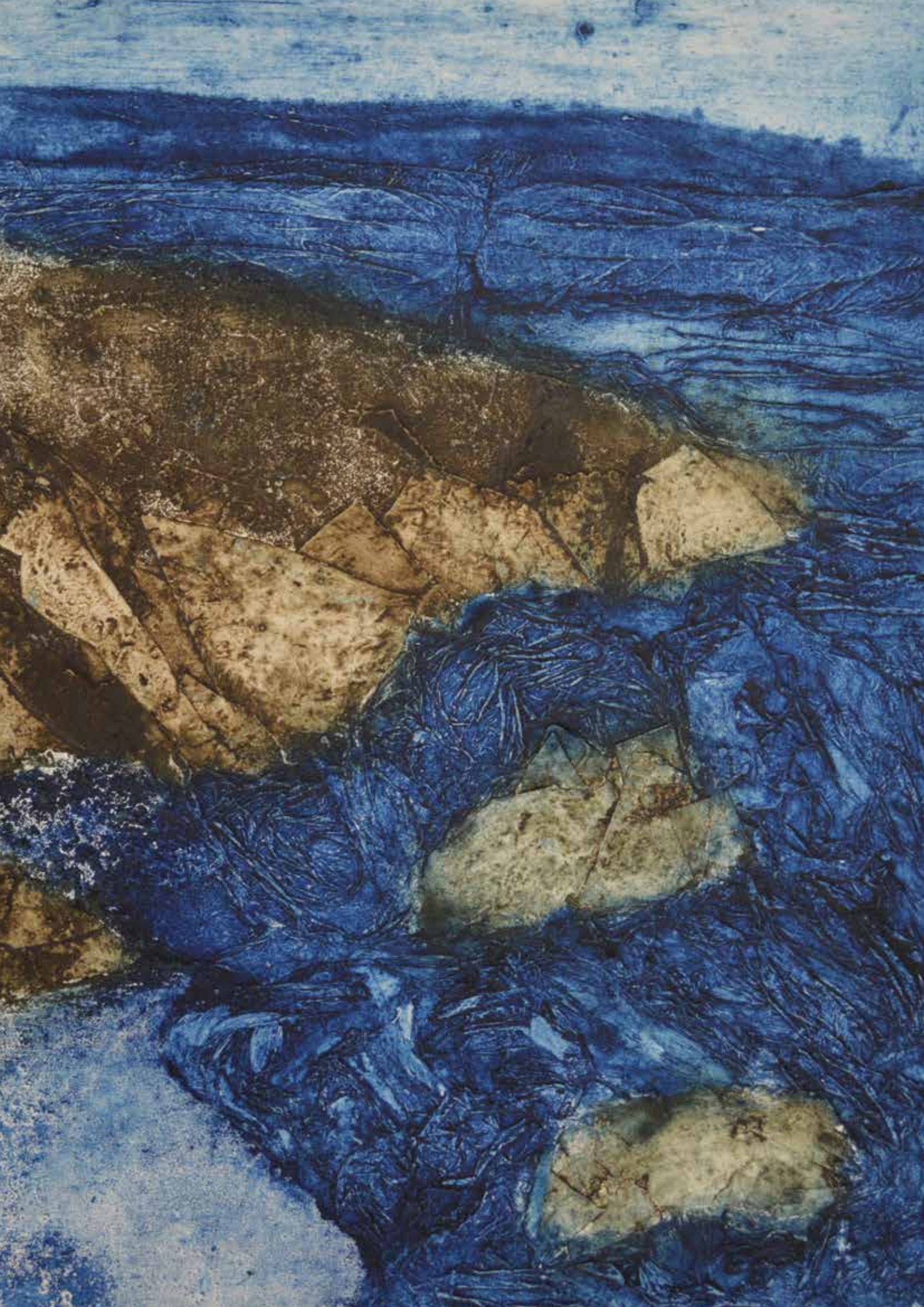
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Foreword

Plastics pollution of the world's open environments — our oceans, rivers and land — is a global challenge that has come to the forefront of public awareness in recent years. The issue has been raised in previous reports from the European Commission's Scientific Advice Mechanism, *Food from the Oceans*, *A Scientific Perspective on Microplastics in Nature and Society*, and *Environmental and Health Risks of Microplastic Pollution.* It is against this backdrop that the Group of Chief Scientific Advisors agreed to address the question of whether applications of biodegradable plastics have a role to play in the implementation of the European Commission's strategy on plastics, set within the context of the circular economy and the waste hierarchy. The work is extremely timely and will help to inform the development of European policy and legislation in this crucial area.

SAPEA was delighted to be asked to undertake this comprehensive evidence review, which informs the Scientific Opinion of the Advisors. It is the eighth Evidence Review Report to be published by the SAPEA consortium, an integral part of the European Commission's Scientific Advice Mechanism.

SAPEA assembled an outstanding working group of European experts from a variety of disciplines, backgrounds and countries. It is this unique interdisciplinary approach that we believe makes the report such a landmark contribution to the field. The project has been overseen by Academia Europaea, acting as the Lead Academy on behalf of SAPEA.

Due to the COVID pandemic, this has been the first review to be conducted entirely by virtual means, rather than through physical meetings. Although this may have seemed like a potential hurdle when work began in the early spring, it is commendable that everyone involved has kept to the agreed schedule. Moreover, the success of the Working Group in fostering a sense of collegiality between its members has demonstrated that it is possible to collaborate in completely new ways.

We would like to thank everyone involved and express our sincere gratitude to those who have contributed directly to the report, above all, the members of the Working Group.

Professor Sierd Cloetingh

President of Academia Europaea and Member of the SAPEA Board

Background to the report: the policy challenge

Plastic has transformed our lives, providing durable, lightweight, and affordable products across a range of industrial and consumer sectors. Yet the very durability of plastic materials, combined with their widespread littering and mismanagement, has resulted in global environmental pollution, raising increasing concerns about the negative effects of plastics litter on the environment, animal and human health, and associated economic costs.

Although a growing proportion of plastic waste is recycled in Europe, it is still relatively small as a proportion of the overall quantity used, and recycling rates vary by country. Globally, a large amount of plastic waste still ends up in landfills or the natural environment. This trend is set to continue on an upward trajectory, with regional 'hotspots' in areas of the world where waste infrastructures are least able to cope with it. Items can end up in the open environment in a number of ways. They include intentional input (e.g. mulch films, tree shelter tubes), as well as those with a high risk of loss (e.g. fishing devices, cigarette butts) and where loss is intrinsic to use (e.g. abrasion of paint, tyres, shoes, textiles, aquaculture nets). The amount of invisible entry through abrasion and intended use of microplastics is estimated to be higher than through visible entry.

This continuing trend has led to interest in specific and carefully selected applications in plastics that can biodegrade in the environment. It presents the scientific challenge of developing plastics that are sufficiently stable to maintain functionality during their life in service in these applications, but then biodegrade completely in an appropriate timescale.

To date, biodegradable plastics hold only a small market share in overall plastics production. In 2019, biodegradable plastics represented 0.3% of global plastics production capacity, albeit with an expected increase in market share over the coming years. Of the materials marketed as biodegradable today and the applications for which they are recommended, many are not subject to sufficient standards for tests of biodegradability, even in environments for which they are intended, let alone those to which they may be intentionally or unintentionally transported. In addition, the lack of standards, specifications and reliable certification schemes — and, in some cases, misleading labelling — confuses end users and can exacerbate environmental pollution.

The European Strategy for Plastics in a Circular Economy acknowledges the uncertainty around biodegradable plastics and sets out a cautious approach for their use, recognising that 'In the absence of clear labelling or marking for consumers, and without adequate waste collection and treatment, [plastics with biodegradable

properties] could aggravate plastics leakage and create problems for mechanical recycling.' However, the Strategy recognises that '… biodegradable plastics can certainly have a role in some applications and the innovation efforts in this field are welcomed', and identifies the need for a clear regulatory framework for plastics with biodegradable properties.

Background to the report: the request for policy advice

To support the preparation of a framework that sets out harmonised rules on defining and labelling compostable and biodegradable plastics, identifying conditions where use of biodegradable plastics is beneficial based on life cycle assessments, European Commissioners Karmenu Vella (Environment, Maritime Affairs and Fisheries) and Carlos Moedas (Research, Innovation and Science) asked the European Commission's Group of Chief Scientific Advisors to provide a Scientific Opinion addressing the question:

> **From a scientific point of view and an end-of-life perspective, and applying to plastics that biodegrade either in the terrestrial, riverine, or marine environments, and considering the waste hierarchy and circular-economy approach: What are the criteria and corresponding applications of biodegradable plastics that are beneficial to the environment, compared with non-biodegradable plastics?**

As an integral part of the European Scientific Advice Mechanism, SAPEA, a consortium of European Academy Networks, was asked to undertake a review of the scientific evidence to inform the Advisors' Scientific Opinion. SAPEA has convened an interdisciplinary and international working group of experts that has been asked to consider, with specific focus on the open environment, the scientific evidence relating to the main scoping question and the following sub-questions:

a) **How can biodegradable plastics be defined?**

b) **What applications can be recommended for biodegradable plastics, compared to non-biodegradable plastics?**

c) **What behavioural aspects play a role? What should be communicated about biodegradable plastics, and how?**

The structure of this report

This report has five main Chapters:

- Chapter 2 provides essential information and definitions to equip the reader with the necessary understanding for the discussion of plastic biodegradation in the open environment in the subsequent Chapters.
- Chapter 3 discusses selected applications of biodegradable plastics in relation to the environment.
- Chapter 4 examines testing, standards, and certification schemes.
- Chapter 5 discusses ecological risk assessment.

- Chapter 6 examines social and behavioural aspects of the perception and use of biodegradable plastics, and how communication and labelling can help support appropriate use, management, and disposal.

Chapter 1 is an introduction and the final Chapter, Chapter 7, offers conclusions and evidence-based policy options.

Definition of key terms

Clarity of terms is essential, and the report uses the following definitions:

- Biodegradable polymers are polymeric materials that can undergo extensive microbial utilisation.
- Plastic biodegradation is the microbial conversion of all its organic constituents to carbon dioxide, new microbial biomass and mineral salts under oxic conditions, or to carbon dioxide, methane, new microbial biomass and mineral salts under anoxic conditions.
- Biodegradation of a plastic material is a 'system property' in that it requires both plastic material properties that allow for biodegradation and suitable conditions in the receiving environment such that biodegradation can take place.

Chapter 2 explains these definitions in more detail, and other technical terms used in the report are also defined in the glossary (page 222).

Applications of biodegradable plastics and the environment

The report identifies some applications of biodegradable polymers that have the potential to bring advantages, compared to conventional plastics. These include applications where it is challenging to remove or collect a particular plastic product or its fragments from the environment after use (e.g. agricultural mulch films, fireworks, dolly rope), or where it is difficult to separate plastic from organic material that is destined for a composting waste stream or wastewater treatment (e.g. produce stickers, bags for compostable food, cosmetic microbeads).

The potential benefits of biodegradable plastics for selected items will only be realised if the formulation of the product is appropriate to the receiving environment, and if any potential for the item or its fragments to escape to a receiving environment in which it biodegrades more slowly, is minimised. There are applications where the potential benefits of using biodegradable plastics are much less certain, such as carrier bags and single-use packaging. To reach robust decisions that guide policy on current and novel uses, it is essential to consider applications in a holistic manner and in relation to the established concept of the waste hierarchy. Failure to do so will perpetuate inappropriate usage, lead to end user confusion and the potential for unwanted environmental consequences.

Testing, standards, and certification

When designing and testing the biodegradability of different materials, consideration is needed of the product and where it will be used, and this must be done before products are marketed.

The four main requirements for testing and certifying are:

- the determination of biodegradability
- the assessment of the biodegradation under environmentally relevant conditions
- the modelling of the lifetime/persistence in the environments of interest
- an assessment of potential effects on the environment on organism and ecosystem level

To assess the biodegradability of a plastic item in the open environment, it is essential to verify the claim by measuring the time taken to complete remineralisation, and record impacts on the environment. All components of the original test material, as well as eventual degradation intermediates, need to be biodegradable and environmentally acceptable in terms of impact. The time to complete biodegradation in the open environment depends on external conditions, material composition and the geometry of the plastic item.

Because biodegradation rates of plastics vary widely between different receiving environments, affected by a diverse range of conditions, the rates and extents of biodegradation need to be reported with reference to the specific receiving environment in which biodegradation took place or was assessed.

Criteria for the selection of tests for biodegradability and biodegradation rate assessment require standardisation, and there is a need to develop tests that consider the diversity of conditions in the open environment. The harmonisation of international standards is urgently needed. Agreed standards should ideally be based on consensus between stakeholders.

Testing and certification must be the bases for labelling on the product. A label should indicate the potential for biodegradability and the appropriate receiving environment required to achieve this. If the receiving environment is a managed waste stream, appropriate labelling of the disposal pathway itself is needed to minimise cross-contamination.

This report puts forward initial suggestions and considerations for standard test methods, standards specifications and certification programmes for biodegradable plastics in the open environment, to be further developed with a committee of interdisciplinary experts.

Ecological risk assessment

The risk assessment of biodegradable plastics in the open environment is currently at the early phase of problem formulation. Biodegradable plastic will accumulate where the amount of input exceeds the rate of biodegradation.

To assess the environmental effects and potential risks of biodegradable plastics, the half-life of plastics objects is of central importance and should be answered by testing. To inform risk assessment, life cycle assessment, and life cycle impact assessment, further research is needed to determine biodegradation rates for different materials in a variety of relevant ecosystems. The likelihood of an item reaching an inappropriate environment, and the potential risk associated with the plastic not biodegrading, need to be evaluated. This applies to all plastic items and should not be restricted to biodegradable plastics.

Although biodegradable plastics may reduce the ecological risks associated with physical harm to wildlife and the environment, their potential new hazards and effects, compared to conventional plastics, are linked to their *actual* biodegradability, and include effects on microbial ecology, biogeochemical cycles, release rates and effects of additives, and effects of intermediate biodegradation products.

The amount of biodegradable plastics released into the environment is determined by factors such as the quantity of biodegradable plastics produced (currently small as a proportion of the total volume of plastics but likely to increase) and, of those that end up in the environment (either intentionally or unintentionally), the likelihood of their persistence there.

Biodegradation rates of biodegradable plastics vary significantly between environments and with ecological and seasonal factors, and require further study. Specific risk assessments need to be designed and conducted, with a focus on environmental biodegradation rates and any potential associated ecological effects in different types of receiving environments.

Any potential ecological risks of additives in biodegradable and compostable plastics are not known and require further study. Microplastics from these items *may* contribute to the negative effects known for microplastics in general, though their contribution is dependent on their biodegradation rate in the receiving environment.

When present in the environment, large items of biodegradable plastics pose a risk of entanglement and ingestion by terrestrial and aquatic wildlife, and smothering of habitats by acting as physical barriers, in the same manner as conventional plastics.

Social and behavioural aspects

Consumer perceptions of biodegradable plastics are positive, as informed by positive environmental associations with the term 'bio' and expected end-of-use disposal options.

However, in the absence of clear, standardised labelling, there is widespread confusion about which plastic materials can be considered biodegradable, their degradation pathways in different environments, and how they should be handled post-use. This may cause unintended consequences, including pollution of recycling streams, improper composting, and an increased risk of materials ending up in the open environment through littering.

Due to positive farmer perceptions and potential benefits of biodegradable plastics in crop protection, there is potential for widespread use of biodegradable plastics in agriculture, albeit with a risk that the materials end up in areas of the open environment for which they were not designed. There is inconclusive evidence regarding the risks of accumulation of biodegradable plastic materials in agricultural fields.

A combination of information policies, such as educational campaigns and labelling, and market-based policies (including taxes, subsidies, and Extended Producer Responsibility) and regulations (bans, standards, and certification) is needed to change the behaviour of actors across different economic sectors and contexts. Policies and standards specific to biodegradable plastics need to work alongside an effective waste management infrastructure to avoid biodegradable plastic materials being mismanaged and ending up in the open environment. Materials which end up in the environment through abrasion, intended input or applications with high risk of loss need special attention under a future policy framework.

Conclusions of the report

The report concludes that biodegradable plastics have a role to play within a Circular Economy that is based on the principles of Resource Efficiency. Biodegradable plastics may bring benefits over conventional plastics in applications where it is challenging or prohibitively expensive to avoid fragments ending up in the open environment or to remove them after use, or where it is difficult to separate plastic from organic material that is destined for a composting waste stream or wastewater treatment. At the same time, we do not consider replacing conventional plastics by biodegradable plastics as a viable strategy by which to address plastic pollution, and emphasise that biodegradable plastics should neither be considered as a universal alternative to improved waste management practices, nor as an answer to inappropriate disposal, in particular littering.

Critical success factors in incorporating biodegradable plastics into the Circular Economy depend on their sustainable production, use and disposal. Integrated approaches should ensure the appropriate uptake and management of plastics that biodegrade in the open environment or can be composted at home.

There are five disposal scenarios for end-of-life items made of biodegradable plastics, with outcomes determined by (1) the application of the plastic (2) the waste management system (3) the regulations in place (4) information or labelling to guide the user on appropriate disposal and (5) the actions or behaviours of the end user in relation to that information. Biodegradable plastics will only deliver benefits over

conventional plastics where applications reach an appropriate end-of-life scenario for which they were designed and tested. It is thus crucial to develop policies and standards specific to biodegradable plastics that work alongside an effective waste management infrastructure. An integrated, systemic approach is essential to avoid further increasing the complexity of existing waste management systems. Promoting the use of biodegradable plastics in appropriate applications, alongside information and incentives for correct disposal, together with the development of *specific* waste collection and treatment infrastructure, are recommended only after making material improvements and increasing incentive schemes relating to the existing waste infrastructure.

Plastics that biodegrade in the open environment may thus present one strand within broader efforts to address plastic pollution. However, the potential of biodegradable plastics to contribute to this goal lies in their use in selected and well-defined applications, where collection can be expensive or challenging, and where there is already a high risk of them ending up in the open environment. The evidence suggests that an integrated policy approach, using principles of Resource Efficiency in the Circular Bioeconomy, can contribute to their successful introduction and management that minimises economic and environmental risks.

We emphasise that, in this rapidly evolving and high-tech field, policy should remain sufficiently flexible to encourage research and development programmes that address the open questions.

The report puts forward a range of options that may serve policymakers in choosing paths that lead to the appropriate use and management of biodegradable plastics, in line with principles of Resource Efficiency in the Circular Economy. These cover the areas of definitions of biodegradable plastics and biodegradation; regulation; standards and certification; risk assessment; incentives, subsidies and business models; information and education; research, development and innovation.

It is important to emphasise that, while the report illustrates examples of where biodegradable plastics may bring benefits as well as those where the benefits are less certain, there is no one-size-fits-all solution. To achieve net benefit from the use of biodegradable plastics as part of the Circular Economy, whilst also keeping in mind the perspective of environmental risk, the potential advantages of biodegradable plastics over conventional plastics must be considered on a case-by-case, application-by-application basis.

Chapter 1: Introduction

What is this Chapter about?

- This Chapter is an introduction to the entire report, highlighting:
  - > **The rapid growth in the use of plastics in modern society**
  - > **The scale of plastics pollution across all types of open environment**
  - > **The challenge for waste management systems worldwide in dealing with plastics**
  - > **Research and development into biodegradable plastics as a potential solution to the problem of plastics pollution in the open environment**
  - > **The challenges of defining and testing for plastic biodegradability in the open environment**
- The Chapter sets out the overarching scoping question posed by the European Commission, which asks what the criteria and applications of biodegradable plastics are that are beneficial to the environment, compared with non-biodegradable plastics. The question is addressed in detail in the subsequent Chapters of the report. The focus of the report is on the open environment, and not managed waste systems.

1.1. BACKGROUND TO THE DEVELOPMENT OF PLASTICS

Plastic is a word that originally meant 'pliable and easily shaped'. Plastics are typically organic polymers of high molecular mass, which often contain other substances and additives. They are usually synthetic and commonly derived from petrochemicals. In 1907, Leo Baekeland invented Bakelite, the first fully synthetic plastic, meaning that it contained no molecules found in nature. In 1920 Professor Hermann Staudinger, a German organic chemist, published *"Über Polymerisation"* (Staudinger, 1920), in which he demonstrated the existence of macromolecules, which he characterised as 'polymers'. For this work, he received the 1953 Nobel Prize in Chemistry. The real 'Age of Plastics' started with the boom of the oil-refining industry, which made it possible to make materials cheaply, using very few resources, but with suitable properties for practical everyday use.

1.2. PRODUCTION OF PLASTICS, BIODEGRADABLE PLASTICS, AND WASTE

❝ *"Few industries like plastic have experienced similar growth in the space of 60 years, both in terms of production tonnage and use in virtually every moment of our daily lives. However, plastic is now victim of its own success. Waste is piling up, collection struggles to keep up, recycling is costly. With everyone pointing a finger at it, plastic is more than ever at the centre of society's debates."* (Chalmin, 2019)

Plastic has become ubiquitous in our everyday lives. The wide availability of mass-produced plastic products from the mid-twentieth century onwards has brought numerous societal benefits to all of us. Plastic provides food and water packaging, as well as lightweight, durable and affordable applications for domestic households and sectors as diverse as medicine, construction, transportation, agriculture and renewable-energy generation (Andrady & Neal, 2009; Millet et al., 2019).

Cumulatively, it is estimated that about 8.3 billion tonnes of plastic have been produced since 1950 and more produced in the past 15 years than in the preceding 50 (Geyer, Jambick, & Law, 2017). Plastics production in Europe is relatively stable, but is growing at a rapid rate in other areas of the world (see Figure 1.1). Forecasts to 2050 vary, but all predict significant growth on today's levels. For example, a report by the International Energy Agency (2018) predicts annual production of around 600 million tonnes by the middle of the century, compared with around 360 million in 2018 (PlasticsEurope, 2019).

Biodegradable plastics currently make up only a small volume of the total plastic market. In 2019, the global production capacity of biodegradable polymers was reported to be 1.174 million tonnes, which corresponds to only about 0.3% of the total plastic production capacity of about 360 million tonnes (PlasticsEurope, 2019). However, it is generally expected that the market share of biodegradable plastics will increase in the next years (i.e. 1.334 million tonnes by 2024), continuing a trend that was seen over recent years.
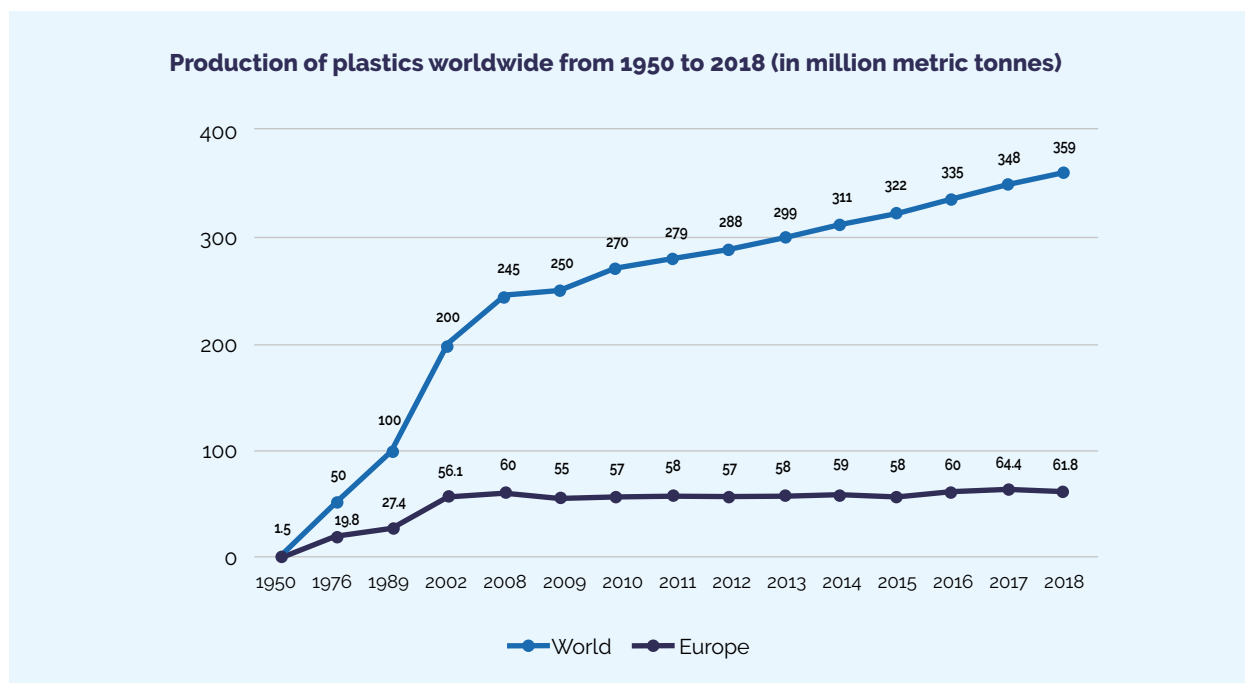
Figure 1.1: Annual production volumes of plastics worldwide 1950–2018 (statista, 2020a); original data source from PlasticsEurope (2019a)

Plastic is largely tied to the oil industry as it is both cheap and easy to convert oil into plastics, often creating single-use or disposable plastics. At the same time, the durability of plastic materials, combined with widespread littering, has resulted in global environmental pollution, and many in the scientific community have increasingly raised concerns about the negative effects of plastics litter on the environment, animal and human health, and the associated economic costs (Werner et al., 2016). Public awareness and concern have also been growing.

To give an idea of the scale of the plastic waste problem, a study by the World Bank estimated that of the 2 billion tonnes of solid municipal waste produced worldwide in 2016, 242 million tonnes (around 12%) were plastic, of which 57 million tonnes are in Asia, 45 million tonnes in Europe and 35 million tonnes in North America (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018). It is difficult to estimate the exact amount of waste that ends up in the open environment, but it is significant. The input of small plastic particles, 'the unseen', is estimated to be larger than the visible and includes for example, abrasion of paint, tyres, textiles, fishing nets, etc. As an indication, Geyer et al. (2017) have estimated that, as of 2015, approximately 6300 tonnes of plastic waste had been generated, around 9% of which had been recycled, 12% was incinerated, and 79% was accumulated in landfills or the natural environment. On that basis, even if current production and waste management trends continued as now, the authors calculate that roughly 12,000 tonnes of plastic waste would be in landfills or in the natural environment by 2050.

Distribution of global plastic materials production in 2018, by region

Region	Percentage
China	30%
NAFTA	18%
Rest of Asia	17%
Europe	17%
Middle East & Africa	7%
Latin America	4%
Japan	4%
CIS	3%
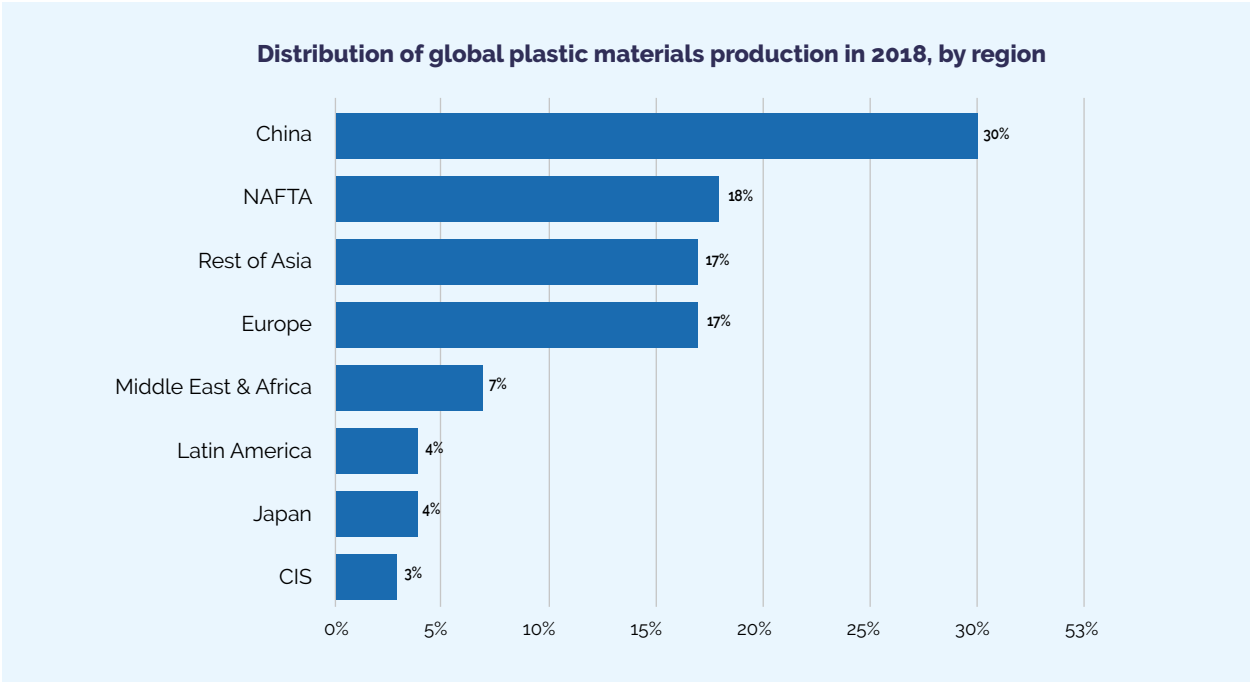
Figure 1.2: Distribution of global plastics materials production, by region, 2018 (Statista, 2020b); original data source from PlasticsEurope (PEMRG); Consultic, 2019b)

1.3. BACKGROUND TO BIODEGRADABLE PLASTICS

Around 50 years ago, the growing awareness and concern over plastic pollution led to interest in making plastics that have the potential to degrade in the environment (Guillet, 2002). The term 'biodegradation' is still not firmly defined, and the field of study covers many interdisciplinary aspects. Moreover, experimentation and testing are challenging because research studies need to address complex and long-term phenomena in natural environments that are extremely variable. There are also many commercial and marketing interests at stake (Albertsson, 1992).

At the heart of the issue is the stark contrast between polymers made in nature and those that have been developed by human society. Naturally occurring biodegradable polymers are the result of a process developed over millions of years of evolution that has led to tailor-made materials for various uses in nature. The typical polymers in nature are proteins, polysaccharides, lignin and natural rubber. They are built of atoms such as carbon, hydrogen, oxygen and nitrogen. These are also are the most frequently used atoms to build synthetic polymers but, in contrast, synthetic polymers are the result of a mere century of research and development work (Albertsson & Karlsson, 1992). Both natural and synthetic polymer samples normally have a distribution of molecular weights and this is usually measured as *number-average molecular weight* and *weight-average molecular weight*. These two values give important information about a material's properties, such as mechanical performance, strength and elasticity. A *degradable* polymer is a polymer that undergoes chain scission, resulting in a decrease of molar mass. A *biodegradable* polymer can be degraded by biological activity, with degradation accompanied by a lowering of its molar mass. The accessibility of a polymer to be colonised by living organisms depends on its molecular composition and architecture (Albertsson & Karlsson, 1992).

Nature builds polymers *in-situ* and these materials are usually sensitive to heat, as well as water, and sooner or later degrade to soil or other natural products, depending on the environment. On the other hand, synthetic materials are built to have reproducible properties, to be stable and to maintain the required properties during everyday use. For example, degradable material in medical applications must have predictable performance during use; the human body is a relatively controlled environment with known temperature and degradation conditions, making it possible to create biomedical materials with predictable degradation rate and products (Albertsson & Hakkarainen, 2017). By contrast, natural environments have a much wider diversity in variables such as humidity, microorganisms, oxygen, sunlight, and temperature, making it extremely difficult to control and ensure the complete breakdown of potentially degradable plastic materials. The major problems relating to the development, use, and disposal of degradable materials is that none are degraded across *all* natural environments. Rather, a specific environment is needed, and the conditions required depend on the type of plastic. Claims of environmental degradability should thus always be related to a specific environment (Albertsson & Hakkarainen, 2017). This is, of course, challenging. A further complication arises from the fact that although we want the material to rapidly degrade in natural environments,

it should not degrade during its practical use. In all cases, it is crucial to remember that degradability is connected to the chemical and physical structure and composition of the material and its interactions with the surrounding environment (Tokiwa, Calabia, Ugwu, & Aiba, 2009). Moreover, any modifications or additives to the polymer will potentially influence the degradability, the type of degradation products formed, and the ultimate environmental fate of the product (Albertsson & Hakkarainen, 2017).

Some early approaches to biodegradable plastics tried to promote the environmental degradation of cheap plastics, such as polyolefins used for packaging and mulch film (Albertsson & Hakkarainen, 2017). However, polyolefins consist of a carbon chain with covalent carbon-carbon bonds, which no natural enzyme can cut directly. The first step in degradation is oxidation, but usually the materials contain a stabiliser to avoid oxidation. Making the materials more sensitive to oxidation by sunlight, for example, also makes them less stable during use. Materials with a simple additive of pro-oxidants have been commercialised and marketed as 'oxo-degradable plastics' or 'pro-oxidant additive containing' ('PAC') plastics. It is much easier to start the oxidation and fragmentation of a material than it is to control the oxidation rate and the degradation products, thereby convincingly proving that the material will be completely mineralised or degraded to acceptable degradation products (Roy, Hakkarainen, Varma, & Albertsson, 2011). As a result, many countries, and also the European Union, have come to the conclusion that the use of these materials should be avoided or banned.

In the scientific literature on degradable or environmentally degradable plastics, many claims of degradability have been made. However, merely reporting weight loss is not a proof of degradation. There are many reasons for weight loss, such as the extraction of additives or the loss of parts or polymer fragments. Moreover, potential degradation products could be persistent in nature and must be identified. Using the correct terminology for describing the type of degradation, as well as correct test methods for the intended aim, is important to avoid misunderstandings and incorrect claims (Vert et al., 2012b), and this issue is discussed in detail in Chapter 2.

1.4. THE POSITION OF BIODEGRADABLE PLASTICS IN WASTE MANAGEMENT SYSTEMS

The European Commission adopted a new Circular Economy Action Plan in 2020 as one of the building blocks of the Green Deal.

The concept of 'circular economy' is not yet well defined from an academic perspective. Its aim is sustainable development, based on the core principle of resource efficiency (the use of resources for as long as possible) and giving priority to the so-called waste hierarchy. The circular economy is designed to prevent the depletion of natural resources (Prieto-Sandoval, Jaca, & Ormazabal, 2018) and is often referred to as the 'restorative use of resources' (Ellen MacArthur Foundation, 2012). For restorative use, a precondition is to keep the extraction of resources, as well as emissions and waste, within sustainable long-term ecological limits (Pearce & Turner, 1990).

Plastics recycling and reuse are growing but still limited. In 2017, around 42% of plastics packaging in the European Union was recycled, but this varies widely between countries (Eurostat, 2019). The growth in biodegradable plastics is related to the growing societal concern about the accumulation of conventional plastics in the open environment and the associated ecological risks, impacts on ecosystem services and on society.

The recycling of biodegradable plastics is not well reported on in the scientific literature. The global production capacity of biodegradable plastics in 2018 was reported to be about 2.0 million tonnes (mostly polyesters and starch), of which 1.1 million tonnes were biodegradable plastics. As stated already, the global production of all plastics in 2018 was about 360 million tonnes, indicating that the amount of biodegradable plastics in in general plastics waste streams would be about 0.3% (European Bioplastics, 2020). The amount of biodegradable plastics in plastics waste streams will most likely stay well below 10% in the foreseeable future. Biodegradable plastics may possibly constitute a minor contamination in general plastics waste streams. Scientific reports on the influence of contamination of sorted plastics fractions caused by minor contents of biodegradable plastics are, however, scarce.

1.5. EU POLICY LANDSCAPE

The 2018 EU Plastics Strategy lays the foundation for a new 'circular plastics economy', where materials are kept in the loop for as long as possible, by promoting reuse and repair, remanufacturing, recycling and the prevention of plastic waste. Oxo-degradable plastics were banned in the European Union in June 2019 as part of the Single-Use Plastics Directive of the European Strategy for Plastics in a Circular Economy

'as that type of plastic does not properly biodegrade and thus contributes to microplastic pollution in the environment, is not compostable, negatively affects the recycling of conventional plastic and fails to deliver a proven environmental benefit'.[1]

However, some plastic products may be either difficult or impossible to collect after use and, as a result, there is a high risk of these products ending up in the environment. On the one hand, biodegradable polymers and additives have been proposed as part of the solution to the problem of plastics pollution. On the other, there are warnings that biodegradable polymers may lead to manufacturing routes that are more energy-consuming or resource-consuming, and the resulting materials may have unintended consequences on the environment.

The European Strategy for Plastics in a Circular Economy[2] acknowledges the uncertainty surrounding biodegradability of plastics and sets out a cautious approach for their use, recognising that 'In the absence of clear labelling or marking for consumers, and without adequate waste collection and treatment, [plastics with

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1 Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019: https://eur-lex.europa.eu/eli/dir/2019/904/oj

2 A European Strategy for Plastics in a Circular Economy, COM/2018/028 final: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0028

biodegradable properties] could aggravate plastics leakage and create problems for mechanical recycling.'

However, the Strategy recognises that '… biodegradable plastics can certainly have a role in some applications and the innovation efforts in this field are welcomed', and identifies the need for a clear regulatory framework for plastics with biodegradable properties.

As already stated, most available plastics labelled as 'biodegradable' degrade only under specific conditions and can thus still cause harm to ecosystems, though some targeted applications, such as compostable plastic bags for collection of domestic organic waste, have shown positive results and standards exist or are being developed for specific applications. However, plastics that are labelled 'compostable' are not necessarily suitable for home composting and may affect the quality of recyclates if compostable and conventional plastics are mixed in the recycling process.

The Plastics Strategy comprises the following measures:

1   For adequate sorting and to avoid false environmental claims, the European Commission will propose harmonised rules for defining and labelling compostable and biodegradable plastics.
2   The European Commission will also develop life cycle assessment to identify the conditions under which the use of biodegradable or compostable plastics is beneficial, and the criteria for such applications.
3   Applications with clear environmental benefits should be identified and, in those cases, the European Commission will consider measures to stimulate innovation and drive market developments in the right direction.

1.6. POLICY QUESTION

The European Commission's Group of Chief Scientific Advisors has been asked to support the preparation of a framework that sets out harmonised rules on defining and labelling compostable and biodegradable plastics and that identifies conditions where use of biodegradable plastics is beneficial based on life cycle assessments[3]. The overarching question put to the Advisors, to be addressed in their Scientific Opinion, is:

> ❝ *'From a scientific point of view and an end-of-life perspective, and applying to plastics that biodegrade either in the terrestrial, riverine, or marine environments, and considering the waste hierarchy and circular-economy approach: What are the criteria and corresponding applications of biodegradable plastics that are beneficial to the environment, compared with non-biodegradable plastics?'*

SAPEA, a consortium of European Academy Networks, has been asked to undertake a review of the scientific evidence to inform the Advisors' Scientific Opinion. SAPEA has convened an international working group of experts, representing a range of different fields (for example, polymer science, environmental chemistry, microbiology and environmental psychology, amongst others). The Working Group has been asked to consider the scientific evidence relating to the following questions:

1. How can biodegradable plastics be defined?

2. What applications can be recommended for biodegradable plastics, compared to non-biodegradable plastics?

3. What behavioural aspects play a role? What should be communicated about biodegradable plastics, and how?

The SAPEA Working Group has been asked to focus only on plastics (substitution materials are not to be considered), to include only biodegradable plastics in open environments (thus excluding composting in industrial facilities, for example), and to consider home composting as a secondary priority. The focus of this report is therefore on the open environment, not managed waste systems.

The resulting Evidence Review Report produced by the expert group is structured around five main Chapters:

- Chapter 2 sets the scene by establishing definitions of plastics and polymers, biodegradation and the open environment; defining the steps involved in plastics biodegradation; and explaining the factors affecting biodegradation of plastics in the open environment.

- Chapter 3 reviews possible applications of biodegradable plastics. It includes considerations relating to environment; the waste hierarchy and where biodegradable plastics fit in; the influence of the receiving environments;

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3 A European Strategy for Plastics in a Circular Economy, COM/2018/028 final: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0028

examples of applications; and the importance of relevant information for consumers and users.

- Chapter 4 focuses on testing and certifications. It includes background and history; testing schema; how to assess; data and extrapolation of results; criteria by which to select tests; available standards; certification; examples; and gaps in data and information.

- Chapter 5 considers risk assessment. It includes ecotoxicology; plastics in the environment and associated risks; the potential risks of biodegradable plastics; a risk assessment of biodegradable plastics; conclusions and identified knowledge needs.

- Chapter 6 looks at public understanding, perceptions and behaviour; unintended consequences (economic, behaviour, environmental); labelling; evidence-based policy options and regulation.

The report ends with a set of conclusions and evidence-based policy options that may serve policymakers in choosing paths that lead to the appropriate use and management of biodegradable plastics in line with principles of resource efficiency in the circular economy.

In this context, it is important to emphasise that we do not consider replacing conventional plastics by biodegradable plastics as a viable strategy to solve the plastic pollution problem. To address the latter, a plastics strategy has been put into place by the European Union that relies on reducing plastic use and reusing and recycling of plastic items. Nor should biodegradable plastics be considered as an alternative to poor waste management. Instead, this report seeks to identify and critically evaluate criteria under which the use of biodegradable plastics in specific applications may contribute to alleviating plastic pollution of the open environment. The report thus aims at providing science-based criteria by to incorporate the use of biodegradable plastics for open environment applications into the existing waste hierarchy concept being implemented by the EU.

Key messages

- We are living in the Age of Plastics. Plastic is incredibly useful in today's society, as a material that is relatively cheap to produce, lightweight and long-lasting, suited to many different purposes.

- The ubiquity and durability of plastic are also its greatest drawbacks. Although the level of plastic reuse and recycling is increasing, it is still limited. Waste management systems are unable to cope with the huge volumes of discarded plastic. Public littering is widespread. It has led to plastics pollution on a massive scale, particularly in open environments like the oceans, rivers, lakes and land. Moreover, all forecasts predict that plastics production and consequent pollution will continue to grow at a rapid rate over the coming years, with the most acute accumulation in certain regions of the world, often those with infrastructures that are least able to cope. Even where infrastructure is available, the input of small plastic particles, 'the unseen', is larger than the visible and includes for example, abrasion of paint, tyres, textiles, fishing nets, etc.

- The scientific community has been engaged in the development of biodegradable plastics for several decades, as a possible way forward to tackling the enormous environmental problems caused by conventional plastic pollution. Extensive commercial and marketing interests are also at stake here.

- There are considerable challenges in defining and testing for biodegradation of plastics in the open environment. Firstly, the range of different polymer materials is immense and continually changing. Secondly, there is no one uniform environment, but rather the range of open environments across the world is complex, each shaped by variables such as temperature, light and humidity.

- In 2018, the European Commission established its European Plastics Strategy in a Circular Economy, backed up by the Single Use Plastics Directive in 2019, which included the banning of oxo-degradable plastic, a type of plastic that does not properly biodegrade. The European Commission's Group of Chief Scientific Advisors is now asked to support the preparation of a framework that sets out harmonised rules for defining and labelling compostable and biodegradable plastics and that identifies conditions where use of biodegradable plastics is beneficial, based on life cycle assessments and compared to conventional plastics.

- SAPEA, a consortium of the European Academy Networks, has been asked to undertake a review of the scientific evidence to inform the Advisors' Scientific Opinion. SAPEA has convened an interdisciplinary and international working group of experts that has been asked to consider the scientific evidence relating to the scoping question:

  > **From a scientific point of view and an end-of-life perspective, and applying to plastics that biodegrade either in the terrestrial, riverine, or marine environments, and considering the waste hierarchy and circular-economy approach: What are the criteria and corresponding applications of biodegradable plastics that are beneficial to the environment, compared with non-biodegradable plastics?**

- The focus of this report is on the open environment, not managed waste systems.

Chapter 2: Setting the scene

What is this Chapter about?

- This Chapter provides essential background and definitions related to the key scoping questions addressed in the report, including definitions of 'plastics' and 'polymers', 'plastic biodegradation', as well as 'the open environment'. The Chapter seeks to provide clarity on terms such as 'bioplastics', 'bio-based' and 'biodegradable' plastics. It highlights the diversity of polymers and commonly used additives to polymers such as stabilisers, plasticisers and fillers.

- This Chapter provides general concepts on plastic biodegradation derived from the scientific literature, to equip the reader with the necessary understanding for the discussion of plastic biodegradation in the open environment in the subsequent Chapters of the report.

- This Chapter summarises key factors that govern the process of plastic biodegradation in the open environment, emphasising that plastic biodegradation is the result of the interplay between plastic material properties that render it biodegradable and the characteristics of the receiving environment that enable the biodegradation to take place.

- The Chapter provides general guidance for a science-based assessment of the biodegradability of existing plastic materials, and critically questions the use of additive technologies that claim to render conventional, non-biodegradable plastic as biodegradable.

2.1 INTRODUCTION

This Chapter aims at providing essential information and definitions related to the theme of this report. The Chapter provides concepts with general validity, derived and condensed from the scientific literature, rather than an extensive detailed review of the primary literature on plastic biodegradation in the open environment. Readers in need of detailed information on specific aspects of the larger topic are referred to the literature review accompanying this report. While the focus here is on generalisable concepts, we illustrate these — where appropriate — by specific case examples. The motivation behind providing generalised concepts is to provide the reader with the essential science-based understanding necessary for the discussion of various aspects of plastic biodegradation in the open environment that are covered in the subsequent Chapters.

This Chapter 2 has the following outline. First, we provide concise definitions of 'plastics' *per se* and of 'plastic biodegradation', as well as 'the open environment'. These definitions help guide the subsequent discussions of the key factors that govern the process of plastic biodegradation in the open environment. We note that for some terms we have adapted existing definitions, as specified below. Other definitions were, however, formed in discussions with members of the SAPEA expert group and

extend on (and in some cases deviate from) previous definitions for the same terms provided in the literature and/or by professional unions and federations, such as the International Union of Pure and Applied Chemistry (IUPAC). As discussed in more detail below, one key point is that we consider plastic biodegradation in the open environment as a **system property**; it is the result of an interplay between polymer properties that render the polymer (or the plastic material in which the polymer is used) biodegradable and the characteristics of the receiving environment that ideally enable (or non-ideally, impair) the biodegradation of the polymer to actually take place. We provide guidance for a science-based assessment of the biodegradability of existing plastic materials and critically question additive technologies that claim to render conventional, non-biodegradable plastic biodegradable.

2.2 DEFINITIONS OF PLASTICS AND POLYMERS

For the purposes of this report, we define 'plastic' as:

> *"a material that contains, as an essential ingredient, one or more organic polymeric substances of large molecular weight [i.e. polymers]. A plastic is solid in its finished form but can be shaped by flow during manufacturing or finishing into finished articles"* (ASTM D883 – 20a, 2020).

We note that this definition excludes water-soluble polymers, even though their fate in the environment, including (bio-)degradation characteristics, is attracting increasing attention (Arp & Knutsen, 2020).

We follow the definition provided by IUPAC that a polymer is:

> *'a substance composed of macromolecules'* (IUPAC, 1996).

with a macromolecule (or polymer molecule) being defined as

> *'a molecule of high relative molecular mass, the structure of which essentially comprises the multiple repetition units derived, actually or conceptually, from molecules of low relative molecular mass'.*

BOX 2.1: Polymers

Most commonly, polymers consist of one or several kinds of small molecules (i.e. monomers), connected by chemical reactions that result in the formation of covalent bonds and hence polymeric molecules. The backbone of a large number of synthetic polymers (e.g. polyolefins) is composed of covalently linked carbon chains. However, there are also many polymers that contain heteroatoms, such as oxygen, nitrogen and phosphorous, in their backbone. These include natural biopolymers (e.g. polyamides), polysaccharides (e.g. cellulose), polyphenols (e.g. lignin), polyterpenoids (rubber), polyesters (e.g. cutin and polyhydroxyalkanoates) and nucleic acids (e.g. DNA), as well as synthetic polymers (e.g. polyethylene glycol, polyesters).

Among the most essential physicochemical properties of a polymer (irrespective of whether these are synthetic or natural) are:

- molecular weight, which can range from tens of thousands up to more than a million grams per mol)

- the shape of the polymeric chains, from linear to branched structures and networks

- chemical composition (varying from polar (hydrophilic) to apolar (hydrophobic) and from uncharged to charged)

These properties jointly have significant effects on the physical stability, performance and characteristics of the polymers. Both natural and synthetic polymers are characterised by their molecular weights, which are commonly classified as number-average molecular weight ($\overline{M}_n$) and weight-average molecular weight ($\overline{M}_w$) and their dispersity (Đ). Average molecular weights and dispersity strongly influence properties such as mechanical performance-strength and elasticity. The architecture of the polymeric chains also affects the propensity of the polymer to form crystalline regions (and hence the degree of crystallinity), which in turn again affects its physical and chemical behaviour (including polymer biodegradation, as detailed below).

Naturally occurring biopolymers undergo abiotic and/or enzymatic reactions that lead to their breakdown into smaller units that can subsequently be taken up and metabolised by microorganisms. This breakdown involves reactions with water or oxygen: bonds in the biopolymer backbone are cleaved through hydrolysis or oxidation. As a consequence, biopolymers commonly biodegrade readily in the open environment; there are a few exceptions that will be addressed in more detail below (e.g. polymers like lignin that rely on oxidative breakdown may persist for extended time periods in oxygen-free environments, such as anoxic sediments).

By comparison, conventional synthetic polymers have traditionally been built and designed to have a reproducible and comparatively high stability that ensures that these polymers maintain their desired material properties during use, including applications in the open environment. Compared to biopolymers, these stable

conventional polymers lack bonds in their backbone that can be readily cleaved through abiotic or enzymatic hydrolysis and oxidation. Consequently, these conventional synthetic polymers undergo only very slow degradation in the open environment, leading to their accumulation and thereby to environmental plastic pollution.

Compared to conventional synthetic polymers that persist in the environment, synthetic *biodegradable* polymers are designed to contain bonds in their backbones that are susceptible to hydrolytic or oxidative cleavage. Most commonly, these bonds are esters that may react with water to form a carboxylic acid and an alcohol (Table 2.1), thereby breaking the ester bond. In fact, many synthetic biodegradable polymers contain chemical motives, such as ester bonds, in their backbones that mimic those of naturally occurring biopolymers. Naturally occurring hydrolytic or oxidative enzymes produced and secreted by microorganisms to cleave backbone bonds in biopolymers may then also cleave backbone bonds in the synthetic polymers, thereby facilitating their breakdown and ultimately their biodegradation.

As mentioned in Chapter 1, the term 'plastic' is derived from the Latin word 'plasticus': an entity that can be moulded and pertaining to moulding.[4] The term 'plastic' thus refers to its malleability into various shapes — such as films, fibres, plates, tubes, and bottles — by casting and pressing as well as extruding (PlasticsEurope, 2019). From a technical point of view, plastics refer to a wide group of materials mainly composed of organic polymers that are used in a variety of applications.

The above definition of plastics implies that plastic contains additional substances, besides one or more polymers. These can broadly be categorised as **additives**. While they are diverse, additives have in common that they are mixed into the polymer to bestow desired material properties on the plastics. Some of the most important classes of additives are stabilisers, plasticisers, fillers, reinforcing agents, colourants and fire retardants (see Annex 5 for further information). It is important to recognise that additives affect the properties of plastic not only during its application period but also after its use. Therefore, additives may also alter the biodegradation characteristics of the plastic after use, irrespective of the environment in which biodegradation takes place. This recognition is important for the discussion of testing and certification of biodegradable plastics with regard to two points:

- If the properties of the plastic material are largely affected by additives, then testing and certification may not be limited to only the polymer(s) that constitute the plastic. Instead, regulations may request that the actual plastic material (or even the final commercialised plastic item containing the additive) is tested.
- The additives themselves may require regulatory assessment for compliance with labelling the plastic as biodegradable.

These two aspects are discussed in more detail in Chapter 4.

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4 https://www.sciencehistory.org/science-of-plastics

Bioplastics

We note that the term 'plastic' has become part of another term that is commonly used, but has proven often to lead to misconceptions and confusion: the term **bioplastics**. In this report, we treat bioplastics as a generic term that subsumes both plastic materials composed of biodegradable polymers (as defined in detail below in Section 2.3) as well as plastic materials composed of bio-based polymers. According to IUPAC, a bio-based polymer is:

> 66 *"composed or derived in whole or in part of biological products issued from the biomass (including plant, animal, and marine or forestry materials)"* (Vert et al., 2012a)

Bio-based polymers themselves include three subcategories: naturally occurring biopolymers (e.g. cellulose, starch, PHA and lignin), bio-derived polymers (e.g. cellulose acetate), and synthetic polymers built from renewable (non-fossil) feedstock (e.g. polybutylene succinate (PBS)). The interpretational ambiguities associated with the term 'bioplastics' arise from the fact that 'biodegradable' and 'bio-based' are attributes that describe fundamentally different polymer characteristics and the fact that bioplastics comprise plastics containing polymers to which either one or both of these two attributes can apply. This is illustrated in Figure 2.1.

biodegradable polymers

fossil-based polymers

bio-based polymers

biodegradable fossil-based polymers

biodegradable bio-based polymers

non biodegradable fossil-based polymers

non biodegradable bio-based polymers

non biodegradable polymers
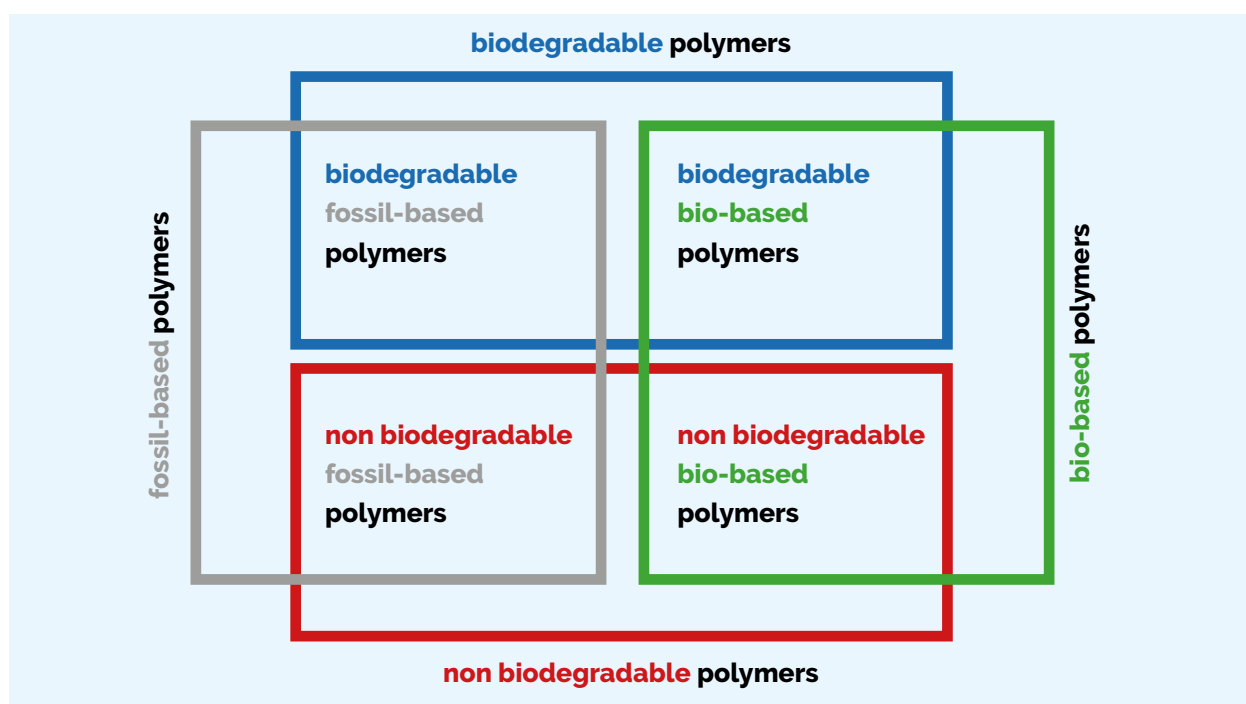
Figure 2.1: Categories of biodegradable and non-biodegradable plastics. Biodegradable fossil-based polymers, biodegradable bio-based polymers and non-biodegradable bio-based polymers make up the larger category of so-called 'bioplastics'. Adapted from a conceptual drawing by European Bioplastics (2020).

Figure 2.1 provides an overview of the three larger subcategories of plastic materials that make up 'bioplastics': (1) biodegradable, fossil-based polymers (top left), (2) biodegradable, bio-based polymers (top right), and (3) non-biodegradable, bio-based polymers (bottom right). Figure 2.1 also shows that there is a fourth category of plastics consisting of non-biodegradable and fossil-based polymers (bottom left).

This category is not part of 'bioplastics' but, in terms of market volume and use, is the dominant polymer class. The conventional synthetic polymers polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS) and polyvinylchloride (PVC) by and large all fall into this fourth group. Although some of these conventional non-biodegradable polymers (e.g. BioPE and BioPET) can also be synthesised from bio-based monomers, they remain non-biodegradable.

Given the topic of this report, subsequent discussions will primarily focus on **biodegradable plastics**, irrespective of whether they are bio-based or fossil-based, in the context of the open environment. We therefore deliberately exclude biodegradable plastics used in biomedical applications, as well as plastics undergoing biodegradation in managed waste systems such as composts (as detailed below) from the subsequent discussion, even though some polymer classes overarch all three application domains (e.g. PLA). It is important to re-emphasise that the nature of the feedstock from which the carbon of a biodegradable polymer was sourced (fossil-based versus bio-based) is completely decoupled from the question of whether the polymer is biodegradable.
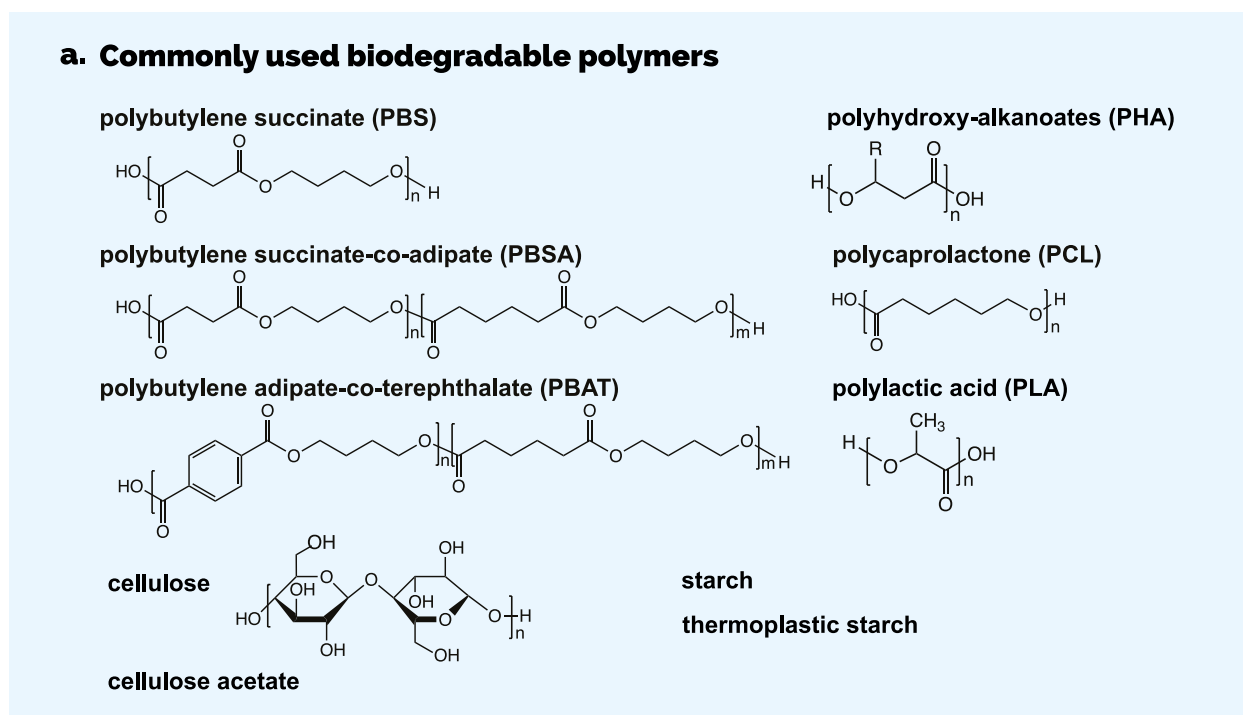
Figure 2.2a: Overview of commonly used biodegradable polymers with some chemical structures. Note that there are various variants of PBSA and PBAT; only a generic structure is shown.
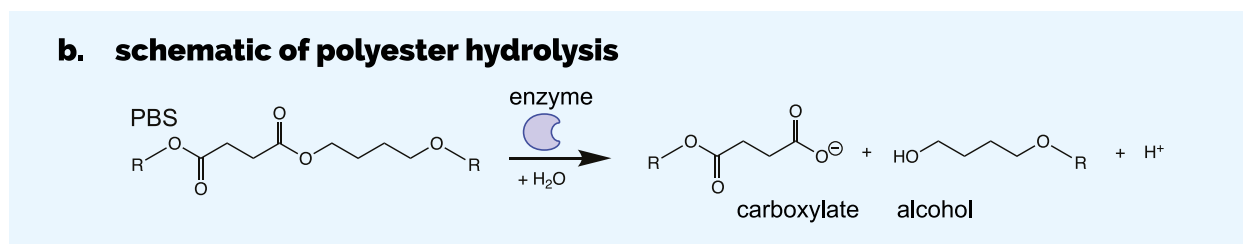
Figure 2.2b: Schematic of enzymatic hydrolysis of the aliphatic biodegradable polyester PBS under formation of the respective carboxylic acid and the alcohol. (Both figures adapted from Sander, 2019)

Biodegradability as a system property

In this Chapter as well as subsequent Chapters, we often discuss biodegradable plastics in relation to conventional, non-biodegradable plastics. The reason for this comparison is clear; this report aims to provide science-based evidence that guides the assessment of which specific applications in the open environment, and under which conditions, biodegradable plastics can be considered viable or possibly even desirable substitutes for the conventional, non-biodegradable plastics that are currently used in the same applications. At the same time, we acknowledge that this delineation of biodegradable plastics from conventional plastics, while scientifically sound, may give rise to a misinterpretation: that all biodegradable plastics — and thus the polymer(s) they contain — are universally biodegradable across all ecosystems that jointly constitute the open environment. As indicated above and further detailed below, whether or not a polymer categorised as being biodegradable actually undergoes biodegradation is strongly dependent not only on the plastic material properties but also on the specific conditions that prevail in the receiving environment in which the plastic resides (Zumstein et al., 2018).

This viewpoint on plastic biodegradation leads to a key statement of this Chapter:

We consider plastic biodegradation a system property, in that it results from the interplay of a specific material property of the plastic that makes it potentially biodegradable as well as the abiotic and biotic conditions in the specific receiving environment that leverage this potential and control the rates and extents of actual plastic biodegradation.

The view of plastic biodegradation as a system property does not rule out the possibility that a plastic material biodegrades across different receiving environments. For instance, a marine biodegradable plastic may well be biodegradable also in limnic systems and in soils. However, the view opposes the idea that biodegradation is exclusively a material property; treating it as such neglects the importance of environmental conditions controlling plastic biodegradation, as well as the large variations in rates and extents of biodegradation of a specific plastic across different receiving systems in the open environment, as defined below.

Before providing definitions for 'plastic biodegradation' and 'the open environment', it is important to point out that biodegradable plastics currently make up only a small volume of the total plastic market. In 2019, the global production capacity of biodegradable polymers corresponded to only about 0.3% of the total plastic production capacity. However, it is generally expected that the market share of biodegradable plastics will increase in the following years, continuing a trend that was seen over recent years (European Bioplastics, 2020). This trend is driven by growing societal concern about the accumulation of conventional plastics in the open environment and the associated risks and impacts on the environment and society (as well as by an increased use of compostable biodegradable plastics). In this context, we make a second important statement in this Chapter:

We fully recognise the benefits of using biodegradable plastics in some specific applications for which recycling and the reuse of plastics is challenging and for which there is a high likelihood of the used plastic remaining in the open environment. Yet it is important to emphasise that completely replacing conventional plastics by biodegradable plastics is neither a viable nor a desirable strategy to solve the plastic pollution problem.

Environmental plastic pollution is better addressed by the waste hierarchy strategy put into place by the European Union, which stipulates the following priorities for plastic use: reducing plastic use, followed by reusing and recycling of plastic items whenever possible (i.e. overcoming the circularity gap in our economy; European Commission, 2012, 2018). In the context of this waste hierarchy, plastic biodegradability cannot (and ought not to) be considered a universal solution to environmental plastic pollution. At the same time, this report fully recognises that, for some specific applications, the use of biodegradable instead of conventional plastics has significant potential to help alleviate plastic pollution of the open environment. This report seeks to identify and critically evaluate criteria for such specific applications (see Chapter 3) and for testing and certification schemes that ensure that biodegradable plastics indeed biodegrade in the anticipated receiving environments (see Chapter 4) and have no ecotoxicological impact (see Chapter 5) in those environments. This report thus aims to provide science-based criteria by which to incorporate the use of biodegradable plastics for open environment applications into the existing waste hierarchy concept implemented by the EU.

2.3 DEFINITION OF 'PLASTIC BIODEGRADATION'

The definition of 'plastic biodegradation' is of central importance to this report. For clarity and brevity, we first provide a concise definition of this term. We subsequently provide a rationale for our definition and discuss the two key steps involved in this process, as well as the polymer-dependent and receiving-environment specific factors that control each of these two steps.

In essence, plastic biodegradation is a complex process that results in extensive reworking of the carbon in the plastic. Based on the scientific evidence, we define plastic biodegradation as follows:

Plastic biodegradation is the microbial conversion of all its organic constituents to carbon dioxide, new microbial biomass and mineral salts under oxic conditions, or to carbon dioxide, methane, new microbial biomass and mineral salts, under anoxic conditions.

The organic constituents referred to in this definition include the organic polymer(s) that compose the plastic as well as any organic additives in the plastics.

This definition requires two clarifying statements. The first statement is that, for regulatory purposes, the scientific definition of plastic biodegradation needs to be complemented by specifications, both of the requested extent of biodegradation

over a pre-defined timeframe and of the (open) environment in which biodegradation is assessed (see Figure 2.3 on page 42). We address this important point in more detail below. The second statement is that this definition of plastic biodegradation applies to only the organic components of a plastic material. In cases where a plastic contains inorganic constituents, or if the plastic is composed entirely of inorganic instead of organic polymers (i.e. non-carbon-based polymers such as polysiloxanes and polyphosphazenes), then these inorganic components and/or polymers do not undergo biodegradation as defined above (i.e. they will not be microbially utilised to form CO_2 (and CH_4) and microbial biomass). Such plastics will therefore require a separate scientific assessment and regulatory considerations related to these inorganic components, possibly on a case-by-case basis. A clear recommendation is that plastics purely composed of inorganic polymers ought not to be labelled 'biodegradable', as this would be in violation of the definition above. For open environment applications, it would need to be demonstrated that inorganic constituents and polymers are benign from an ecotoxicological perspective and, for the inorganic polymers, do not persist in the environment but instead readily react to form low molecular weight inorganic compounds and salts.

For the above definition of plastic biodegradation, one type of inorganic additive in plastics requires particular attention in the assessment of plastic biodegradation: carbonates (i.e. inorganic salts of the anions HCO_3^- and CO_3^{2-}). Carbonates can readily protonate under acidic conditions to form carbonic acid H_2CO_3, which then may decompose under the formation and release of CO_2. Since CO_2 is the key measurement endpoint of biodegradation according to the definition above and in laboratory plastic incubation tests (see Chapter 4), the potential contribution of carbonates to the total CO_2 output during incubations needs consideration when assessing or certifying biodegradation of plastics that contain carbonates. Not considering the contribution from carbonates may lead to an overassessment of plastic biodegradation and thus possibly false claims of plastic biodegradation.

The above definition of plastic biodegradation is more specific and restrictive than the generic definition given by IUPAC: 'Breakdown of a substance [plastic] catalysed by enzymes in vitro or in vivo' (Vert et al., 2012a). We decided against adopting the latter definition for a number of reasons:

- First, we feel strongly that the definition of biodegradation requires clearly defined measurement endpoints that capture the critical step in plastic biodegradation: microbial utilisation of the plastic carbon. These measurement endpoints are the formed amounts of CO_2 (or CO_2 and CH_4 under anoxic, methanogenic conditions), as well as microbial biomass.
- Second, the breakdown of the plastic into smaller units (i.e. Step 1 of biodegradation, as detailed in Section 2.5 below) is a required and necessary but, by itself, insufficient step to claim plastic biodegradation. For biodegradation, it is critical also to demonstrate microbial utilisation of the formed lower molecular weight plastic degradation products.

- Third, while microbial enzymes play a key role in catalysing the breakdown of many biodegradable polymers (as well as of natural biopolymers), it is conceivable that this breakdown occurs either in part or completely abiotically (e.g. through abiotic hydrolysis of ester bonds in the backbone of polyesters).

- Fourth, we refrained from using the attributes *in vitro* or *in vivo* because the focus is on plastic biodegradation in the *open environment*. While laboratory (i.e. *in vitro*) tests play an important role in assessing plastic biodegradation, Chapter 4 addresses challenges and uncertainties associated with using laboratory test results to predict biodegradation in the open environment. Also, we deliberately excluded biomedical applications of biodegradable plastics, so the attribute *in vivo* is inappropriate for the considerations in this report.

In the context of this report, plastic biodegradation is considered a *desirable* process that ensures that the plastic used in specific applications does not persist after its use in the open environment. The definition of plastic biodegradation provided above reflects this view; the definition clearly delineates 'biodegradation' — which involves extensive reworking of the plastic carbon to CO_2 (or CO_2 and CH_4 under anoxic, methanogenic conditions) and microbial biomass — from purely 'biodeterioration' processes. 'Biodeterioration' more broadly refers to the impact of microorganisms on the properties of plastics (which, as a matter of fact, are often considered undesirable), but does not stipulate extensive metabolic utilisation of the plastic carbon by microorganisms. For instance, a plastic cannot be classified as biodegradable on the basis of data that only shows that a biofilm forms on the plastic surface (i.e. biodeterioration of a plastic by biofilm formation). This is because microbial colonisation occurs not only on biodegradable plastics but also on the surfaces of conventional, non-biodegradable plastics (Amaral-Zettler et al., 2020; Zumstein et al., 2018). Finally, the definition of plastic biodegradation provided herein also aims at preventing unjustified claims of plastic biodegradability on the basis of data only showing decreases in the average molecular weight of the polymer(s) composing the plastic, but falling short of providing proof for subsequent extensive microbial metabolic utilisation of the plastic and its degradation products. The importance of the latter aspect is explained in more detail below, after introducing the steps involved in plastic biodegradation.

We specified above that plastic biodegradation is a desirable process *after* the plastic has been used in its specific application. Clearly, *during* the specific application, the plastic material needs to be sufficiently stable in its characteristics to fulfil its desired function. This highlights one of the major challenges of designing biodegradable plastics: ensuring function during use (which requires stability over the application period), while at the same time 'encoding' instability after use to allow for fast biodegradation. These two traits can be challenging to align, requiring the combined expertise of material and polymer chemists on the one side and of environmental chemists, microbiologists, and ecologists on the other side.

In the following discussion, we deliberately refrain from complementing the term 'biodegradable plastic' by additional attributes such as 'inherent', 'ready', 'primary' and 'ultimate' (or combinations thereof). While these attributes have been proposed to

help categorise biodegradation characteristics of low molecular weight compounds of concern (e.g. traditional agrochemicals) and some of these attributes now have been defined also for polymers (e.g. ultimate and inherent biodegradation; Chinaglia & Degli-Innocenti, 2018a; Müller, 2005; Vert et al., 2012a), the attributes have the potential to create confusion and, for this report, are not considered helpful in terms of clarity. Nonetheless, we choose to briefly address the meanings of the terms 'inherent' and 'ultimate' and to provide a rationale for not using these attributes explicitly:

The **inherent biodegradability** of a compound (here, plastic or polymer) typically refers to tests that are deliberately designed and set up to favour biodegradation of the compound. The idea is to readily assess if the compound (here, plastic or polymer) has the *potential* to undergo biodegradation (OECD, 2005). While we do not disagree that this concept is helpful to assess whether a plastic or polymer can, in principle, undergo biodegradation, we are concerned that the concept of 'inherent biodegradability' may be misunderstood, misinterpreted or even misused to insinuate that biodegradation is a specific material property of the plastic or polymer and not, as specified above, a system property. We strongly favour the conceptual approach of treating plastic biodegradability as a system property, given that the open environment consists of distinct ecosystems which broadly vary in abiotic and biotic conditions that affect plastic biodegradation (as detailed below). Biodegradability is considered to result from the interplay between material properties that provide the potential for biodegradation to occur, in combination with the environmental conditions that match this potential and, thereby, allow for biodegradation to occur. Viewing biodegradation as a system property has been proposed as a conceptual idea also for the stability of naturally occurring biopolymers in the open environment (Schmidt et al., 2011). We prefer this latter concept because of the large variations in the conditions affecting biodegradation in the open environment. Due to these large variations, we may find plastics that biodegrade in idealised test systems but fall short of biodegrading to an acceptable degree in many natural systems in the open environment. In such cases, the attribute 'inherently biodegradable' for that plastic is misleading. We note, however, that the view of plastic biodegradation as a system property by no means precludes the possibility that a specific plastic biodegrades across different ecosystems, nor that there are many types of plastics that biodegrade in a specific receiving environment.

Ultimate biodegradation is typically used when there is evidence for a given compound to be biodegraded completely to CO_2, biomass, H_2O and, if the compound contains other heteroatoms such as N, to other inorganic compounds, like NH_3 or N_2. However, we refrain from the use of this attribute, as we have incorporated the necessity for complete microbial metabolic utilisation of plastic or polymer carbon under formation of CO_2 (or CO_2 and CH_4) and microbial biomass into the very definition of plastic biodegradation itself.

2.4 DEFINITION OF 'OPEN ENVIRONMENT'

In this report, we use the term 'open environment' in a generic sense:

> **Open environment refers to all natural (eco)systems, ranging from systems that are (near to) pristine to systems heavily impacted by human activities.**

These ecosystems include terrestrial environments (e.g. soils), riverine and lacustrine freshwater environments, as well as marine environments (e.g. estuaries and oceans).

While the term 'open environment' includes both pristine and human-impacted ecosystems such as agro-environments, we exclude completely man-made, managed systems such as industrial and domestic composts from the term. Even so, in this report we repeatedly refer to compost and plastic biodegradation in compost, for a number of reasons:

- First, biodegradable compostable plastics (i.e. plastics that biodegrade in compost) make up a major share of the current market of biodegradable plastics. Furthermore, some of the polymers used in compostable plastics are also used in biodegradable plastics for applications in the open environment.

- Second, plastic biodegradation in compost, as opposed to in many natural systems, has been extensively studied and is, compared to the open environment, better understood (Kale, Auras, Singh, & Narayan, 2007; Mohee, Unmar, Mudhoo, & Khadoo, 2008; H. S. Yang, Yoon, & Kim, 2005). Thus, the information on biodegradation in compost provides a mechanistic and conceptual understanding that can inform our understanding of plastic biodegradation in the open environment (in full recognition that conditions prevailing in compost fundamentally differ from those in the open environment).

- Third, industrial compost itself may be a source of biodegradable plastics in the open environment; for instance, compostable bags that did not undergo complete biodegradation during composting may be co-transferred with the compost to agricultural soils that are amended by compost (Weithmann et al., 2018).

While the focus in this report is on the biodegradability of plastics in the open environment, we note that biodegradable-compostable plastics play an important role in the waste hierarchy also for managed composting systems. For instance, polymeric packaging and labelling materials that undergo biodegradation in industrial composting facilities can divert waste from undesired end-of-life scenarios, such as landfilling and open dumps. These biodegradable-compostable materials are designed to biodegrade with food, paper, and biowastes to CO_2, microbial biomass, and, if applicable, mineral salts in managed composting systems (Narayan, 2014a; 2014b).

The use of the term 'open environment' by no means implies that there is only one open environment in which plastics biodegrade. Instead, a central point in this report is that the open environment comprises a multitude of ecosystems with a range of abiotic and biotic conditions that affect plastic biodegradation. This point is addressed more explicitly in the subsequent discussion.

Extension of definitions of 'biodegradation' and 'open environment' for regulatory purposes.

The above science-based definitions of 'plastic biodegradation' and 'open environment' need further elaboration when considering their implementation in a regulatory context. This elaboration concerns two critical aspects related to plastic biodegradation in the open environment.

First, the above scientific definition of '*plastic biodegradation*' specifies neither the duration over which, nor the extent to which, a plastic material is required to undergo biodegradation. Yet, from a regulatory perspective and for product certification, it is critical to define the maximum timeframe over which a certain extent of biodegradation needs to be attained in a given receiving environment to allow the plastic to be considered or labelled biodegradable. This aspect is detailed further in Chapter 4 and addressed also in Figure 2.3 below. The required biodegradation times and extents are application- and product-specific. In defining them, consideration needs to be given to potential ecological impact, as well as steady state (i.e. transient) concentrations of biodegradable plastics in a specific environment that are considered environmentally acceptable.

Current regulatory timeframes over which biodegradation is assessed range from a few months up to two years (see Chapter 4). Over this time period, biodegradation is typically required to result in a high percentage conversion (e.g. in excess of 90%) of the carbon of the tested plastic or polymer to CO_2 (or CO_2 and CH_4; see Chapter 4 for details). For many applications, defining such high percentage conversions over comparatively short timeframes are meaningful and desirable (e.g. the conversion of a biodegradable-compostable bag in an industrial composter or a biodegradable mulch film in agricultural soils). At the same time, we note that future research efforts, as well as regulatory considerations, ought to be directed also towards addressing biodegradable plastics that biodegrade more slowly over slightly longer periods of time (e.g. 2-10 years). We raise this point because currently there is a clear disconnect between biodegradable plastics, which are requested to biodegrade over a few months, and conventional, non-biodegradable plastics that persist in the open environment for hundreds of years (Chamas et al., 2020). We anticipate numerous applications of plastics that currently lead to long-term environmental pollution by conventional plastics but for which plastics cannot be used if these readily biodegrade over periods of less than 2 years (i.e. the plastic is insufficiently stable for the specific application). In such applications, which clearly would require particularly careful regulatory and scientific assessment, more slowly biodegrading plastics may play a role in decreasing environmental plastic pollution. Recent publications highlight the need for considering slowly degrading polymers for applications in the open environment and suggest accelerated biodegradation tests for the certification of such slowly biodegrading polymers (Šerá, Serbruyns, De Wilde, & Koutný, 2020).

Second, the term 'open environment' is too broad and generic when it comes to regulation and certification of biodegradable plastics. This is due to the fact that both abiotic and biotic factors governing the rates and extents of plastic biodegradation

vastly vary between different natural systems in the open environment, as detailed below. It therefore is important to rigorously define in which specific natural environment biodegradation is considered and assessed. Biodegradation rates may vary not only between different ecosystems (e.g. a forest and an open ocean) but even between individual members of each ecosystem (e.g. among agricultural soils; Narancic et al., 2018). These variations reflect differences in the conditions between these systems, such as temperature, humidity, pH, and the community composition and activity of microorganisms involved in biodegradation. The importance of specifying in which system biodegradation of plastic is assessed is further discussed in detail in Chapter 4. Here, it suffices to say that a discussion of biodegradation of plastics always needs to take place in a context that specifies the receiving environment under discussion. Doing so clearly does not preclude the possibility that a plastic (or polymer) biodegrades in multiple very different receiving environments.

2.5 STEPS INVOLVED IN PLASTIC BIODEGRADATION

We have provided a definition of plastic biodegradation above and emphasised the importance of ensuring that the organic constituents in the plastic are extensively reworked by microorganisms to CO_2 (or CO_2 and CH_4 under anoxic conditions), microbial biomass and mineral salts. The definition of plastic biodegradation itself, however, does not provide a deeper process understanding of the underlying process. This section aims at providing this understanding.

According to the current scientific understanding, the overall process of plastic biodegradation results from successful completion of two consecutive steps (Figure 2.3; e.g. Agarwal, 2020):

1. **Step 1 is the breakdown of the polymer in which the carbon in the polymers composing the plastic (i.e. macromolecular organic carbon) is converted into low molecular weight organic compounds that are released from the bulk plastic material and that are of sufficiently small size (i.e. have sufficiently low molecular weights) to subsequently enter Step 2.**

2. **Step 2 is the microbial uptake of these low molecular weight compounds followed by their intracellular metabolic utilisation, leading to the above-defined endpoints of biodegradation (CO_2, CH_4 and microbial biomass).**

We explicitly note that we decided against considering 'microbial colonisation' of the plastic surface as a separate, initial step (which would result in a total of three consecutive steps for plastic biodegradation), even though microbial colonisation is often considered a separate, initial step in the literature (e.g. Haider et al., 2019). The reason for this decision is twofold. First, microbial colonisation can be involved but need not be involved in the formation of low molecular weight organic compounds; breakdown of the plastic may also occur purely abiotically, without the involvement of microorganisms and their extracellular enzymes (e.g. Lucas et al., 2008). Strictly speaking, even for plastics for which Step 1 is catalysed by extracellular enzymes secreted from microorganisms (and for which there are no abiotic reactions that lead to the release of low molecular weight organic compounds in Step 1), Step 1 does not require microbial colonisation

of the plastic surface but instead may proceed as long as the enzymes secreted by microorganisms reach the plastic surface. Second, microbial colonisation of a plastic surface by itself provides no evidence in support of Step 1 (nor of biodegradation itself). This is due to the fact that microbial colonisation is well documented also of conventional, non-biodegradable plastics in the open environment. The widespread occurrence of microorganisms on plastic surfaces may simply reflect that these are microenvironments favourable for microbial cell attachment and proliferation (Kirstein, Wichels, Gullans, Krohne, & Gerdts, 2019; Zettler, Mincer, & Amaral-Zettler, 2013) and does not imply that the colonised plastic item acts as a carbon and energy source to the colonising microorganisms.

Step 1 entails chemical reactions — abiotic or enzymatically mediated — that act on the bulk plastic material and that result in the release of low molecular weight organic compounds from the polymers that constitute the bulk plastic. In general, this first step can be referred to as 'plastic breakdown'. If, for instance, the plastic is composed of one or more polyesters, a key reaction is the hydrolytic cleavage of ester bonds in the polyester backbone under release of short oligomers and monomers that constituted the polyester. This first step may, in principle, occur through abiotic reactions (e.g. by non-enzymatic hydrolysis or through photochemical scissions in the backbone of the polymer), biotic reactions (e.g. catalysed by extracellular enzymes secreted by microorganisms), or a combination of both. Since many biodegradable plastics are based on polymers with hydrolysable bonds (e.g. esters, amides and glycosidic bonds) in their backbone, the enzymes that catalyse Step 1 are often hydrolases (Gan & Zhang, 2019; Meereboer et al., 2020; Urbanek et al., 2020). It is critical that the organic molecules released in Step 1 are of sufficiently small size that they can be taken up and subsequently be metabolically utilised by microorganisms. It is likely that the upper molecular weight limit of organic compounds that can be taken up by microorganisms is dependent on the microbial strain and is affected by the polarity, charge and conformation of the molecule. While no exact number can be given, it is likely that the molecular weight for passive diffusive uptake into the cell is in the range of a few hundred grams per mol. This limit applies to the passive, diffusive uptake of molecules across the cell membrane, as microorganisms may also actively take up very specific molecules, also of larger size, by transporters in their cell membranes.

It is important to emphasise that plastic breakdown in Step 1 is a necessary but, by itself, insufficient step to ensure that the plastic biodegrades. Plastic biodegradation requires that Step 2 is also completed. It is clear that plastics are non-biodegradable if they undergo Step 1 but only break down or fragment to micro- and nanometre-sized particles and oligomeric chains that subsequently cannot be taken up into microbial cells and be metabolically utilised.

Step 2 is the uptake of the low molecular weight organic compounds into microbial cells, followed by the metabolic utilisation of these molecules for energy generation (catabolism) under formation of CO_2 (or CO_2 and CH_4 under anoxic conditions) and the synthesis of new microbial biomass (anabolism). This conversion of polymer-derived carbon to CO_2 (or CO_2 and CH_4) and the incorporation of polymer-derived carbon

into microbial biomass are both desired endpoints of biodegradation. In this report, we refer to the conversion of the plastic-derived carbon to CO_2 (or CO_2 and CH_4) as 'mineralisation'. The end products CO_2 (or CO_2 and CH_4) are accessible in laboratory plastic biodegradation tests by coupling incubations of the plastic in an environmental matrix (e.g. soil, sediment, water) to respirometric analyses of the CO_2 (and CH_4) that builds up in the headspace of the incubation vials (Eubeler, Zok, Bernhard, & Knepper, 2009). By comparison, incorporation of carbon into microbial biomass over the course of the incubation is considerably more difficult to quantify. The use of stable carbon isotope labelled biodegradable polymers, combined with isotope-sensitive and selective surface imaging techniques of microorganisms colonising the surface of these polymers, has recently been shown to demonstrate incorporation of polymer-derived carbon into the microbial biomass (Zumstein et al., 2018). In any case, it is important to keep in mind that microbial biomass containing plastic-derived carbon is also subject to re-mineralisation to CO_2 (or CO_2 and CH_4), such that CO_2 (or CO_2 and CH_4) are the designated ultimate end products of plastic biodegradation. Respirometric analyses in laboratory incubations thus form the mandatory basis of laboratory testing and certification of biodegradable plastics (Eubeler et al., 2009) as detailed in Chapter 4.
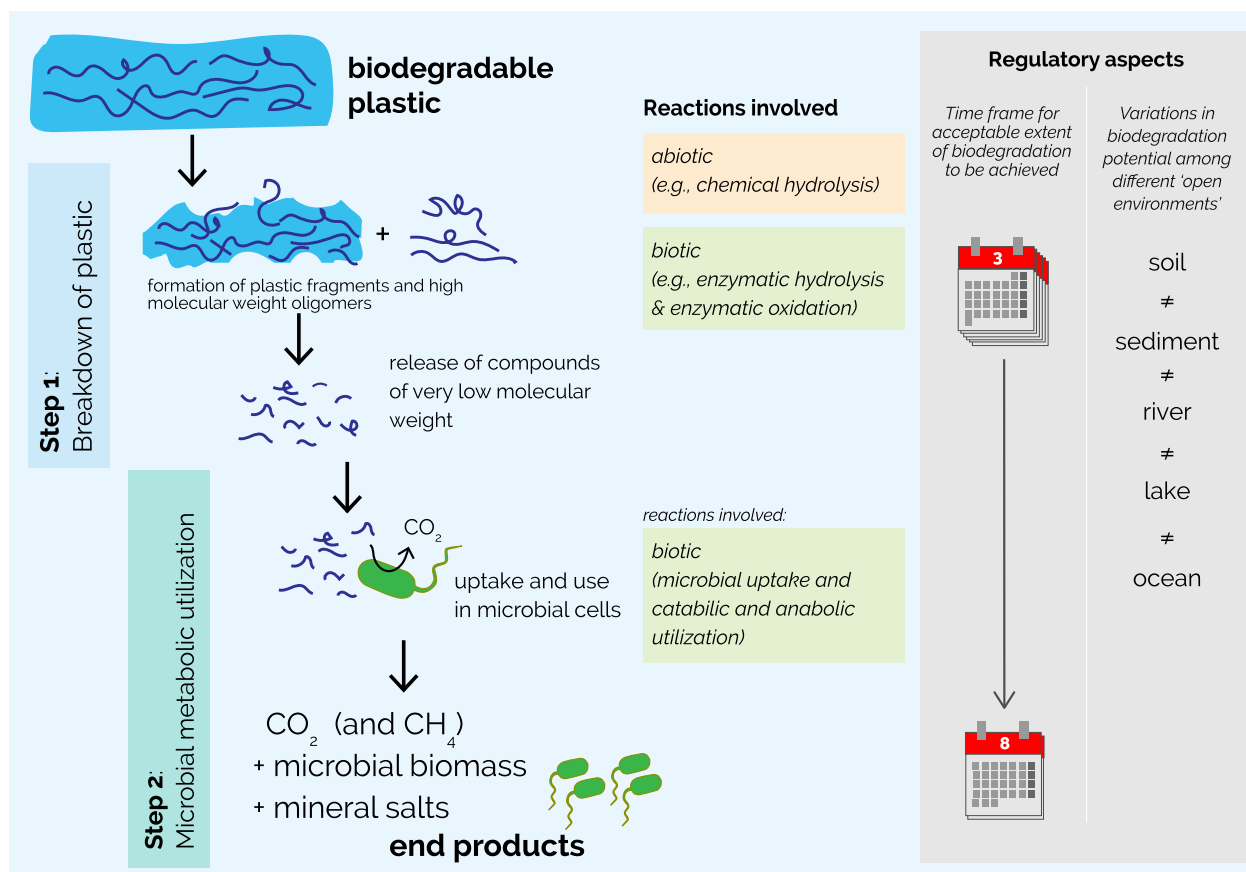
Figure 2.3:. Overview of two key steps involved in plastic biodegradation. Step 1 is the breakdown of the plastic into low molecular weight products that have sufficiently low molecular weights to be utilised by microorganisms. Step 2 is the microbial utilisation of plastic degradation products formed in Step 1, under formation of CO_2 (or CO_2 and CH_4 under anoxic conditions) and microbial biomass. In grey are regulatory aspects that require consideration; the timeframe and extent of biodegradation that is environmentally acceptable and the need to specify the environment in which biodegradation occurs or is assessed, given large variations in the conditions that affect biodegradation across the open environment.

An important implication of the above is that any claims of plastic biodegradability requires a demonstration, in laboratory tests, of the successful completion of Step 2, and thus that all organic components of the plastic are converted to CO_2 (or CO_2 and CH_4) and microbial biomass (see Chapter 4). Providing data only on completion of Step 1 (i.e. data demonstrating a decrease in the molecular weight of the polymeric building blocks of the plastic) is not a sufficient measurement endpoint for biodegradation because it falls short of demonstrating this process.

However, it is important to emphasise that it often is Step 1 that controls the overall rate at which plastic items biodegrade in the open environment, independent of the receiving system. In other words, the release of plastic-derived low molecular weight organic compounds is often significantly slower than the subsequent uptake of these compounds into microbial cells and their intracellular metabolic utilisation (i.e. Step 2). While it is impossible to put generally valid timeframes on these two steps, for many biodegradable plastics in the open environment Step 1 occurs over the range of weeks to months to years whereas Step 2 typically has timescales of hours to weeks. We can therefore draw two conclusions. First, plastic physicochemical properties and environmental conditions that facilitate Step 1 will increase the rates and extents of plastic biodegradation in the open environment. We will discuss the plastic properties and environmental conditions that affect plastic biodegradation in more detail below. Second, studies that assess controls on rates and extents of plastic breakdown (i.e. Step 1) are of critical importance to understanding overall biodegradation dynamics of these plastics in the open environment (Kijchavengkul et al., 2010) as well as for designing future biodegradable polymers for open environment applications.

In general, the importance of Step 1 to the environmental stability of plastics, including biodegradable as well as conventional plastics, cannot be overestimated. For a plastic to readily biodegrade, Step 1 must occur over the timeframe of weeks to months to at most a few years (according to current regulations; Narancic et al., 2018). If Step 1 is extremely slow, the respective plastics persist in the environment. This is the case for many conventional plastics, including PE, PP, PS and PET. Low molecular weight building blocks of these materials (i.e. short chain alkanes, terephthalic acid and ethylene glycol), if they were to be released from these polymers, would be readily taken up and metabolically utilised by microorganisms (Yoshida et al., 2016). The importance of Step 1 for plastics biodegradation also puts plastic into a different category than low molecular weight organic pollutants and chemicals of concern. These include, for instance, conventional pesticides, drugs, and hormones. Such low molecular weight compounds can often be directly taken up into microbial cell and therefore, in contrast to plastics, do not require prior extracellular breakdown into lower molecular weight products. This difference between plastics and traditional low molecular weight organic molecules of concern also implies that care must be taken when applying regulatory concepts developed for low molecular weight compounds to plastic materials. The latter have one additional layer of complexity that results from plastic breakdown being required (Step 1) to allow for microbial uptake and ultimately for biodegradation.

2.6 FACTORS CONTROLLING PLASTIC BIODEGRADATION IN THE OPEN ENVIRONMENT

This report considers plastic biodegradation to be a system property, in that it results from the interplay of physicochemical properties of the plastic material that define the potential for the plastic to be biodegraded as well as suitable conditions in the receiving environment that leverage this potential. A direct consequence of considering plastic biodegradation as a system property is that any assessment or claim of biodegradation needs to be contextualised to a specific receiving environment (e.g. terrestrial, riverine, lacustrine or marine systems).

While biodegradation arises from the interplay between material-dependent and environmental factors, we will, in the following, separately discuss material-dependent and environmental factors that control plastic biodegradation. We separate these factors to provide a more systematic insight into the controls of plastic biodegradability in the open environment and, by no means, indicate that these factors act in isolation.

2.6.1 Polymer-dependent factors

Chemistry of the polymer backbone

As detailed above, plastic biodegradation necessitates that the polymer(s) composing the plastic break(s) down into compounds that have sufficiently low molecular weights (i.e. Step 1 above) to be taken up and be metabolically utilised by microorganisms (i.e. Step 2). A key factor that affects the propensity of a polymer to undergo Step 1 is its backbone chemistry. More specifically, the backbone chain needs to contain chemical bonds that are prone to undergo a reaction that leads to bond breakage and thus backbone chain scission. Most commonly, these are hydrolysable bonds (that is, water molecules react with these bonds; C.-C. Chen, Dai, Ma, & Guo, 2020; Gross & Kalra, 2002). These hydrolysable bonds include esters and amides as well as glycosidic bonds (Gross & Kalra, 2002; Haider et al., 2019; Vroman & Tighzert, 2009). It is, however, important to recognise that not every polymer that contains a hydrolysable bond in its backbone actually hydrolyses readily in the open environment. A clear example of a polymer that contains a hydrolysable bond but does not readily hydrolyse in the open environment is polyethylene terephthalate (PET). PET is considered persistent in the open environment because the ester bonds in its backbone between a terephthalic acid (T) building block and the ethylene glycol (E) units are not readily enzymatically nor abiotically cleaved. Persistence of PET in the environment does not preclude that some microorganisms exist that can secrete PET-hydrolysing esterases. We note that such 'PET-ases' may play an important future role in PET recycling under controlled conditions (Kawai, Kawabata, & Oda, 2020; Taniguchi et al., 2019; Tournier et al., 2020; Yoshida et al., 2016), but their existence certainly does not render PET biodegradable in the open environment. The example of PET shows that case-by-case assessment and testing is needed whether or not a hydrolysable bond in a polymer backbone undergoes abiotic and/or enzymatic hydrolytic cleavage in a specific receiving environment.

It is possible to deduce from the above that polymers without chemical bonds that can be readily broken (e.g. by hydrolysis) persist in the environment. This logic indeed holds true. Here, illustrative examples are polyolefins (e.g. polyethylene (PE) and polypropylene (PP)), and for instance polystyrene (PS) or polyvinylchloride (PVC). The backbone chains of these polymers are composed entirely of carbon-carbon bonds, which are extremely stable and cannot readily be cleaved, either abiotically or enzymatically (Gross & Kalra, 2002). Therefore, these polymers are non-biodegradable and persist in the open environment by virtue of Step 1 being extremely slow under open environment conditions.

Because of the high stability of C–C bonds in polyolefins and other petrol-based vinyl polymers, in combination with their high production and market volumes and their ubiquitous occurrence in the environment, efforts have been and are still directed towards developing chemical additives for these polymers that supposedly allow for or facilitate breakdown of the polymer backbone upon thermal or light activation of the additives. The most recognised among these chemicals are so-called 'oxo' (pro-oxidant) additives. These contain metal salts (often iron, nickel and cobalt) that — upon external UV-light or thermal treatment for activation — trigger oxidation reactions involving radical species that ultimately result in breaking of the C–C backbone bonds in the polymers and, thereby, the formation of compounds of lower molecular weight.

However, considerable concern has been raised within the scientific community that these oxo-additives do not render polymers biodegradable, as claimed by the oxo-additive industry (Ellen MacArthur Foundation, 2017; Kubowicz & Booth, 2017; Roy et al., 2011; Selke et al., 2015). These concerns are typically founded on two points (Deconinck & De Wilde, 2013):

- First, while light or thermal activation on the additive-containing polymers was indeed shown to shift the molecular weight distribution of the polymers towards lower values, there is still no experimental evidence that the entire polymer is converted into low molecular weight molecules that are sufficiently small to be completely taken up and metabolised by microorganisms. In other words, it is conceivable that the initial breakdown remains incomplete and that breakdown products of the polymer (Step 1) remain too large for microbial utilisation (Step 2) to proceed. Clearly, polymer incubation studies that demonstrate extensive conversion of all polyolefin carbon to CO_2 (or CO_2 and CH_4) and microbial biomass are needed to demonstrate biodegradation.

- Second, evidence in support of Step 1 for oxo-additive containing polymers often stems from experiments in which the activation of the additive is conducted at temperatures and light intensities that are higher than those found in the open environment. The accelerated weathering conditions during the tests are deliberately chosen to facilitate the additive-induced breakdown process and were justified by arguing that higher rates under accelerated weathering conditions can be used to extrapolate lower rates of the same process under open environment conditions at lower temperatures or light intensities. However, such extrapolations have not been experimentally validated (e.g. by demonstrating that the Arrhenius rate law applies to polymer breakdown during weathering) and thus remain speculative.

While these two points by themselves suffice to dismiss claims that oxo-degradable plastics are biodegradable according to the definition provided above, there is a third consideration that raises principal concern on any activation-dependent additive technology marketed to render non-biodegradable polymers biodegradable in the open environment. This concern is based on the fact that it is challenging to control the whereabouts of plastic items in the open environment (particularly when resulting from mismanaged waste and littering) and, as a consequence, that plastics containing these additives may reside in environments in which activation does either not occur or in which activation is extremely slow (e.g. lack of photochemical or thermal activation in dark or colder (aquatic) environments). We note that this concern holds true even for applications of plastics in which most, but not all, of the plastic undergoes activation. An illustrative example may be agricultural mulch films. While most of the foils may be exposed to light and thereby activated, the edges of the foils are typically buried in the soil to hold the foil in place. These buried parts would not undergo light activation and thus not undergo breakdown in Step 1. By contrast, biodegradable polymers that rely on the hydrolytic cleavage of bonds in their backbone to achieve breakdown in Step 1 are expected to undergo hydrolysis in almost all open environments (with maybe the sole exception of very dry environments, such as some deserts).

Crystallinity

As detailed above, the backbone chemistry of a polymer is key in defining its potential to undergo biodegradation. However, even for polymers that have chemical bonds in their backbones that favour Step 1 of biodegradation (e.g. hydrolysable ester bonds), the propensity for these bonds to actually react and break is strongly modulated by how strongly the individual polymer strands in a plastic material interact with one another. This phenomenon is particularly well documented for the enzymatic hydrolysis of ester bonds in biodegradable polyesters (Benedict et al., 1983; Chen et al., 2020; Zhihua Gan et al., 2004; Kuwabara et al.,, 2002; Marten et al., 2003, 2005; Mueller, 2006; Müller et al., 2001; Nikolic & Djonlagic, 2001; Scherer et al., 1999; Timmins, 1994; Tokiwa et al., 2009; Tokiwa & Suzuki, 1981; Wei & Zimmermann, 2017; Welzel et al., 2002). Many of these polyesters are semicrystalline, meaning that the bulk polymer contains two different types of regions. In the amorphous region, the individual polymer chains lack ordered arrangements. As compared to the crystalline regions, the chains in the amorphous region are packed relatively loosely and have a comparatively high degree of freedom, particularly at temperatures above the so-called glass transition temperature (T_g) of the amorphous region of the polymer (the T_g is the temperature at which there is a reversible transition between a glassy state ($T<T_g$) with restricted chain mobility to a rubbery state ($T>T_g$) with increased chain mobility). Conversely, in the crystalline regions, the individual polymer chains adopt a highly ordered 'lamellae' structure in which the individual chains strongly interact with one another and have little degree of mobility. These crystalline lamellae are nanometer-sized but can often form larger spherulites that are embedded into the amorphous regions. Enzymatic hydrolysis of backbone ester bonds is typically much faster for polymer strands in the amorphous (particularly at temperatures above T_g) than in the crystalline regions; as compared to the crystalline region, the higher

flexibility of chains in amorphous regions facilitates that ester bonds within the chains enter the active site of the esterase and are cleaved. The melting temperature, T_m, defines the temperature at which these crystals melt and thus the temperature at which crystalline regions are transformed into amorphous regions. Numerous studies have shown for series of polyesters that their enzymatic hydrolysability decreases as T_m increases (Marten et al., 2005; Mueller, 2006; Tokiwa et al., 1990; Tokiwa & Suzuki, 1978; Zumstein et al., 2018). In part, this explains why PET is environmentally persistent despite having hydrolysable ester bonds in its backbone: the T_m of PET is very high at approximately 255°C, and its T_g is 69°C, which is well above temperatures of the open environment (Jog, 1995; Mehta, et al., 1978).

There are three additional and important points that need consideration when discussing the effect of crystallinity on plastic biodegradation.

The first point is that crystallinity is, in many cases, desired for the application phase of the plastic; while crystalline regions slow down the breakdown (Step 1) in overall biodegradation, the presence of crystalline regions typically makes the plastic stronger and stiffer. A polymer with little or no crystallinity may be too soft for its intended application. The objectives 'desired material properties during use' and 'biodegradability after use' may thus oppose each other when it comes to plastic material design and crystallinity and may require careful balancing. In other words, the challenge is to design plastics with the desired material properties to fulfil their function during use, yet readily biodegrade thereafter.

The second point that needs consideration is that the processing history of a given plastic may strongly modulate its crystallinity (Iwata, 2005; Kumagai, Kanesawa, & Doi, 1992; G. Li, Shankar, Rhim, & Oh, 2015; Parikh & Gross, 1992) and thus its biodegradation characteristics in the open environment. This point may imply that the actual commercial plastic product — and not only the polymers from which the plastic is composed — are required to be tested in biodegradation assays for certifications. This is particularly true in cases where the processing of the polymers into the plastic results in a higher crystallinity of the plastic product (and hence likely slower biodegradation) than of the original polymer(s) from which the plastic was formed.

The third consideration is that the crystallinity of a given polymer is strongly affected by its molecular weight and dispersity. Thus, the biodegradation of a particular polymer may vary even in the same environment if two polymer specimens are compared that vary greatly in molecular weight and dispersity, both of which may strongly modulate polymer crystallinity (and hence its propensity to undergo biodegradation).

Plastic surface to volume ratio

As detailed above, breakdown Step 1 of plastic biodegradation involves abiotic as well as enzymatically mediated chemical reactions that lead to the formation of polymer-derived low molecular weight organic compounds. In principle, these reactions may occur both in the bulk of the plastic (e.g. abiotic hydrolysis of polylactic acid), a process then referred to as 'bulk erosion', as well as on the plastic surface, a process referred

to as 'surface erosion'. Enzymatically mediated reactions are considered to lead initially to 'surface erosion' (Abe & Doi, 1999), as most of the enzymes are too large to enter into the plastic. As a consequence, the rate at which a specific biodegradable plastic will undergo Step 1 will scale positively with the surface-to-volume ratio of a plastic item; for a given mass of plastic, items are more prone to surface erosion when present as thin objects or as small particles, as opposed to being present as a single object with a low surface-to-volume ratio.

The importance of the specific surface area to enzymatic degradation has important implications. First, testing and certification of plastic biodegradation is often performed on plastic powders (e.g. particles sieved to < 250-300 µm). Biodegradation rates obtained in these tests may therefore be higher than for the actual objects used in open environment applications, if these objects have a much smaller surface-to-volume ratio. This point needs consideration in tests on polymer biodegradation (Chapter 4). A second implication is that physical disintegration and fragmentation of a biodegradable plastic object in the open environment (e.g. under mechanical forces caused by the action of waves or tear by macrofauna) is expected to increase the overall biodegradation rate of this plastic because of the resulting increase in its specific surface area. Concerns that biodegradable plastics, as compared to conventional plastics, bear an elevated risk of forming micro- and nanoplastics would clearly be unjustified if biodegradation rates increase with decreasing particle sizes (unless the plastic contains nanometer-sized crystalline domains and/or polymers that do not readily degrade, even at a high surface-to-volume ratio).

Additives

As already alluded to above, plastics typically contain additives to bestow material properties on the plastics that are desired or necessary in their specific applications. Additives are commonly stabilisers and thus are expected to also affect the plastic's biodegradation characteristics after use. In any case, potentially negative but also positive effects of additives on plastic biodegradation warrant assessment in testing and certification of plastic biodegradation (Chapter 4). One example to highlight the complex effects of additives on biodegradation is photo-stabilisers. These are added to the plastic to protect it against photochemically-induced oxidations and radical chain scissions during use. On the one hand, these additives prevent polymer breakdown reactions, thereby decreasing the rate at which the plastic fragments and forms lower molecular weight compounds that may ultimately be microbially accessible. On the other hand, the photo-stabilisers may, in some plastics, prevent the formation of photo-induced cross-linking reactions between individual polymer chains which can negatively impact the enzymatic hydrolysability of these plastics, as shown for aliphatic-aromatic polyesters (De Hoe et al., 2019). This example highlights that photo-stabilisers may have opposing effects on plastic biodegradation.

A critical assessment of additives is particularly important when these are claimed to render non-biodegradable plastic (e.g. those composed of polymers with C-C bonds in their backbone) biodegradable. While concerns about oxo-additives have already been raised above, there are numerous, putatively new, additive

technologies on the market. These new technologies often claim to go beyond the traditional oxo(bio)degradation additives by involving some 'biological' enhancers, enzymes, or biotransformation technologies. While the exact composition of these new technologies remains undisclosed for proprietary reasons, such information needs to be disclosed and critically assessed when these products seek certification of biodegradation.

2.6.2 Environment-dependent factors

We have already emphasised the importance of considering plastic biodegradation in the open environment as a system property that depends on both plastic-specific factors, which define the potential of the plastic material to undergo biodegradation, and the characteristics of a specific natural receiving environment, which determine the extent to which the biodegradation potential of the plastic is leveraged. For the subsequent discussion of environmental factors that affect plastic biodegradation, it is important to realise that all of the listed factors vary widely between different ecosystems in the open environment. In fact, these variations are so large that traditional concepts which ascribe biodegradability mostly (or even exclusively) to plastic material characteristics need to be reconsidered.

The strong variations in conditions in the open environment have a number of implications for assessing plastic biodegradation. First, biodegradation rates and extents of a given plastic must always be linked to and discussed in the context of a particular type of receiving environment. Second, any transfer of biodegradable plastic items between receiving environments is expected to affect (either decrease or increase) the rates at which the item biodegrades and, therefore, the concentration and lifetime of that biodegradable plastic in the open environment. For instance, the sinking of a plastic item from the water column of the open ocean to the ocean sediment surface may increase its biodegradation rate. Examples for decreasing biodegradation rates are likely to include the unintended and undesired transfer of compostable plastic from an industrial composting facility to agricultural soils via the use of compost as soil amendment (noting that this transfer is unintended, as the compostable bags are designed such that they are expected to undergo complete biodegradation in the industrial composting process). However, the likelihood and the effects of such unintended transfer events of biodegradable plastics on their biodegradation rates are currently difficult to assess because reliable data on the extent to which the transfer of biodegradable plastics between receiving environments occurs is missing, and because there is a lack of biodegradation data on a consistent set of biodegradable plastics across different environments. Benchmark biodegradation rates of plastics across different receiving environments are a clear research need.

In this context, it is important to recall that differences in the biodegradation rates of polymeric substances between ecosystems are not plastic-specific but equally affect natural biodegradable biopolymers. A good example is lignin, a complex organic biopolymer that conveys structural stability to higher plants. While lignin readily biodegrades under oxic conditions with involvement of specific fungal

degraders, for instance, it persists for centuries to millennia in aerated forest soils under anoxic conditions. Manifestations of the slow biodegradation of lignin under anoxic conditions are Viking ships preserved in marine sediments. The reason for the high stability of lignin under anoxic, water-saturated conditions is that its breakdown relies on oxidases and peroxidases, which are enzymes that require oxidants (e.g. O_2 or peroxides) as co-substrates. These co-substrates are not available under anoxic conditions, so lignin becomes highly stable. In essence, the environmental conditions govern the extent to which the biodegradation potential of a plastic or of natural biopolymers is actually realised.

Arguably the most critical environmental factor that controls plastic biodegradation is the presence and activity of specific microorganisms that are involved in the overall biodegradation process. This is particularly true for those plastics that require the presence of specific extracellular enzymes to catalyse breakdown of the plastic (i.e. for plastics for which Step 1 of biodegradation does not occur or only slowly occurs abiotically). As a consequence, all environmental factors that define the community composition and regulate the activity of microorganisms will affect plastic biodegradation. These factors include temperature, moisture, availability of essential nutrients and electron acceptors, pH and salinity (Ahmed et al., 2018; Bonifer et al., 2019; Deroine et al., 2015; Dilkes-Hoffman et al., 2019; Ho & Pometto III, 1999; Pischedda et al., 2019; Volova et al., 2007). The discussion below will focus on temperature, the presence of microbial plastic degraders, and the availability of nutrients. We will not explicitly discuss the effects of salinity and pH as factors. The reason is that we consider these factors to have an indirect effect on plastic biodegradation, through shaping the microbial communities that form under the given conditions. Similarly, we will not explicitly discuss the effects of mechanical forces, such as impact by waves and wind or microfauna, or sunlight on plastic biodegradation. Mechanical forces are expected to facilitate fragmentation of biodegradable plastics and thus an increase in its specific surface area, and thus likely increase rates of biodegradation (see Section 2.6.1 above).

Irradiation of plastic by UV light is often considered to enhance microbial utilisation of plastic by virtue of photochemical reactions, leading to both plastic fragmentation and the formation of low molecular weight components that result from scission reactions in the plastic. While these effects are undoubtedly documented, it is important to point out that such reactions proceed very slowly and therefore affect only a very small fraction of the total carbon in the plastic. Furthermore, photochemically triggered reactions are restricted to sunlit environments. For plastics that reside in dark environments (or environments without UV light), photochemical reactions are absent, and the plastics persist. Finally, as alluded to above in the section on additives, photoirradiation-induced reactions may also result in the formation of cross-links between polymer strands, which may negatively impact the biodegradation of the plastic (but which may be prevented by the presence of environmentally-benign photo-stabilisers in the plastic).

Temperature

Temperature is arguably among the most important factors governing the rates of plastic biodegradation in the open environment (Deroine et al., 2015; Dilkes-Hoffman et al., 2019; Volova et al., 2007). First and foremost, as temperature increases, the rates of most abiotic and biotic reactions will increase (up to the point at which temperatures are so high that enzymes start to denature, and/or the activity of microorganisms starts to be impaired). The extent to which the rate of a specific reaction increases with temperature depends on the activation energy of that reaction. We illustrate the importance of temperature, assuming an enzymatically mediated hydrolysis reaction that controls the overall rate of plastic biodegradation and that has an activation energy of E_a= 50 kJ/mol (chosen here for simplicity of the following calculation). According to the Arrhenius rate law, the rate of this hydrolysis reaction increases by a factor of two for each increase in temperature of 10°C. The rate of this microbially mediated reaction (and hence plastic biodegradation) would therefore vary by a factor of eight if the temperature changes by 30°C (i.e. the rate is eight times lower at 5°C than at 35°C). Such temperature changes may be temporal (e.g. between seasons) or may occur spatially (i.e. environments with very different temperatures). The temperature dependence of the reaction will decrease as E_a decreases.

Besides affecting the rates of biotic and abiotic reactions, the prevalent temperature in a given ecosystem also selects for specific microbial consortia that thrive under these conditions; cold habitats are inhabited by psychrophilic microorganisms growing well at temperatures in the range 0-15°C and psychrotrophs in the range 4-25°C. Mesophilic microorganisms thrive between 20 and 45°C. We note that extreme environments, as well as industrial composting sites, may harbour thermophilic and hyper-thermophilic microbes that generally grow in the temperature range 50-80°C and 80-110°C, respectively. We will separately address the presence of competent microbial degraders below.

Temperature may further affect plastic biodegradation rates by affecting the physical state of the plastic. As alluded to above, many biodegradable plastics are composed of semicrystalline polyesters, composed of amorphous and crystalline regions. As compared to the polyester strands in the amorphous regions (and particularly when present in a rubbery state at $T>T_g$), the polyester strands in crystalline regions undergo much slower abiotic and enzymatic hydrolysis. These hydrolysis rates may, however, be largely accelerated as the temperature increases towards the melting temperature of the crystallites in the polyester or, in addition, above the T_g of the polymer when discussing a system with a rather high T_g. This finding has been ascribed to increasing diffusion rates of water into the polymer and the fact that higher temperatures facilitate the movement of polymer strands and thereby their propensity to bind to the active site of hydrolases.

While the effect of temperature on the enzymatic hydrolysis of polyesters is well studied and understood in laboratory systems, there are limited studies that have assessed the effect of temperature on complete plastic biodegradation. The latter is true not only for laboratory plastic incubations coupled to respirometric analyses of

CO_2 (or CO_2 and CH_4) as endpoint measurement for biodegradation. It is particularly true for biodegradation studies under field conditions. Scarcity of field studies on the effect of temperature are understandable, as temperature is neither easily controlled nor readily manipulated at a given field site. Such assessments would require multi-site and multi-year field experiments in which the receiving environments are similar (e.g. all soils) yet systematically differ in their temperature characteristics. A case example that assessed the effect of temperature is a study that assessed the biodegradation of selected polymers over a range of geographically spread soils and therefore under different climatic conditions. This study nicely demonstrated that biodegradation was positively correlated with the sum of effective days with temperatures above 10°C (Hoshino et al., 2001), suggesting that there may be 'threshold' temperatures below which biodegradation may become very slow.

Overall, it is to be expected that increases in temperature will facilitate biodegradation, provided that no constraints arise from other temperature-dependent factors (e.g. decrease in humidity or thermal inactivation of enzymes) nor other limitations (e.g. nutrient availability). However, because temperature affects biodegradation rates by several means (as discussed above), care must be taken when using results from plastic biodegradation experiments run at a specific temperature to extrapolate to other temperatures, particularly when extrapolating from high to low temperatures. This point needs consideration when critically assessing the transferability of results from laboratory incubation studies on plastic biodegradation conducted at elevated temperatures to open receiving environment that have, at least periodically, significantly lower temperatures (Chapter 4).

Presence of competent microbial degraders

Biodegradation of many polymers relies on the presence of specific microorganisms capable of secreting specific extracellular enzymes that have the capability to catalyse the breakdown of the polymer into smaller units (see Step 1 above). These enzymes are often hydrolases, given that the most important marketed biodegradable polymers contain hydrolysable bonds in their backbone chains (Figure 2.2). However, as discussed below, there are other types of reactions that can be enzymatically mediated and lead to the breakdown of polymers, including oxidations. A more detailed discussion of extracellular enzymes involved in plastic biodegradation is thus warranted for two reasons. First, as argued above, plastic breakdown in Step 1 controls the overall biodegradation of many plastic types in the open environment. By comparison, the microbial uptake and metabolic utilisation of the resulting low molecular weight products (Step 2 in biodegradation) is often faster and can likely be performed by a much wider spectrum of microorganisms, as compared to Step 1. It is therefore critical to understand the controls on enzyme catalysis of Step 1. Second, understanding enzymatic hydrolysis (or enzymatically mediated chain scissions in general) helps in the design and selection of biodegradable polymers for specific applications.

Before discussing specific enzyme classes in more detail, we note that many of the enzymes active on biodegradable plastics have been evolved by microorganisms

not for degrading the plastics, but instead to catalyse the breakdown of naturally occurring biopolymers. As a consequence, biodegradable polymers often contain structural features that are similar to those in specific biopolymers that undergo enzymatic degradation. A good example are cutinases: these enzymes hydrolytically cleave ester bonds in cutin, a complex polyester that forms the wax layer on leaves. These cutinases are also active on many biodegradable polyesters, even though the cutinases were not evolved for these plastics.

Studies show there are clear differences in microbial abundance, diversity and activity found on biodegradable plastics compared to non-biodegradable plastics (Dussud et al., 2018; Jacquin et al., 2019; Pinnell & Turner, 2019). It is reasonable to postulate that these differences are linked, in part or in full, to the utilisation of the biodegradable plastic as carbon and energy source. We decided not to discuss in detail the microbial community composition developing on biodegradable plastics, nor to list biodegrading strains that have been isolated for specific plastics. Interested readers are referred to the primary literature.

> **Box 2.2: Enzymes involved in the breakdown (Step 1) of plastic biodegradation**
>
> Microorganisms have evolutionarily acquired the capability of synthesising and secreting extracellular enzymes that facilitate the degradation of natural, high molecular weight biopolymers to low molecular weight products that the microorganisms can then take up and metabolically utilise. These natural biopolymers include, but are not limited to, cutin, cellulose, lignin, starch, polyhydroxyalkanoates, proteins, as well as nucleic acids. The enzymes act as effective biocatalysts in these degradation reactions; they lower the activation energy for the chemical reaction that leads to the degradation of the biopolymer and thereby facilitate product formation. These extracellular enzymes are optimised to work best under the conditions under which they are secreted by microorganisms. For example, while microorganisms that inhabit hot springs have enzymes that work best at high temperatures, soil microorganisms have enzymes that work best at temperatures of 20–30°C. Similarly, while enzymes produced by most organisms work best at a neutral pH, extracellular enzymes produced by microorganisms in acidic environments also have highest activity at acidic pH. As such, environmental factors such as temperature and pH affect plastic biodegradation through the type of 'biocatalysts' that are produced at any particular site. Collectively, these extracellular enzymes can be considered the 'machinery' of microorganisms to access carbon bound in macromolecular substances. In the following, we provide a brief overview of two major enzyme groups involved in the breakdown of (bio) macromolecules: hydrolases and oxidases/peroxidases. We note that these plastic-degrading extracellular enzymes are secreted by specific microorganisms that are not equally abundant (or sometimes even missing) and active across the open environment. Thus, enzymatic breakdown (and thus overall biodegradation) of a given polymer may vary largely between natural receiving environments.

Hydrolases. We re-emphasise that the chemistry of the bonds that link monomers together to form polymers is the primary determinant of whether or not a polymer is biodegradable. Polyesters arguably are the most important class of biodegradable polymers (Figure 2.2). Polyesters, in principle, have the potential to undergo biodegradation as the esterification reaction that leads to the formation of an ester bond is a reaction that is chemically reversible, meaning the ester bond can be broken back to a carboxylic acid and an alcohol.

Hydrolytic enzymes relevant for the biodegradation of polyester-based plastics include those that are evolved to cleave ester linkages present in natural biomolecules including lipids, cutin, and carboxyloxoesters of bacterial polyesters (polyhydroxyalkanoates). Most hydrolases that can hydrolyse macromolecular polyesters share some common features. First, their substrate-binding grooves are extensive to allow the binding of long-chain polymers. They feature a catalytic amino acid triad in the active site which may also aid enzyme–substrate binding. Most of them show a broad and relaxed substrate specificity range (lipases, cutinases, proteases etc.) and are thus able also efficiently cleavage ester bonds in synthetic, biodegradable polyesters such as PBS, PLA and PCL (Butbunchu & Pathom-Aree, 2019; Hajighasemi et al., 2016; Noor et al., 2020). However, the active site architecture of some other esterases are quite restricted to binding a specific substrate structure.

Besides esterases, there are also amidases that may catalyse the hydrolysis of amide bonds. In addition to esterases and amidases, in recent years there has been significant research into the enzymes that degrade cellulose acetate (CA). Non-derivatized cellulose can be hydrolysed very efficiently by the cellulolytic enzyme system consisting of several cellobiohydrolases, acting from the reducing and non-reducing end of the cellulose chain, and endoglucanases, which act randomly within the chain. It has been known for a long time that, in addition to cellulose main chain degrading enzymes, acetyl esterases play a key role in the biological degradation of CA (Puls, Wilson, & Hölter, 2011).

Oxidases and peroxidases. Oxidases and peroxidases are important extracellular enzyme classes that are involved in the breakdown of natural biomacromolecules that lack hydrolysable bonds, such as lignin, a complex cross-linked aromatic polymer composed of phenylpropanoid units. These oxidases and peroxidases use oxidising co-substrates that initiate electron transfer reactions with radical intermediates to break C-C bonds. These enzymes include laccases (EC 1.10.3.2), manganese peroxidases (MnP, EC 1.11.1.13) and lignin peroxidases (LiP, EC 1.11.1.14).[5]

For the reasons specified above, biodegradation does not readily occur in plastics composed of conventional synthetic polymers that contain only C-C bonds in their backbones. These include the polyolefins polyethylene (PE) and polypropylene (PP), but also polyvinyl chloride (PVC) and polystyrene (PS). There

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5 https://enzyme.expasy.org/EC/1.10.3.2; https://enzyme.expasy.org/EC/1.11.1.13; https://enzyme.expasy.org/EC/1.11.1.14

are indications in the scientific literature that PE and PS may be attacked by oxidases from microorganisms that colonise the gut of insect larvae that feed on and ingest some large polyolefins (Yang et al., 2014). However, the description of the underlying degradation processes often remains at an observational level and their underlying mechanisms (including the enzymes that mediate the reaction) remain unexplored. Also, these studies commonly do not demonstrate extensive conversion of polymer carbon to CO_2, as required by the above definition of biodegradation. While we consider these findings of potential breakdown of conventional plastics in insect guts undoubtedly interesting and warranting further investigation, the results ought not to be misinterpreted; these reports refer to very special conditions that are specific to insect guts. The conventional polymers PE and PS remain non-biodegradable in the open environment.

In this context it is important to clarify another, related misconception. There are studies demonstrating that microorganisms can metabolise low molecular weight degradation products of polyolefins (Yoshida et al., 2016). This finding *per se* is not surprising, as microorganisms can degrade longer-chain alkanes which have structural similarity to the building units in polyolefins. However, these studies are often misinterpreted in that it is concluded that 'microorganisms 'actively' (bio) degrade these polymers'. It is, however, more likely that microorganisms take up and utilise low molecular weight compounds that leach from the bulk polyolefins — without actual active involvement of the microorganisms in forming the low molecular weight compounds. These low molecular leachates may, for instance, be residual short chain oligomers left over from synthesis, additives, or formed by slow environmental degradation processes such as photochemical chain scissions.

We conclude this section on the importance of extracellular microbial enzymes in plastic biodegradation with a qualifying statement that may guide and direct research on and development of future biodegradable polymers for applications in the open environment: *polymers that rely on enzymatic hydrolysis to degrade in Step 1 of biodegradation are more likely to undergo the desired hydrolytic degradation across different open receiving environment than polymers that rely on enzymatic oxidations for breakdown*.

This statement is based on the following considerations. First and foremost, water is present in most environments to allow for enzymatic hydrolysis, suggesting that hydrolytic backbone cleavage of such polymers can occur across a range of environments. Conversely, oxidases and peroxidases rely on oxidants as co-substrates (i.e. dioxygen and peroxides). However, these co-substrates are absent or available only in very low concentrations in environments with anoxic or sub-oxic conditions. Because such conditions prevail in many open environments (e.g. many sediments, anoxic deep water in lakes, as well as in some soils), polymers that rely on backbone cleavage by oxidases will not undergo oxidative breakdown in these environments. The strong dependence of oxidase activity on environmental conditions is also apparent for the natural biopolymer lignin; low activities of oxidases and peroxidases in sub- and anoxic sediments lead to only

very slow biodegradation of wood in these systems (Chen et al., 2020). Second, hydrolytic and oxidative reactions fundamentally differ in their directedness; hydrolytic reactions are specific to certain bonds, such as esters and amides. By comparison, oxidations, particularly when involving radical reactions, are less directional and specific. Hydrolytic reactions are therefore expected to be more efficient in causing bond breakage in polymers containing hydrolysable bonds as compared to oxidative reactions, particularly when involving radical species, which may have multiple reaction sites in polymers and that may lead to a range of oxidation products, some of which may not involve polymer chain scissions.

We deliberately refrain from generalising statements that compare biodegradation of specific polymers across different receiving environments (soils, sediments, lakes, rivers, ocean), for two reasons. First, there are no systematic benchmarking studies comparing the biodegradation of a consistent set of polymers across ecosystems. This data is needed in order to compare biodegradation rates and extents of polymers across ecosystems. Second, variations in plastic biodegradation rates across ecosystems ought to be contextualised to variations in the biodegradation rates of the same plastics across members of the same type of ecosystems (i.e. variations across marine sediments or across soils). Such comparative, systematic studies within ecosystems are also missing.

Key messages

- Biodegradable polymers are defined in the report as polymeric materials that can undergo extensive microbial utilisation.

- Plastic biodegradation is the extensive conversion of polymer carbon to CO_2 (under oxic conditions) or CO_2 and CH_4 (under anoxic conditions), and new microbial biomass, over a specific timeframe.

- Biodegradation of a plastic material is a 'system property' in that it requires both plastic material properties that allow for biodegradation and suitable conditions in the receiving environment such that biodegradation can take place.

- The 'open environment' is used as a generic term that refers to all natural (eco) systems, ranging from systems that are pristine to systems heavily impacted by human activities, and includes terrestrial, freshwater and marine ecosystems. The 'open environment' comprises a multitude of ecosystems with a range of abiotic and biotic conditions, which affect plastic biodegradation.

- The biodegradation of polymers involves two sequential key steps. Step 1 is the abiotic and/or biotic breakdown of the polymer into smaller, low-molecular weight units. It typically relies on the presence of reactive (most commonly hydrolysable) bonds in the polymer backbone and often is catalysed by extracellular microbial enzymes. This step is necessary but by itself insufficient to ensure that the plastic biodegrades, and often controls the overall rate at which plastic items biodegrade in the open environment. Step 2 is the subsequent uptake and metabolic utilisation of these smaller

units in microbial cells and is considered to be relatively fast compared to step 1 in many open environments.

- Plastic additives that claim to render non-biodegradable plastics (e.g. polyolefins) biodegradable in the open environment raise concerns, given that the elevated temperatures and/or sunlight needed for activation of the additives are absent from various open environments, including the targeted receiving environments for which these additive-containing plastics are proposed.

- Because biodegradation rates of plastics vary widely between different receiving environments, with a diverse range of conditions (such as temperature and the abundance and activity of plastic-degrading microorganisms) that affect biodegradation, the rates and extents of biodegradation of a plastic, as well as certification of plastic biodegradation, needs to be reported with reference to the specific receiving environment in which biodegradation took place or was assessed.

Chapter 3: Applications of biodegradable plastics: considerations relating to environments

What is this Chapter about?

- This Chapter discusses biodegradable plastics in the context of the waste hierarchy and identifies conditions and usage scenarios in which biodegradable plastics may be beneficial in comparison to conventional polymers.

- It examines the influence of the receiving environments on the potential benefits of biodegradable plastics, considering five contrasting disposal scenarios for end-of-life items made of biodegradable plastics.

- It considers specific examples of where the use of biodegradable plastics may bring benefits compared to conventional plastics, as well as examples where the benefits of biodegradable plastics are less clear.

- It emphasises the importance of labelling and appropriate user information to equip users with the necessary information to correctly dispose of (biodegradable) plastics and thus achieve environmental benefits.

- It emphasises the need for legislation and enforcement to facilitate appropriate testing, certification and labelling, and to minimise the potential for fraudulent use of terminology or slogans relating to claimed biodegradability.

3.1. APPLICATIONS OF PLASTIC PRODUCTS IN RELATION TO THE WASTE HIERARCHY — WHERE DO BIODEGRADABLES FIT?

The accumulation of end-of-life plastic items, both as waste in managed systems and as litter in the open environment, is seen as a global environmental issue (GESAMP, 2015). An additional category of particular relevance to this discussion is the deliberate use of plastics in open environments, such as in agriculture, which also presents the potential for end-of-life plastics to accumulate if they are not completely removed or if they are intended to biodegrade in the environment, but fail to do so.

Addressing the challenges associated with waste requires consideration of the applications of plastic products, like any other product, in the context of a waste hierarchy. Conventional plastics are typically very durable materials. Indeed, durability is one of the four key benefits, alongside being inexpensive, lightweight and versatile, that make plastics especially suitable for such a wide range of applications (Andrady & Neal, 2009; Thompson et al., 2009). However, this

durability creates a challenge because the major uses of plastics are in relatively short-lived applications such as packaging, which alone accounts for around 40% of plastic production (PlasticsEurope, 2019).

From the perspective of the waste hierarchy it is important first to consider, for any application, the potential societal benefit derived from the product. If the benefit is low or better alternatives are available, a **reduction strategy** might be appropriate. This is an especially important consideration where the potential benefits of the application are short-lived, but the persistence of the end-of-life item is considerable, as is the case for many plastic items. Therefore, a first consideration is to establish the need for the item in terms of societal benefit, noting that this is not the same as the demand for an item. Simply because an item is traded does not mean it automatically brings commensurate benefit — consider for example, plastic toys given free of charge as a marketing initiative with a takeaway meal, or a single-use carrier bags at the point of sale in a shop. With the bag, there is a demand, but the same benefit could be achieved with a reusable bag. With the plastic toy — is this (sometimes compulsory) gift really necessary, considering the issues of waste management and littering? So, one could argue these applications are avoidable and, in some nations, recognition of this has resulted in legislation or campaigns by non-governmental organisations that are intended to **reduce plastic usage**.

Assuming the societal benefit is sufficient, then, according to the waste hierarchy, the next steps would be to consider reuse and recycling of end-of-life items. However, these strategies are not feasible if the end-of-life item cannot be effectively collected from the environment, for example, or separated from other materials or contaminants. Challenges in material collection may occur as a consequence of inadequate infrastructure and it is critical to note that this varies geographically. Hence, decisions in relation to the waste hierarchy that apply in one location may not be appropriate in other locations, and the following considerations are context-dependent.

Challenges with collection may also occur if the product is used in, or released to, the open environment and subsequent removal of the item or its fragments is not practically or economically feasible. (See the examples later in this Chapter: (a) mulch film and (b) fireworks.) A related scenario is that of fragments, including microplastics, that are generated as a consequence of wear during the regular use of an item, as happens for example with the abrasion of sacrificial components in a fishery such as dolly rope (example (c) later in this Chapter).

Alternate scenarios for collection, separation and handling in a managed system versus biodegradation in open environments need to be examined carefully, as lack of full consideration could lead to inappropriate regulatory decisions. For instance, there is a potential misconception among the public and some policymakers that biodegradable plastics offer a key solution to littering (UNEP, 2015; see examples (g) carrier bags and (h) single-use packaging, later in this Chapter). Hence, it could

be argued that biodegradable plastics may be more advantageous as potential solutions in locations with inadequate waste management infrastructure. Although many producers of biodegradable plastics take the view that biodegradable materials should not be considered a solution to the problem of litter, some take the contrary stance of promoting products as potential solutions to the issue of littering. In our view, the key point here is to ensure that biodegradable plastics are considered as part of a waste hierarchy, not in place of one — i.e. that their use is not advocated as an alternative to establishing appropriate waste management infrastructure. As discussed below, it is also important to assess whether any potential benefits of biodegradable materials will actually be realised in littering scenarios.

A further obstacle hindering progression within the waste hierarchy occurs where collected waste materials are mixed together and difficult to separate. An example is the contamination of organic waste with plastics, where the presence of plastics could contaminate the resultant compost. In cases where organic waste and plastics are unavoidably mixed, and this cannot readily be resolved by designing better products or modifying the application or separation procedures, the use of plastics that are biodegradable in specific managed systems such as composting may be appropriate (Carus, 2020; see examples (d) fruit stickers and (e) bags for compostable food waste). Similarly, there may be advantages in using biodegradable plastics in scenarios where small pieces of plastic are unavoidably mixed with sewage and are likely to accumulate in the sludge that is separated during wastewater treatment (see example (f), cosmetic microbeads) or escape to the environment in treated effluent (Lusher et al., 2018; Mintenig et al., 2017). In such scenarios, the use of biodegradable plastics may bring advantages over conventional plastics. However, there are potential concerns if plastic biodegradation in wastewater treatment is incomplete, since in many locations the sludge that is separated during wastewater treatment is returned to the land as an enrichment medium and hence presents a pathway for the release of any partially degraded plastic particles (Mahon et al., 2017).

Where the appropriate waste collection and separation infrastructure can be put in place, further options within the waste hierarchy become available via product **reuse, mechanical recycling or chemical recycling**. Final options within the waste hierarchy are for the disposal of residual waste which is not compatible with reuse or recycling via **waste to energy, incineration or landfill**.

While consideration within a waste hierarchy is a useful approach to ensure aspects are evaluated in an appropriate order, it is important to note that the trade-offs between options vary regionally, for example with available infrastructure, and that the categories within the hierarchy are qualitative ranks rather than being on a numerical integer scale. There are also trade-offs within the hierarchy; for example, if all plastic products were recyclable or reusable, the need for material reduction would become less important than when only a small proportion of plastics are effectively reused or recycled, as is currently the case.

Over 360 million tonnes of plastics are produced annually (PlasticsEurope, 2019). Within this, the market for biodegradable plastics is currently relatively small at around <1%, with applications primarily in flexible and rigid packaging and the agricultural sector (European Bioplastics, 2020). However, there is increasing use of biodegradable plastics for consumer products, electronics, automotive, building and construction, and textile sectors (European Bioplastics, 2020) . Many of these applications have evolved, and are evolving, without a holistic consideration of the waste hierarchy alongside their potential advantages and disadvantages (see Box 3.1). This is especially likely where the producers do not bear the full external costs associated with waste management or environmental impacts, and is further nuanced by potential marketing advantages associated with products that appear to present the pro-environmental characteristics that some consumers associate with biodegradable materials (see Chapter 6). Current applications include products where there are clear benefits from the use of biodegradable materials, as well as applications where the benefits are more equivocal, and some cases where there is evidence of negative consequences.

In summary, biodegradable plastics may bring benefits in relation to conventional plastics in applications where it is challenging to remove or collect a particular product or its fragments from the environment after use, or where it is difficult to separate plastic from organic material that is destined for a composting waste stream or wastewater treatment.

3.2. THE INFLUENCE OF THE RECEIVING ENVIRONMENTS ON THE BENEFITS OF BIODEGRADABLE PLASTICS

Balancing the potential advantages and disadvantages of utilising biodegradable plastic materials for different applications needs careful consideration (Box 3.1). The potential benefits in terms of biodegradability are only likely to be realised if, at the end of life, the plastic item reaches a receiving environment that is appropriate for the biodegradation of the particular plastic and product formulation (see Chapter 2). Broadly speaking, we consider that there are five disposal scenarios for end-of-life items made of biodegradable plastics (Table 3.1). These scenarios are determined by the application of the plastic, the waste management system, the regulations and enforcement in place, information or labelling to guide the user on appropriate disposal, and the actions or behaviours of the end user in relation to that information (Chapter 6).

Table 3.1: Alternative end-of-life disposal scenarios for biodegradable plastics and the potential for success, i.e. for biodegradable materials to bring advantages compared to conventional plastics (see the examples referred to for illustration).

Disposal scenario	Potential outcome		
	positive	neutral	negative
Release into a natural environment that has been appropriately considered and evaluated from the design stage (see examples (a), (b), (c)).	√		
Release into a natural environment that has <u>not</u> been appropriately considered and evaluated from the design stage, for example as litter (see examples (g), (h)).		√	√
Transfer to an <u>appropriate managed system</u> for biodegradable materials, e.g. industrial composter (but see examples: (d), (e)).	√		
Transfer to an <u>inappropriate managed system</u> for biodegradable materials, e.g. recycling streams for conventional polymers such as PE.			√
Transfer to a managed system for <u>residual waste</u>.		√	

A major challenge is for a biodegradable product to deliver reliable performance, including durability during life in service, but also to biodegrade completely in an appropriate timescale at the end of the product's lifetime. This reflects the key point that there is no single, consistent open environment — the natural environment is intrinsically very variable. Designing a biodegradable plastic to perform appropriately in life and then, at the end-of-life, biodegrade across a wide range of natural environments (see example (b) fireworks) is potentially more challenging than designing a biodegradable plastic for more restricted end-of-life conditions, either in the open environment (example (a) some mulch films) or as managed waste (Table 3.1). A further constraint is the performance requirements, especially in terms of durability, of the product during life in service. If the product needs to be durable in a range of different conditions over a sustained period of time (e.g. a mulch film over crops) then it is likely to be more challenging to also ensure the item will biodegrade completely in an appropriate timeframe when it is no longer required. This is less challenging for items with relatively limited requirements while in service, such as the plastic components of a firework.

The greater the probability of a biodegradable product reaching an appropriate end-of-life scenario for which it was designed and stringently tested (see Chapter 4), the greater potential it has to deliver benefit over conventional plastics. Failure of a biodegradable plastic to reach an appropriate receiving environment may to lead to inefficient or incomplete biodegradation (see examples (d) and (e)) with the associated environmental risks (Chapter 5), and in these circumstances biodegradable materials are less likely to convey benefit over conventional plastics. Similarly, if biodegradable plastics are mixed with conventional plastics in recycling, they may compromise the quality of the recyclate. In addition, if biodegradable plastics are disposed of in

the residual waste stream, the negative consequences of reaching an inappropriate receiving environment are eliminated, but it is unlikely that any benefits of using a biodegradable plastic will be realised. In this evaluation, it is important to consider that the availability of biodegradable plastics in some applications could well lead to increased levels of disposal to, or reduced removal from, the environment. This is because the availability of products described as biodegradable may be seen to legitimise applications that would be considered unacceptable for conventional plastics, for example, single-use carrier bags as opposed to reusable bags. So even if biodegradable plastics are likely to degrade faster than conventional plastics, irrespective of the receiving environment, this alone is not a sufficient justification for their adoption. For accelerated degradation to be seen as an advantage it needs to be sufficiently accelerated that it makes a meaningful difference in an environmental context relative to the current level of plastic accumulation. In circumstances where escape to inappropriate receiving environments is probable, there is a clear risk that that use of biodegradable products could inadvertently accelerate the accumulation of plastics in the environment (Table 3.1). Hence it is important to evaluate and certify products across the range of probable receiving environments.

The discussion above helps identify a number of key questions that may be worth considering so as to determine, for particular applications, the efficacy of using biodegradable compared to conventional plastics (Box 3.1). A key initial consideration from the perspective of the waste hierarchy is the societal, economic and or environmental benefit that the item offers. If an item brings little clear benefit, then, irrespective of the material or its biodegradability, the first consideration should be towards reducing usage. For products where the benefits are clear, some applications lend themselves more toward the use of biodegradable plastics than others (see Section 3.3). Box 3.1 examines considerations along the waste hierarchy and with respect to potential disposal pathways and accumulation in the environment. This needs to be assessed with due regard to the end users and their likelihood of following appropriate disposal guidance, along with the quantity of material being used in a particular application and in a particular environment or location. From a risk assessment perspective, the quantity of material will directly influence consideration of the adverse effects, meaning that applications that result in substantial localised usage and accumulation may have a higher likelihood of risk than those with small and fairly diffuse usage patterns.

> **Box 3.1:** Potential considerations in making a holistic evaluation in terms of the waste hierarchy and potential environmental benefits or risks associated with the use of existing or novel biodegradable plastics compared to conventional plastics. Note: Unless there is a clear benefit, a switch to biodegradable material is a distraction and likely to bring consumer confusion (see Chapter 6); so where biodegradable and conventional plastics are seen as equivalents this does not justify the replacement of conventional plastics by biodegradable plastics. Please refer to specific examples indicated, which follow in Section 3.3.

1 If the extent of the societal, economic or environmental benefit is low, the use of biodegradable plastics is not relevant; it would be more import to consider a reduction strategy.

2 For applications that unavoidably result in direct release of plastics to the environment, either as the end-of-life item or its resultant fragments, and where it is also challenging to remove those items or fragments from the environment, the potential for re-use or recycling is limited. In these circumstances, a biodegradable product might bring advantages. For advantages to be realised, the biodegradable product must meet the performance requirements in service and biodegrade completely in the relevant receiving environment(s) at the end-of-life (see examples (a), (b) and (c)). Note that, for applications that require high durability/performance during life in service, it may be challenging to also achieve timely biodegradation at end-of-life (see examples (a), (e), (f), (g) and (h)).

3 If an item requires a very specific receiving environment to biodegrade appropriately, it is important to determine the potential for the item to accumulate in a different open environment or waste stream, because of either a) inappropriate waste management or b) transfer between environmental compartments, for example by wind or water. If so, then it may be important to establish biodegradability across the range of potential receiving environments (examples (a), (c), (d), (e), (f), (g) and (h)).

4 If specific decisions or handling by the consumer/end user are required to ensure the end-of-life product enters the appropriate receiving environment for disposal, then it is important to establish, firstly, whether the method of communication/guidance has been evaluated to assess how effective it will be (see examples (g) and (h) and Chapter 6); and, secondly, whether the product is likely to be used by a narrow range of end users with ownership in the outcome (e.g. farmers disposing of mulch film, example (a)). In the latter scenario, the potential for appropriate disposal is likely to be higher than if the product is used by a wide range of end users (e.g. general public, examples (g) and (h)).

5 Considerations 2–3 require accredited testing and certification to assess biodegradation across a range of relevant receiving environments. It is important to establish whether such tests exist or need to be developed (see Chapter 4).

6 If there is the potential for an item to reach an inappropriate receiving environment for its biodegradation (or if the standard for biodegradation does not require complete biodegradation), then it may help to establish the likely distribution in the open environment (localised, e.g. examples (a), (d)–(f); or dispersed e.g. example(b). It is also important to establish whether the severity of any impacts associated with accumulation has been established or if it is unknown (see Chapter 5).

3.3. EXAMPLES OF APPLICATIONS IN WHICH THE USE OF BIODEGRADABLE PLASTICS MAY BRING BENEFIT

The examples below consider some current applications of biodegradable plastics in relation to the considerations identified in Box 3.1. These illustrations, together with Box 3.1, may be useful in guiding the evaluation of the potential risks and benefits for new types of biodegradable polymers or new applications for biodegradable polymers in the future. There are multiple other current uses, including trimmer lines, brushes for pavement cleaning, geo-textiles, other agricultural films such as silage wrappings, and coffee capsules, and the framework identified above and the examples below may help in evaluating these. There are also applications that use coatings of soluble biodegradable material, and further evaluation of these is needed as there is currently very limited information on which to base an assessment.

3.3.1 Applications where collection from the environment is challenging

In specific applications, where plastics are used directly in the open environment, these can present a source of contamination if collection (e.g. for reuse, recycling or other forms of managed disposal) is either not cost-effective (e.g. agricultural mulch films), incomplete or not possible (e.g. fireworks, dolly rope used in fishing). In such applications, biodegradable plastics could convey benefits over conventional polymers if they reach an open environment in which they are able to biodegrade adequately within appropriate timescales, as confirmed by suitable testing. By default (i.e. unless there is a strong precedent from previous testing of other very similar products), testing should be on the final product as opposed to a sample of the material prior to its conversion into a final product (see Chapter 4).

Example (a) Agricultural mulch films

Agricultural plastic mulch films are widely used to increase crop yields (European Bioplastics, 2020). This process has been used since the late 1930s (Kasirajan & Ngouajio, 2012) and can bring clear societal benefit in terms of food production and food security (Box 3.1, Consideration 1). Presently, both conventional polymers such as LDPE and HDPE, and biodegradable polymers such as PCL, PBAT, PHA, PLA, PBS, TPS, cellulose and starch are used in this application (Bandopadhyay, Martin-Closas, Pelacho, & DeBruyn, 2018). Biodegradable mulch films only account for around 5% of the market share (APE Europe, 2020).

Mulches made from conventional plastics present challenges once they have reached the end of their life. The cost of removal and disposal is high and for thin (<20μm) films this is not feasible (Box 3.1, Consideration 2). Hence, end-of-life films can accumulate in the environment, compromising gas exchange and water infiltration (Sander, 2019). In addition, plastic mulches can fragment into microplastics, leading to reduced soil functioning (Y. Qi et al., 2018; Steinmetz et al., 2016; Zhang et al., 2018).

Thin biodegradable plastic mulch films are designed to be ploughed into the soil over which they were used, where it is anticipated that fragments will biodegrade (Hayes

& Flury, 2018). The standard BS EN 17033:2018 requires that at least 90% of the carbon is converted to carbon dioxide within two years under ambient soil conditions (Hayes & Flury, 2018; ISO 17556:2019). In this application, biodegradable plastics may offer advantages over conventional plastic because there is a high likelihood that end-of-life products will reach a receiving environment where they are designed to biodegrade, hence there are potential advantages over conventional plastics (Table 3.1, page 62). However, care is required to adequately assess the timescale of biodegradation in situ (Chapter 4). There is also potential that, as film begins to biodegrade, fragments may be transported by wind or rainfall into other receiving environments for which biodegradation has not been assessed (Box 3.1, Consideration 3b).

Soils vary widely in their abiotic characters and assemblages of microorganisms, which could affect rates of biodegradation. Similarly, the prevailing weather conditions will vary considerably between locations and seasons, thus influencing the onset and rate of biodegradation. To perform appropriately, films will require a high degree of performance, persisting for long enough for the desired benefits in terms of crop yields to be achieved. This degree of durability may create a challenge once the life in service is complete and requirements switch to biodegradability (Box 3.1, Consideration 2). Based on the biodegradation standard BS EN 17033:2018, some of the film is allowed to persist, potentially leading to accumulation over multiple years of application (e.g. Miles, DeVetter, Ghimire, & Hayes, 2017). While the biodegradation of some biodegradable polymers used as mulches can be demonstrated by tracing isotopes of carbon in laboratory settings (Zumstein et al., 2018), field-based studies indicate the degree of persistence of biodegradable plastic mulch films can be highly variable, in one case with as much as 99% remaining after 24 months (Li et al., 2014b) . Another study found initial degradation (the study was unable to confirm the mechanism of degradation, see Chapter 2) of biodegradable mulches in soil to be slow for the first year (15-20% degradation) and rates were particularly slow for PLA/PHA film (Sintim et al., 2020) and subject to seasonal variation with increased biodegradation during the summer. Hence, there is potential for localised accumulation (Box 3.1, Consideration 6). Studies appear to have conflicting results about the effects of biodegradable plastic mulches on soils; in some, few impacts were observed (Henry Y. Sintim et al., 2019), while others report significantly altered microbial community structure (Li et al., 2014b; Moon et al., 2016; see Chapter 5 for discussion).

A potential advantage in this setting is the relatively narrow user group which has ownership of the outcomes. Farmers need to maintain the functionality of their soils, hence the potential for product information to be followed is relatively high (Box 3.1, Consideration 4 i) compared to applications with multiple end users such as in single-use packaging (examples (g) and (h)).

Example (b) Fireworks

Large-scale firework displays and domestic use of fireworks are commonplace worldwide, with fragments directly falling into terrestrial or aquatic habitats. While clean-ups are undertaken in some locations, it can be difficult to locate and remove

fragments (Box 3.1, Consideration 2). For example, on beaches in the southern Baltic Sea, 12% of litter was firework debris attributed to New Year's Eve celebrations (Haseler et al., 2019) and reports identify fireworks on beaches in other locations (Scisciolo et al., 2016). Hence, the potential for collection and waste management is minimal and the most likely end-of-life scenario is the open environment. The casing of some fireworks contains plastic components typically made from conventional polymers (HDPE, PP, ABS or PVC). However, unlike the mulch films in example (a), where the range of open environments for end-of-life biodegradation is relatively narrow, end-of-life fireworks have the potential to enter a very wide range of open environments (contrast, example (a) and Box 3.1, Consideration 3).

With the exception of appropriate health and safety criteria (The European Parliament, 2013), the plastic components of fireworks have relatively modest performance criteria (Box 3.1, Consideration 2). Since fireworks need be stored in controlled conditions prior to use, the plastic components do not need to be especially resistant to biodegradation, for example by moisture or UV, prior to or during use. Therefore, for biodegradable plastics to bring advantage over conventional plastics, the key properties would be to degrade in an acceptable timeframe across a wide range of environments. To ensure appropriate end-of-life performance, all plastic components would need to be tested for biodegradability in a range of field conditions where end-of-life fireworks might accumulate (Chapter 4).

Fireworks marketed as being biodegradable and/or 'eco-fireworks' are currently available[6,7]. However, the polymers used, and biodegradability standards applied, are not stated on the products, hence their end-of-life performance in terms of degradability is uncertain. Unless appropriate certification and labelling can be enforced, this will lead to consumer confusion (see Chapter 6) around the environmental credentials of these products and the potential for unwanted environmental accumulation, effectively as litter (Box 3.1, Considerations 4 and 5).

Example (c) Dolly rope

Dolly rope is a component of seabed trawl gear that is designed to protect the cod end of the net from wear and is typically made of conventional polymer such as polypropylene (OSPAR Commission, 2020). As the gear is dragged along the seabed, the rope sacrificially abrades, progressively wearing away and is then replaced (Cuttat & De Alencastro, 2018). The societal benefit of the application is clear since use of dolly rope helps minimise gear loss, increasing the efficiency of the fishery (Box 3.1, Consideration 1). In addition, the requirements for functionally in service are relatively low, requiring durability that is compatible with the desired wear rate (Box 3.1, Consideration 2). Since it is not feasible to remove the resultant fragments and microplastic pieces from the marine environment, the use of biodegradable plastic in this setting may bring advantages (Box 3.1, Consideration 2). For these advantages to be realised, dolly rope would need to be made of a material that biodegrades in

6 https://www.alibaba.com/showroom/biodegradable-fireworks.html

7 http://www.hidrosoluble.com/

marine seabed conditions either in water or mixed with sediment, and potentially at low temperatures, with limited light or UV, and in some circumstances limited oxygen — which may be required to initiate phase 1 of biodegradation (see Section 2 of this Chapter). While the potential for fragments to transfer from this receiving environment to another is relatively low (Box 3.1, Consideration 3), it should be recognised that these environmental conditions may be challenging from the perspective of biodegradation. One company has developed dolly rope described as 'degradable' and commenced commercial sales in 2020.[8]

3.3.2 Applications where separation of the plastic from other organic waste presents a challenge

Example (d) Produce (fruit and vegetable) stickers

Within Europe, between 500 to 600 tonnes of stickers are used on fruit and vegetables each year (Carus, 2020). Typically, the stickers are made from coated paper, PE or PP, with non-biodegradable adhesive and inks. These stickers identify particular producers, types of production or indicate product lookup codes for point-of-sale identification (Sood, 2009). The application brings moderate societal benefits, since labelling next to the produce could have similar effectiveness (Box 3.1, Consideration 1), and requires relatively low functionality compared to other examples presented here (Box 3.1, Consideration 2). Stickers are likely to stay associated with fruit and vegetable peelings and thus pass to organic waste bins along with the peelings; they have also been reported in samples of wastewater. Hence end-of-life stickers have a potentially high likelihood of entering managed waste facilities such as industrial composting and wastewater treatment plants but may also be released to the open environment (through consumer behaviour such as littering). So there is considerable potential for end of life to occur in a range of different receiving environments (Box 3.1, Consideration 3). It is important to note the material from commercial composters will be returned to the open environment together with any products of incomplete biodegradation, and there is the potential for high levels of localised accumulation (Box 3.1, Consideration 6). Hence, certification needs to be based on biodegradation across an appropriate range of open environments, for example including soil and compost (Box 3.1, Consideration 5).

Example (e) Bags for compostable food

In some locations, there is a dedicated domestic collection system for organic waste that is destined for commercial composting (European Commission, 2000). In settings where relatively small quantities of domestic food waste need to be stored prior to collection, the use of compostable plastic bags could bring benefits, since using conventional plastics bag as an alternative would contaminate the waste stream (Ren, 2003; Box 3.1, Consideration 3). However, unlike in the case of produce stickers (example (d)), high functionality is required because the bag needs to hold degrading

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8 https://www.senbis.com/products/products-by-industry/marine/marine-degradable-fishing-net-protection-dolly-rope

food waste including raw meat, together with any liquids released, for periods of up to several weeks (Ren, 2003); for example, in locations where the waste collection operates via alternate weekly collections (Box 3.1, Consideration 2). The end-of-life bags have a potentially very high likelihood of entering managed waste facilities such as industrial composting but may also be released to the open environment (through consumer behaviour, such as littering). As above (example (d)) it is important to note that the material from commercial composters will be returned to the open environment together with any products of incomplete biodegradation, and there is the potential for high levels of localised accumulation (Ruggero, Gori, & Lubello, 2019; Box 3.1, Consideration 6). Hence, certification needs to be based on biodegradation in managed waste facilities and across a range of open environments as appropriate (Box 3.1, Consideration 5).

Example (f) Cosmetic microbeads

Small plastic beads or grains, typically less than 1mm in diameter, are used as abrasives or lubricating agents in a range of cosmetic and cleansing products (Leslie, 2014). In some products, the quantities used in a single application can be very substantial (Napper et al., 2015) and will be released with wastewater (Mason et al., 2016; Ziajahromi et al., 2017). A relatively high degree of performance is required such that the plastic does not deteriorate when suspended in various liquids, creams and gels. Because of their size, these microplastic particles can escape wastewater treatment and enter the environment (SAPEA, 2019). Even for those particles that are intercepted in wastewater, the resultant sludge together with the plastic may be applied to the land as an enrichment media (Talvitie et al., 2017; Box 3.1, Consideration 3). As a consequence of the relatively low societal benefit (Box 3.1, Consideration 1), coupled with the persistence of conventional plastics, the use of plastic particles in this application has been prohibited in some countries (European Parliament, 2018). In this context, provided there is a demonstrable case that the benefits from the inclusion of plastic beads in a product is sufficiently high (Box 3.1, Consideration 1), the use of biodegradable microbeads may be worth considering. This should be done in view of any alternative approaches that are being considered as a consequence of recent legislation. For biodegradable plastics to bring benefits in this application, the plastic would need to deliver the necessary functionality in service, and, critically, also degrade rapidly once it passes to a managed wastewater treatment facility or to open environments (Box 3.1, Consideration 2). Biodegradation therefore needs to be evaluated in the context of a range of open environments because the plastic particles have a high probability of escaping into aquatic habitats with treated effluent or particularly rapidly in the case of stormwater overflows, or being applied to the land if they are retained in sewage sludge (Box 3.1, Consideration 3). In some locations, wastewater will pass directly to the environment without treatment. In locations where sludge from wastewater treatment is applied to the land, there is the potential for high levels of localised accumulation (Kacprzak et al., 2017; Box 3.1, Consideration 6). Hence, certification should be based on appropriate biodegradation across a range of open environments (Box 3.1, Consideration 5).

3.4. APPLICATIONS WHERE BENEFITS ARE LESS CLEAR

For some applications, the potential benefits of using biodegradable plastics over conventional plastics are less certain. In the examples below, biodegradable plastics are currently utilised, yet the benefits they offer over conventional plastics cannot clearly be mapped onto the criteria identified in Section 3.1. In addition, the end-of-life products have the potential to enter a range of managed and unmanaged receiving environments (Table 3.1) and their fate is heavily driven by the behaviour of the end user. These factors combined increase the likelihood of the plastic entering a receiving environment for which it was not designed, and thus increase the probability of environmental accumulation.

Example (g) Carrier bags

Bag production was the main application for biodegradable plastics in Europe during 2019, accounting for 68% of consumption (Nova Institute, 2019). Hence, it is concerning that the use of biodegradable plastics for this application falls into this category, where the benefits are uncertain. Unintentional release, through mismanaged waste and consumer behaviour, will cause carrier bags to enter the open environment or to be transferred to inappropriate managed waste streams (Box 3.1, Consideration 2). Indeed, plastic bags are documented on coastlines worldwide (Martin, Almahasheer, & Duarte, 2019), on the deep seafloor (Chiba et al., 2018), in the terrestrial environment (Hurley, Horton, Lusher, & Nizzetto, 2020), and in freshwaters rivers and lakes (Blettler et al., 2018; Winton et al., 2020). Such widespread occurrence as litter illustrates the challenges associated with designing a bag that provides required performance to the consumer during life in service, for example being strong and durable in a range of environmental conditions (Box 3.1, Consideration 2), yet that will biodegrade within adequate timescales in a range of open and managed environments, each with varying characteristics (e.g. Table 3.1; see also Chapter 2).

We are not aware of any empirical evidence of carrier bags degrading across such a range of environments. By contrast, there are some indications that materials currently on the market and clearly labelled as being biodegradable cannot be relied upon to do so (Napper et al., 2015; Nazareth et al., 2019). This may be because the product was inappropriately or inadequately tested or labelled (see labelling, Section 3.5), but clearly indicates the potential for consumer confusion and the need for appropriate regulations relating to labelling (Chapter 6). Also, see Section 3.2 for discussion about the availability of biodegradable plastics in some applications potentially legitimising single-use products (as opposed to a reusable bag) and therefore leading to increased levels of disposal to, or reduced removal from, the environment.

Example (h) Single-use packaging

Biodegradable plastics have been utilised for single-use packaging, partly due to consumer-driven demand and partly through legislation (European Commission, 2018). There are now many types of packaging on the market advertised as 'biodegradable', 'green' or 'plastic-free' options. A key driver of whether consumer products, such

as on-the-go food packaging, reach an appropriate waste management stream is reliant on consumer action (Taufik, Reinders, Molenveld, & Onwezen, 2020). In certain instances, where the purchase and disposal of goods is centralised and remains within a controlled setting from the perspective of waste management, such as a sports arena or festivals, biodegradable plastics have a high potential to reach appropriate receiving environments. However, in settings where consumers are diverse and dispersed over larger areas, such as high street fast food outlets or transport hubs, the disposal pathway is less controlled and so the potential for the end-of-life packaging to reach an appropriate waste stream is reduced. This is because items that are used by a wide range of consumers, who typically have a limited understanding of the consequences of their actions around end-of-life disposal, and limited direct ownership of this (compare with the example of farmers using mulch films, Box 3.1, Consideration 4). To maximise success in applications with diverse user groups, clear and succinct communication, for example via labelling to indicate appropriate and inappropriate disposal pathways (see Figure 3.1), may help reduce the risk of inappropriate disposal. However, this also requires that the labelling is evaluated in terms of its efficacy (Section 3.5). It is also essential to ensure there is adequate availability of the specific waste reception infrastructure, for example for compostable waste.

There is currently a lack of adequate product labelling to indicate end-of-life disposal pathways, and general confusion among commercial and domestic users on the performance of different plastics in relation to end-of-life disposal (D'Souza, Taghian, Lamb, & Peretiatko, 2006). This deficiency, coupled with reliance on understanding and participation in disposal practices by multiple end users and the need for dedicated infrastructure for waste disposal to be widely available, limits the potential for clear benefits over conventional plastics.

3.5. THE IMPORTANCE OF LABELLING AND APPROPRIATE USER INFORMATION

In order for products that are tested and certified as biodegradable to convey benefits over conventional plastics, it is necessary for those items to reach appropriate receiving environments at the end of their life. If, at the end of life, a biodegradable plastic fails to reach an appropriate receiving environment, then it is likely that unintended consequences will arise (Chapter 5). In many applications, this is reliant on guiding end users to maximise the likelihood that biodegradable items are disposed of correctly. Such guidance will require clear and accurate labelling on the items to indicate appropriate and inappropriate waste receiving streams (see Figure 3.1), and in some cases additional complementary labelling on the waste-receiving infrastructure itself (e.g. on waste bins). Evaluation will also be essential to ensure such labelling is effective in communicating its message.

In a recent study of four different types of carrier bags clearly labelled from the perspective of the consumer as being either degradable, biodegradable or compostable (Napper & Thompson, 2019), only one featured information to the

consumer on the appropriate waste stream for degradability. Two had no information at all on disposal, and one indicated it was recyclable, but without guidance on the appropriate recycling stream. None of the bags had any information to guide the user against littering and most were subsequently shown to have persisted intact for several years in marine and soil conditions (Napper & Thompson, 2019). This may be because the bags were inappropriately labelled in relation to any certification performed, and also highlights the need to inform the end user not just about the potential for biodegradation but also the receiving environment required to achieve it (see Chapter 2).

Figure 3.1: An example of clear labelling on a magazine wrapper (left) prominently featuring 1) a description of the category of degradation 2) consumer guidance on both appropriate and inappropriate disposal options; and on the reverse side (above) the certification. Note that we make no assessment here as to the performance of the product but only include it as an illustration of labelling.

3.6. THE IMPORTANCE OF LEGISLATION AND ENFORCEMENT

For the benefits of biodegradable materials to be realised, there is a key requirement for accurate and appropriate testing and certification, and also labelling informing the end user, not just about the potential biodegradability of an item but critically also about the receiving environment required for that biodegradation to be achieved. For example, in the state of California the term *biodegradable* cannot be used on products unless it is accompanied by information on the receiving environment required to achieve that biodegradation (California Legislative Information, 2012; see also Chapter 4). Legislation around labelling needs to consider both the appropriate labelling of products that are properly tested and certified, and perhaps more critically the potentially fraudulent use of the terms like degradable, biodegradable and compostable on products that have not been appropriately tested, or have failed to perform adequately.

There is a wider discussion here that is outside the scope of this report, which relates more generally to appropriate and inappropriate use of pro-environment slogans and statements on products. Use of such statements is widespread across a range of products, but often relates to an opinion formed by the company producing the product. It does not seem appropriate to expect industry to be able to optimise for

the environment and its shareholders, and a more independent assessment to the use of slogans is needed. In addition, for responsible companies who are testing and certifying products appropriately, their efforts are diluted and undermined by the less scrupulous. An important policy priority is therefore to consider developing general guidelines on appropriate and inappropriate usage of pro-environmental statements in marketing.

Moreover, there is a requirement for legislation to be enforced. Unless enforcement is in place, it will not be possible to maximise the potential benefits from appropriately tested and certified products that are used in the proper context, nor will it be possible to minimise consumer confusion or the potential for detrimental environmental outcomes. There has been recent legislation within the EU to try to prevent the use of materials that do not meet the necessary requirements.

The European Union has recently banned the use of oxo-degradable plastics because of a lack of consistent evidence about speed of breakdown in the environment, and fears that false claims around this are misleading consumers (European Commission and Eunomia, 2016; also see technical discussion in Section 2.4.5.1). Directive 2019/904[9] came into force on 3 July 2019 and has to be transposed by the Member States by 3 July 2021. After well over a decade of widespread use as plastic carrier bags throughout the EU and internationally, this legislation emphasises the need to for appropriate testing of materials and products to occur in advance of these coming to market, and the need for associated enforcement.

Key messages

- Some of the applications of biodegradable polymers identified in the report have the potential to bring advantages compared to conventional plastics. These include applications where it is challenging to remove or collect a particular product or its fragments from the environment after use; or where it is difficult to separate plastic from organic material that is destined for a composting waste stream or wastewater treatment. However, these benefits will only be realised if the formulation of the product is appropriate to the receiving environment, and if the potential is minimised for the item or its fragments to escape to a receiving environment that is not compatible with biodegradation. The greater the probability of a biodegradable product reaching an appropriate end-of-life scenario for which it was designed and stringently tested, the greater potential it has to deliver benefit over conventional plastics.

- Broadly speaking, we consider that there are five potential disposal scenarios for end-of-life items made of biodegradable plastics. These scenarios are determined by the application of the plastic; the waste management system; the regulations and enforcement in place; information or labelling to guide the user on appropriate disposal; and the actions or behaviours of the end user in relation to that information. In some instances, the behaviour of the end user will strongly influence the probability of the end-of-life item entering the intended versus

9 https://eur-lex.europa.eu/eli/dir/2019/904/oj

unintended receiving environment. The scenarios are considered in terms of the potential for both positive and negative effects.

- The likelihood of an item reaching an inappropriate environment, and the potential risk associated with the plastic not degrading, needs to be evaluated when considering testing and certification standards for existing and novel polymers, and in relation to the specific products and applications as opposed to samples of the polymer prior to conversion into products.

- Consideration of the product and where it will be used is needed when designing and testing the biodegradability of different products. This must be done before they are released onto the open market.

- Testing and certification must also link directly to labelling on the product, indicating the potential for biodegradability and the receiving environment required to achieve this. If the appropriate receiving environment is a managed waste stream, appropriate labelling of the disposal pathway is needed to minimise cross-contamination.

- There is a requirement for legislation relating to the use of standards and associated labelling. However, unless this legislation is enforced, it will not be possible to maximise the potential benefits from appropriately tested and certified products that are used in the proper context, nor will it be possible to prevent fraudulent use of terms such as 'biodegradable' in a context where there is no testing or where testing indicates a failure, nor will it be possible to minimise consumer confusion or potential for detrimental environmental outcomes.

- There are applications where the potential benefits of using biodegradable plastics are much less certain and the potential for advantages much lower. To reach robust decisions in order to guide policy on current and novel uses, it is essential to consider applications in a holistic manner and in relation to the waste hierarchy. Failure to do so will perpetuate inappropriate usage, consumer confusion and the potential for unwanted environmental consequences.

Chapter 4: Testing, standards and certifications

What is this Chapter about?

- This Chapter summarises the development of tests, standards, and certification schemes for biodegradability of polymers. It discusses the need to consider the interplay between the material and the environment of marketed plastic objects, rather than solely the materials themselves.

- It introduces testing schemes and requirements for the assessment of the biodegradability of plastics, including biodegradation under environmentally relevant conditions, lifetime, persistence, residence time in different environments, and impacts and effects on the environment.

- It gives an overview of the possibilities by which to arrive at an efficient, competitive and innovation-friendly testing scheme, while under the time pressure of continuous environmental impact from plastics in the open environment.

- The Chapter gives an overview of the possible options by which to set up an efficient, competitive and innovation-friendly testing scheme to support substitution efforts. It explains that it is important to do so as quickly as possible, due to the continuous input of plastic into the environment.

4.1 INTRODUCTION

Biodegradable plastic materials are increasingly discussed as an alternative to conventional non-biodegradable plastic for specific applications in the open environment, as part of a larger mitigation strategy against plastic pollution. After all possible measures have been taken to reduce or prevent the further release of plastic into the open environment, biodegradable plastics may offer a solution for plastic items with:

- **intentional** input (e.g. mulch films (Sintim et al., 2020), plant seedlings (Casarin et al., 2017), tree shelter tubes, cosmetics etc.)

- **high risk of loss** (e.g. fishing devices, cigarette butts etc.)

- where **loss is intrinsic to use** (e.g. abrasion of paint, tyres, shoes, textiles (Corradini et al., 2019), aquaculture nets (Krüger et al., 2020), shotgun shells, etc. (EPA Network, 2019; see also Chapter 3).

The amount of invisible entry of plastic material through abrasion and intended use of microplastics is estimated to be higher than the visible entry (Bertling, Bertling, & Hamann, 2018; Fraunhofer UMSICHT, 2018).

Regardless of the source of conventional, non-biodegradable plastic waste, all these applications contribute to the accumulation of plastic in the open environment and

have impact. Substituting conventional with biodegradable plastics raises the political and societal question of how to assess and regulate biodegradable plastic that is known to end up in the open environment. Biodegradation of plastic is generally seen as an advantage, and separate regulations for biodegradable plastic are being considered. At the same time, there is a fear of abuse. The precautionary principle demands careful assessment of the biodegradation characteristics of plastics for specific applications (including those listed above), given that any plastic object or item that has reached the open environment will start to have an impact on the ecosystem. This Chapter summarises the current status and possible future activities and developments with regard to the testing and certification of plastic biodegradation in the open environment.

The development of polymers designed to be biodegradable in specific environments was intensified 35 years ago (Bastioli, 2020). Biodegradable polymers have been introduced to the market on an industrial scale since the end of the 1990s (Kunkel et al., 2016). Biodegradation tests on organic compounds and substrate were developed much earlier in the field of microbiology and focused on the identification of pathways and metabolic processes. The test conditions were optimised for the selection of cultivable microorganisms capable of biodegrading certain carbon-based materials and did not necessarily reflect conditions that were representative of the (open) environment (Beek, 2001). In the 1960s, as environmental pollution of the environment by low molecular weight organic compounds was increasingly detected, methods to test biodegradability of these compounds under laboratory conditions were further developed. This resulted in **screening tests** with simple and optimised test conditions, allowing a statement on the biodegradation potential of a specific compound of interest, and **simulation tests** that better mimicked environmental conditions (for details, see Beek (2001). Common test approaches were based on quantifying the increase in microbial biomass, the depletion of substrate, changes in substrate properties and reaction products over the course of the tests (Andrady, 2000). For these organic compounds, the collected data from simulation tests were used to put the tested materials into categories, according to persistence and impact. Also, testing under real field conditions was already being discussed (Beek, 2001).

These tests, originally designed for low molecular weight organic compounds, provided the basis for the development of tests for solid polymers. In the 1980s, motivated to a large extent by the US Navy's need to assess disposal of waste at sea, aquatic field and tank tests were also further developed (e.g. Brandl & Püchner, 1992; Doi et al., 1992; Imam et al., 1999; Puechner et al., 1995). Ratto and colleagues from the US Navy (Ratto et al., 2001) developed a three-tier system (lab, tank and field) in a pre-normative study which increased the environmental relevance of the tests and their comparability. This was achieved by promoting the development and use of standards. Pre-normative studies on the assessment of impacts had not been considered to the same extent at that time, however the need for the development of standard test methods was obvious.

Standards and **certification** are a tool to formally confirm a certain procedure or the accuracy of a claim. Standards for biodegradable plastics were beginning to be developed in the early 1990s, led by the American Society for Testing and Materials (ASTM; De Wilde, 2020). Some years later, the Deutsches Institut für Normung (DIN) and the Comité Européen de Normalisation (CEN) joined and, besides standard test methods, also introduced the normalisation of standard specifications. The International Organization for Standardization (ISO) followed the national and regional efforts to adopt test methods on a global level. **Standard test methods** for the biodegradation of plastic materials were introduced for compost in 1992 (ASTM D5338-15, 2015), for soil in 1996 (ASTM D5988-18) and 2003 (ISO 17556:2019, 2019), for the sea in 1993 (ASTM D5437-93, 1993; weathering only, no true biodegradation test) and 2009 (ASTM D6691-17), and for aqueous media in 1999 (ISO 14852:2018, 2018; focus on waste water treatment). **Standard specifications,** as well as **certification schemes,** were first developed in the late 1990s for the managed environment of industrial composting facilities, to enable proof of the claim 'industrially compostable'. Later, 'home compostable', 'biodegradable soil', and 'biodegradable water' followed and the most recent was 'biodegradable marine' in 2015. The existing standards for soil, water and marine are criticised as not sufficiently environmentally relevant (ECOS, 2019).

This leads to the questions of how to test and certify the biodegradability of polymers, taking into account the interplay of material properties and environmental conditions, how to assess biodegradation kinetics and effects in an environmentally relevant way, and which aspects to include in tests and risk assessments to verify the claims of biodegradation.

This Chapter focuses on two aspects:

1   **With regard to general *biodegradability* of a plastic in the open environment, it is necessary to verify the claim.**

2   **With regard to the materials' actual *biodegradation* in the open environment, it is necessary to measure the time to complete remineralisation and its impact on the environment.**

All components of the original test material, and also eventual degradation intermediates, need to be biodegradable and environmentally acceptable. The end products of biodegradation are CO_2 (and CH_4), water, (in some cases, mineral salts) and microbial biomass. There should be no persistent microplastics created and no persistent intermediate products left in the environment. Biodegradation can occur from very fast (a few weeks) to very slow (many decades), depending on the external conditions, plastic composition and the geometry of the object.

Consideration in this Chapter is not limited to pure polymers but extended to **marketed plastic objects**, i.e. the specific items that are entering the environment (EPA Network, 2019). They are rarely made from pure polymers, but usually from blends or are mixtures including additives, adhesives, pigments, inks, prints, coatings, etc. (see Chapter 2). Even if the biodegradation of all components has been demonstrated in appropriate tests, it is recommended that the objects also be tested as the final

product. This recommendation reflects the fact that a combination of materials and/or the manufacturing process can result in a change in biodegradability or in its effects on the natural environment.

In summary, from these considerations there are four needs identified for testing and certifying of a plastic item:

1. the determination of biodegradability
2. the assessment of the biodegradation rates under environmentally relevant conditions
3. the modelling of the lifetime/persistence in the environments of interest
4. the assessment of the effects on the environment on organism and ecosystem level

In this Chapter, we summarise the status and gaps in testing and certification in this context.

4.2 TESTING SCHEME AND REQUIREMENTS

4.2.1. How to assess 'biodegradability' of plastic

Direct testing methods

Biodegradability of plastic describes its potential to undergo biodegradation in a suitable environment (Degli Innocenti & Breton, 2020; Van der Zee, 2020). The biodegradation of plastic is defined as its complete microbial metabolic utilisation, resulting in its conversion to CO_2/CH_4 and biomass by the metabolic activity of microorganisms (for a detailed definition, see Chapter 2). Scientifically, the correct way of applying a direct test for the biodegradation of a material is to trace all organic constituents, from the test material (input) to its end products (output). For plastics that mainly consist of carbon-based polymers and additives, it is desirable to follow biodegradation according to:

$$C_{polymer} = CO_2 (+ CH_4) + C_{biomass} + C_{residual\ polymer}$$

where $C_{polymer}$ is the plastic item of interest

Technically, this can be done by labelling the test material with stable (^{13}C) or radioactive (^{14}C) isotopes and following the labelled carbon through the biodegradation process until completion in a closed system, as described in ASTM D6340-98, ASTM D6692-01 and ASTM D6776-02. However, with these methods it is not possible to distinguish between biomass and residual polymer and therefore should not be applied for the assessment of the biodegradation of a plastic item. NanoSIMS (nanoscale secondary ion mass spectrometry) is successfully used to measure labelled material within microbes and can be used to track carbon into biomass (T. Li et al., 2008; Musat et al., 2008; Zumstein et al., 2018). This direct test method, however, is technically complex and expensive, and therefore neither well suited nor feasible for a testing scheme.

A practical simplified approach to assess 'biodegradability' typically is conducted in (standard) laboratory tests in small (0.1 – 4 L) closed vessels (Fig. 1a) under controlled conditions favourable for biodegradation. These tests are coupled to a respirometric analysis of the amount of the evolved gas(es) CO_2 (and/or CH_4). Techniques to measure the gas evolution may differ, and the reader may consult the work of van der Zee (2020) for further information. Relevant for this report is that the amount of end product evolved over time serves as a proxy for the extent of biodegradation (Figure 4.1, e.g. ISO 17556:2019 for soil, ISO 14852:2018 for aqueous medium, ISO 18830:2016 at the marine seawater/sediment interface). Mechanistically thinking, one would expect a 100% yield of the original carbon in the evolved gas. However, as living organisms (microbes) are involved in the process, this is practically not reached because part of the carbon is incorporated into biomass and will therefore not be detectable as CO_2. Carbon use efficiency (conversion to biomass) is theoretically a maximum 60% and known to be around 40-50% (Sinsabaugh, Manzoni, Moorhead, & Richter, 2013). It is important to understand that tests are carried out with biological systems and that these are never identical, and that heterogeneity must therefore be taken into account. Tests typically stipulate a conversion extent of 90%, either absolute or relative to the reference material (usually cellulose = positive control) and/or reaching the plateau phase.

Figure 4.1: Laboratory tests: (a) closed bottles of the sublittoral water-sediment interface lab test, measuring the development of CO_2; and (b) incubation bottles of the pelagic (water column) lab test to measure O_2 consumption. (Weber et al., 2015).

The kinetics of biodegradation are composed of three phases (Figure 2):

1 Biodegradation typically has an initial lag phase, during which an initially small population of biodegrading microorganisms multiplies in response to the new carbon source (Wiggins, Jones, & Alexander, 1987).

2 Then follows the linear phase, where the system is in good balance and biodegradation occurs at maximum rate.

3 In the plateau phase, the substrate (here, the plastic) or, in some cases, also other factors (e.g. nutrients) become limiting such that biodegradation slows down markedly, relative to the linear phase.

All phases are influenced by the composition of the inoculum, the concentration of the test material, temperature, sorption, oxygen content, sediment and soil types and

grazing, as well as the interactions of these factors (Pischedda et al., 2019; Wesnigk, Keskin, Jonas, Figge, & Rheinheimer, 2001).
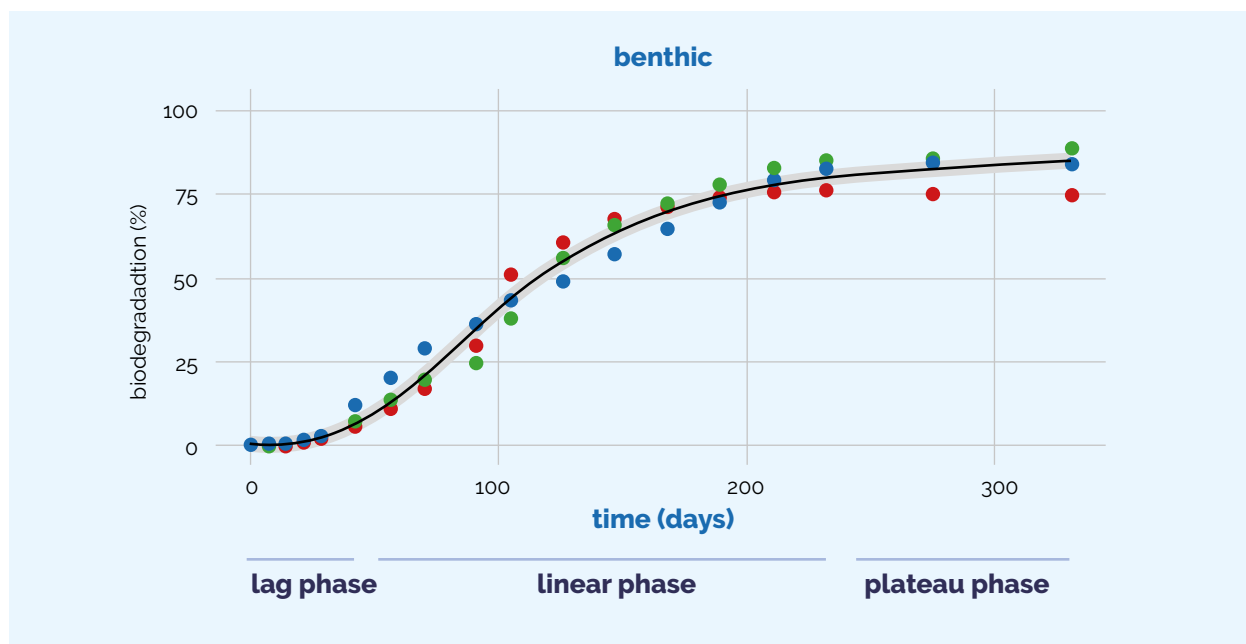
benthic

Figure 4.2: Typical graph from a lab test showing the three phases (lag, linear and plateau phase) of PHA being biodegraded in a marine benthic scenario.

Ideally, at the end of the incubation tests, potential polymer or plastic residues that remain unmineralised should be extracted and quantified with a suitable method (e.g. Soxhlet or accelerated solvent, coupled to quantitation by nuclear magnetic resonance (Nelson, Remke, Kohler, McNeill, & Sander, 2020)) and incorporation of polymer carbon into microbial biomass can be demonstrated (Zumstein et al., 2018). These additional steps, however, require more sophisticated analyses and are not required by standard tests, thus are generally omitted for simplicity. It should be considered that not all constituents of a plastic product can be extracted with the same methodology and hence that plastic-specific adaptations may be needed.

Indirect testing methods

The only indirect method to assess biodegradation that is accepted in standards is assessing the oxygen demand as substrate-induced respiration (Figure 1b, e.g. ISO 16072:2002 (2016) for soil, ISO 14851:2019 for aqueous medium, ISO 19679:2016 at the marine seawater/sediment interface). For further details on the method, the reader may consult the work of van der Zee (2020).

However, oxygen consumption measurements bring along the problem that other oxygen consuming processes can adulterate the results. For example, nitrification or chemical oxidation could lead to false positive results (UBA, 2017). The same holds true for CO_2 measurements. For example, matrices like sediment or soil, with high background CO_2 development are problematic, due to interfering compounds, and might need methodical adaptation accordingly (Van der Zee, 2020; Tosin et al., 2016b). All tests need good controls or blanks to account for these problems.

Other indirect measurements that consider material alterations (e.g. change in molecular weight, tensile property etc.) are often applied and used as an interpretation or even proof of biodegradability in the scientific literature (Harrison et al., 2018). Although these parameters can give additional information, according to the definition given in Chapter 2, it is not reasonable to use such data alone for the purpose of biodegradation assessment. This should be assessed by the methods mentioned above.

Generally, two types of lab tests are distinguished: screening and simulating tests (Beek, 2001).

- **Screening tests** do not consider that conditions for biodegradation vary considerably across the open environment. The focus is on the biodegradation potential of a plastic item under suitable test conditions. These conditions include that the test substance (polymer or plastic) is the sole carbon source, and that the pH, oxygen, temperature and nutrients are suitable for the microorganism inoculum. From a material point of view, the aim of a screening test is to demonstrate that a tested plastic material is indeed biodegradable (or not). However, rates of plastic biodegradation from screening tests cannot be used to predict biodegradation rates in the open environment, particularly when environmental conditions markedly differ from the ones in the screening tests.

- In order to reach higher environmental relevance, the test should **simulate** as well as possible the conditions of the environment of interest and use its matrices (soil, water, aquatic sediment; Weber, 2020). Yet, finding a balance between an optimized screening test and environmental representation is a difficult task and under debate (Kowalczyk et al., 2015). Environmental relevance is required by certain standards, for example, ISO 14852:2018 for aqueous media with a focus on activated sludge. However, given that the conditions vary substantially across ecosystems that constitute the open environment, many more conditions need to be considered (Beek, 2001).

As biodegradability is a system property and hence needs to be seen in the context of the environmental conditions (Chapter 2), from the environmental point of view, laboratory tests under controlled conditions are mandatory but, by themselves, give only a first indication of biodegradation rates of a plastic material in the open environment (Beek, 2001; Degli Innocenti & Breton, 2020). Transferability into the environment is best validated by field and tank tests, in order to achieve environmental relevance and to assess biodegradation under *in situ* conditions (Tosin et al., 2016a; Tosin et al., 2016b; Weber et al., 2015).

Consideration of how to limit the possibilities and variations of tests is discussed further below, also in terms of innovation, economic competition and time constraints due to continuous environmental impact.

4.2.2 How to assess 'biodegradation under environmentally relevant

conditions'

The artificial nature of optimised lab tests leads to criticism that they are not environmentally relevant enough and 'are not designed to predict biodegradation kinetics in environmental compartments, due to their unrealistic high test concentrations, inoculum concentrations and higher temperatures, compared to nature' (Beek, 2001; UBA, 2017).

In order to integrate both accuracy and reproducibility of a lab test and to be environmentally relevant, a two-tier scheme was developed already by 1995 (Puechner et al., 1995) and a three-tier testing scheme (Ratto et al., 2001) was refined as one outcome of the EU project Open-Bio (Figure 3; Lott et al., 2020; Lott et al., 2018; Weber et al., 2018). In the first step, and as a prerequisite for further testing, the biodegradability of the plastic material needs to be demonstrated in optimised laboratory tests (Figure 1; (Briassoulis, Pikasi, Briassoulis, & Mistriotis, 2019; Tosin, Weber, Siotto, Lott, & Degli-Innocenti, 2012)), ideally using water and sediment from the location of interest in the natural environment (EPA Network, 2019).

In the second step, to assess the biodegradation behaviour of a material under real natural conditions, field tests are carried out in relevant habitats and conditions (examples in Figure 4, (Lott et al., 2020)). However, as each field test also only reflects a selection of reality and because field tests might require special technology and higher costs, further tests are carried out in mesocosms (tanks) that simulate the environmental conditions in larger volumes (10s – 100s L) than usual lab tests (soil: Casarin et al., 2017; Rudnik & Briassoulis, 2011; marine: Figure 5; Lott et al., 2016b; Lott et al., 2020). Mesocosms methodologically link laboratory (well-controlled) and field tests (poorly-controlled) and allow testers to control and manipulate some of the conditions (e.g. temperature). In this way, it is possible to test other relevant conditions more cost-effectively than directly in the field. All three tiers together then result in a dataset that reflects the relevant environmental conditions and proof of biodegradation.
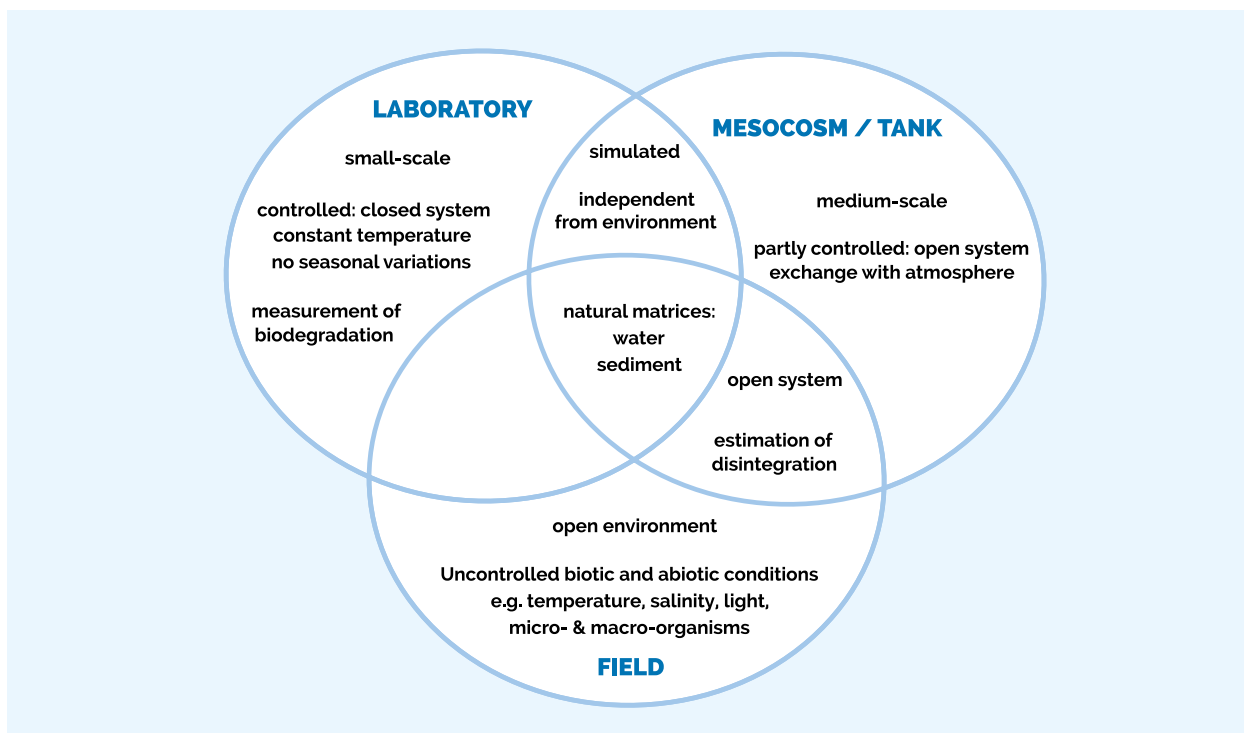
Figure 4.3:. Interconnectedness of the three tiers. Description of the environmental and technical conditions of the lab tests (measurement of biodegradability), the mesocosm and field tests (estimation of disintegration). Modified after Tosin et al., 2016b; Open-Bio D5.7 part 1.
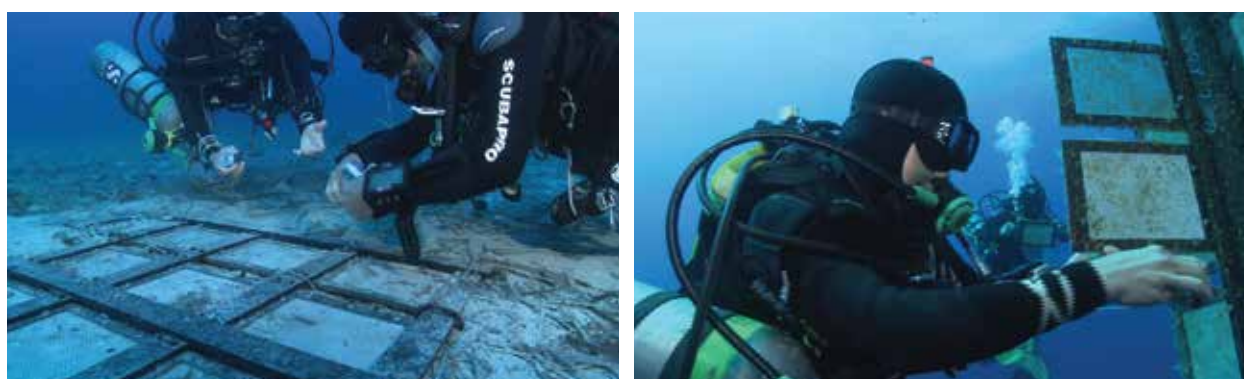
Figure 4.4: Example of marine field tests (a) at the water/sediment interface and (b) in the pelagic (water column) in the Mediterranean Sea, Italy (Weber et al., 2015).

Figure 4.5: Example of a mesocosm system for testing under controlled conditions of (a) the eulittoral (intertidal), (b) sublittoral (water/sediment interface) and the pelagic (water column) habitats. (Weber et al., 2015).

4.2.3 How to assess the lifetime, persistence, or residence time and select the environment of interest

Lifetime or persistence data are needed for life cycle assessments and life cycle impact assessments. In order to assess potential environmental effects and risks of plastic items, information is required on 'how long this item remains in the environment'. This information is of central importance and should as best as possible be answered by plastic biodegradation tests and modelling.

Because both field and tank tests are 'open' test systems, the end products (CO_2 and CH_4) cannot be captured and measured. In these cases, disintegration is measured as a proxy for biodegradation (Lott et al., 2020; ISO 14855-1:2012; ISO 14855-2:2018; ISO 22766:2020). However, field and mesocosm tests should be designed in such a way that mechanical impacts are reduced to a minimum or practically excluded. Only then, and under the already mentioned prerequisite of proven biodegradability in a closed-vessel lab test, the measured disintegration can be safely assumed as being prevalently caused by biological and chemical degradation, indicating biodegradation.

The disintegration can be measured in the form of weight attrition or areal mass loss (∂ mass per area and time) or erosion rate (∂ distance per time). From these, the lifetime could be assessed by mathematically modelling the half-life or the duration until complete disintegration, interpreted as complete biodegradation (lifetime, persistence or residence time).

Measuring mass loss is a challenge for samples exposed in an open environment (e.g. Lott et al., 2020). Accurate weighing of samples exposed to seawater bears several sources of error, due to so-called 'fouling' of the plastic by organisms growing on the test material. If the test material is cleaned (chemically or mechanically) before the measurement, this might lead to the loss of embrittled parts of the material and subsequent overestimation of material loss due to disintegration. If the fouling organisms (or sand grains, in the case of soil or sediment exposure) remain on the sample, weighing would underestimate the extent of disintegration. For thin film such

as plastic foil, which can be considered a two-dimensional structure, a suitable way of determination is the measurement of the area of remaining material via image analysis (ISO 22766:2020, 2020). This method is not suitable for objects with a three-dimensional structure, where a volume loss must be recorded. The latter can be done by measuring the thickness using a micrometer screw or computer tomography, which is currently under further development by the public project MabiKu.[10]

Successive serial measurements from field and tank tests are usually exemplary and no lifetime or half-life can be deduced from the raw data alone. Statistical modelling is used to calculate the desired value from a non-linear process (Eich et al., 2019; Lott et al., in prep.). Because such models are asymptotically infinite, from a purely mathematical point of view, the lifetime can never be over. For this reason alone, from a scientific point of view, the determination of the half-life is preferred. Alternatively, a specific surface degradation rate (SDR) is currently being discussed for use (Maga et al., 2020). It is independent of the shape and size of the object. The authors propose a data catalogue where, according to the results, the polymers are divided into degradation classes (SDR <1 μm/year; 1–10 μm/year; 10–100 μm/year; 100–1000 μm/year; >1000 μm/year).

In order to be able to tell how long it requires for an object to be degraded, e.g. 'in the sea', the disintegration must be recorded under the corresponding environmental conditions. Such data provide the basis for the representation of the range of lifetimes or degradation rates of an object under the relevant environmental conditions. The answers to the questions of 'what rate or degree of degradation in a certain time is *acceptable?*' as well as 'what effects are *acceptable?*' (see also 4.2.4) are decisions for an interdisciplinary team of experts and will not be addressed here.

Formation of micro- and nanoplastics and implications for the lifetime of plastic objects

During the time an object is present in the terrestrial, freshwater or marine ecosystem, it affects its surrounding environment. This happens first as an intact object and then also during the degradation process, in the form of fragments of various sizes. Larger fragments become microplastics (<5mm) and then nanoplastics (<1μm) and finally mineralise completely to CO_2 (and/or CH_4). As the surface/volume ratio increases with decreasing particle size, the bulk biodegradation rate has been shown to increase (Chapter 2; Chinaglia et al., 2018b). Thus, with an accelerating degradation rate, the smaller the particles get, the faster they degrade, and no micro- or nanoplastics should remain in the environment. In the case of a mixture, blend or copolymer, it is necessary to know whether all components biodegrade at the same rate, or whether individual compounds have slower rates. The results of dedicated laboratory tests can provide such rate information.

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10   www.mabiku.de

Extrapolation of available biodegradation results

A good example of the fact that data on plastic biodegradation cannot be extrapolated from one test condition to another is Civancik-Uslu et al. (2019). They assumed (because no specific data were available) that biodegradation rates obtained from industrial compost tests can be taken to estimate the residence time of a plastic object in the marine environment. This assumption, however, is questionable, given that conditions in technically managed industrial compost are very different from those in the natural environment. The temperature in industrial composting facilities usually varies between 50 and 60°C, and pH, carbon/nitrogen ratio and oxygen availability are optimised (European Bioplastics, 2009). Thus, biodegradation kinetics from a composting facility cannot be extrapolated to the open environment. Degli Innogenti and Breton (2020) stated that 'The results obtained under these conditions are not considered to be straightaway predictive of the potential for biodegradation in most open environments where mesophilic microorganisms thrive'. The biodegradation of an object that occurs rapidly over weeks in compost can take months or many years, depending on the environmental conditions. As an example, the half-life of a plastic film (home-compostable ecovio®grade, thickness 20 μm), tested both in tropical (south-east Asia) and warm-temperate (Mediterranean) marine field conditions in the water column, ranged from 357 to 1519 days (Weber, 2020). On the shallow water seafloor, the half-life was 173 to 1000 days, whereas the half-life of PHA film (thickness 85 μm) at the warm-temperate test site was 738 days. This shows clearly that half-lives are specific to test conditions and materials.

Variations in biodegradation kinetics of plastics in the open environment were also apparent in the Open-Bio project (Briassoulis et al., 2019; Lott et al., 2020; Lott et al., 2016a) through field tests conducted in parallel in the same climate (Mediterranean Sea), in two locations in Greece and Italy. Disintegration of plastic film was faster in tests in Greece than in Italy. In Greece, the tests were carried out near an active fish farm and it can be assumed that the disintegration was favoured by higher nutrient availability and thus faster microbial growth. Therefore, biodegradation kinetics cannot be extrapolated from one condition to another and conditions should be reported with each test result.

Lack of data

There is a general lack of observational or experimental data, both for conventional plastics and biodegradable plastics (Chamas et al., 2020). The figures that describe the lifetime of common litter objects, which have been published on information posters and also by intergovernmental organisations over several decades, are purported without scientific proof and rather legendary (e.g. Ward & Reddy, 2020) but used by authorities, policymakers, NGOs, industry, and society.

Whether conventional or biodegradable polymers have been studied, statements based on indirect measurements are problematic. In-depth reading and understanding is needed for publications like for example 'Degradation Rates of Plastic in the Environment' (Chamas et al., 2020). It is important to understand that data

collected on presumed (bio)degradation are still often based on indirect methods, measuring changes in molecular structure, and should not be confused with true biodegradation rates.

For biodegradable plastics, attempts to summarise data from the few experimental studies scattered in the literature are beginning to increase. Dilkes-Hoffmann et al. (2019) reviewed eight studies for area mass loss and estimated the residence time in the marine environment, in an attempt to provide a range of lifetimes for biodegradable plastic products in the marine environment. For example, the estimated lifetime for a PHA plastic bottle ranged from 1.5 to 3.6 years. The authors pointed out that this range does not yet cover all key factors and conditions, and more data are needed to understand whether the range is even larger. So far, the range covered by the studies was not based on systematic ecological considerations but deduced instead from a compilation of existing results. A catalogue of materials with their biodegradation rates in a variety of ecological settings is urgently needed but not available.

4.2.4 How to assess the impacts and resulting effects to the environment

Impacts and effects of biodegradable plastics in the open environment need to be known for risk assessment, life cycle assessment (LCA), and life cycle impact assessment (LCIA). The intact object itself and all intermediates and biodegradation products can have several physical and (biogeo-)chemical effects (see Chapter 5), according to the receiving environment, habitat and conditions. From the environmental perspective, two aspects are important to consider: the organism and the ecosystem level. There are then a number of further aspects to be addressed: for example, the time a certain effect will last, the recovery time, and the intensities (for instance, which acute and chronic effects may occur). Classical ecotoxicity tests are used to examine the effects by biodegradation of a plastic item at the *organism level,* whereas tests on the *ecosystem level* are not available as standards and need to be developed.

For LCA and LCIA, an approach is to compare the behaviour of products in the environment. Categories used are the amount of input, fate, biodegradation or lifetime and potential effects on the environment (Strothmann, Sonnemann, Vázquez-Rowe, & Fava, 2018). In this respect, biodegradation is a key aspect for product lifetime and impact assessment, especially when comparing polymers with different biodegradability properties, as these can change the life of products once they are released into the environment, as well as their potential negative impact. LCIA aims to quantify the extent of these effects. To do so, it takes into account aspects such as where the waste remains secondarily or finally, and whether or not it biodegrades (Everaert et al., 2018). During this process, compounds such as additives might be released, and degradation products will be generated which are also taken into account (Zimmermann, Dierkes, Ternes, Völker, & Wagner, 2019). Impacts are described in the form of effect factors, in order to model the potential effects in a comparative manner.

With regard to degradation rates, Maga et al. (2020) went a step further and proposed an approach to improve comparability by becoming independent from

shape and size. The authors developed a 'shape factor' and included, for example, the 'characteristic length' for cubes, sheets and fibres to calculate the specific surface degradation rate (note, not explicitly biodegradation rates). To further ease comparability, they proposed to define 'degradation rate classes' (see also 4.2.3). When applying the formula to existing study results, the authors concluded that data availability is still challenging because the degradation rates differ strongly, and too little information on the test items and the testing conditions were given, rendering comparisons difficult. Therefore they call for better comparable testing and more data.

Integrating biodegradability and the residence time of plastics into LCA and LCIA is a current research topic. It was concluded recently that insufficient data is available yet to allow for such integration, leaving LCA and LCIA incomplete (JRC 2018). Larger research projects on this topic were started in 2019.[11] There is, as yet, no concrete proposal publicly available on how to comprehensively address the impacts and effects of (biodegradable) plastics in the 'open environment'. Only a representative coverage of tests on effects could reduce uncertainty and a multi-tier test scheme should be developed for this. Results could then be used for modelling and further for risk assessments. As mentioned, it should be considered that potential impacts occur directly to single organisms, as well as to entire ecosystems. Both levels must be assessed:

- The **effects on organisms** during degradation should be measured in the form of ecotoxicological tests. These should represent a cross-section of the organisms in the environment of interest, which should be selected based on the occurrence of plastic waste. Aspects like, for example, trophic levels and acute/chronic toxicity should be addressed and can be covered by the same methods as applied for conventional plastics. Some aspects are linked specifically to the property of biodegradability and should be addressed specifically (e.g. residence time, effect duration, recovery time).

- The **effects at the ecosystem level** should be considered to determine the impacts in a representative manner, for example, for soil in terrestrial and the bottom of the water body in aquatic ecosystems. The effects on the most relevant biogeochemical processes such as photosynthesis, respiration (aerobic degradation) and, if possible, exoenzymatic hydrolysis, should be considered for assessment.

In summary, the lack of specific data on the biodegradation rates and the impact of available plastic materials claimed to be biodegradable is still significant. The same is true for conventional plastics, making a comparison even more difficult. To be able to compare items reliably, the same testing scheme should be applied for all plastics, no matter if biodegradable, conventional or even from another material.

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11   http://marilca.org

4.3 CRITERIA FOR THE SELECTION OF TESTS AND MODELLING

Biodegradation in the 'open environment' largely depends on the environmental conditions at the place where plastic litter passes through and finally ends up, or where polymers are intentionally applied. In order not to hinder innovation, economic development and regulatory implementation, the systematic assessment of biodegradation rates in selected relevant conditions is needed. The selection should be based on defined criteria, be product-specific and should provide a good overview of the environments of interest.

4.3.1. Criteria to select the tests for biodegradability and biodegradation rate assessment

So far, there is no publicly available proposal to say on what basis the tests should be selected. Here we present a selection of criteria and propose that the ultimate selection is made following a cascade of decisions:

First level: Selection of 'open environments' – [*Identify in which environments the plastic will be*]

Identify according to own surveys or available literature:

- *Usage/leakage*: Identify where the object is used or enters the environment (intentionally or unintentionally).

- *Volume and time*: Identify the amount of input at its source and estimate (if possible, measure) how long it will remain in the specific receiving environment before being transported across its boundaries into adjacent environments.

- *Fate, volume and time*: Identify relevant pathways, estimate (if possible, measure) the amount in transport and the time of transport.

- *Sinks, volume*: Identify where the litter finally remains and estimate (if possible, measure) its amount.

Second level: Selection of habitats – [*Identify them at the locations of usage, transport and sink*]

Identify, according to the transport behaviour, the habitats of transport and sinks of relevant amounts of plastic waste:

- Wind-driven/airborne (lightweight objects, fibres): bottom of terrestrial ecosystem, surface waters

- Floating (gas-filled objects: bottles, foams, etc., small pieces): surface waters, banks, beaches

- Sinking: bottom of terrestrial ecosystem, bottom of a lake or slow-flow area in a river, seafloor, within aquatic sediment or soil

Third level: Selection of conditions – [*Identify the main conditions in the corresponding habitat*]

Identify the principal conditions in the selected habitat:

- Temperature: warm, moderate, cold
- Oxygen: present, absent
- Nutrient concentrations: oligo-, meso- and eutrophic
- Moisture content: dry, percentage of moisture, inundated
- Salinity: freshwater, brackish, marine
- Other relevant physical conditions: e.g. UV, wind, water movement

The question here is on which basis to select the open environments, habitats and conditions. The first reference point could be to look at where relevant quantities of the product are introduced and transported to; but 'relevant quantities' need to be defined. It could be the balance between input volume, persistence and impact. The latter should remain at an environmentally acceptable level and should be assessed by Environmental Risk Assessments.

4.3.2. Criteria to select the tests for effect studies and to select data for modelling the impact for risk assessment and LCA

So far, there is also no publicly available proposal to identify on which basis the tests and effect factors should be selected. Here, we present a selection of criteria and propose that the selection be made along the cascade decision system from Section 4.3.1, adding two more levels:

Fourth level: Selection on organism level – [*Identify the main potentially affected functions*]

Identify, in the selected habitat, the main estimated impacts on the level of:

- Trophic level, including mode of nutrition (filter feeder, predator, etc.)
- Acute and chronic toxicity
- Effect level: lethal, sublethal (e.g. biochemical, histological, physiological and behavioural changes)
- Impact level: physical, chemical, spreading

Fifth level: Selection of impacted ecosystems – [*Identify the main potentially affected functions*]

Identify, in the selected habitat, the main estimated impacts on the level of:

- Biogeochemical processes

The development of this list of criteria within this evidence report should be seen here as a first step, to be further developed in an appointed project with a committee of interdisciplinary experts.

4.4 STANDARDISATION

Standardisation is used to achieve comparability, by defining details of procedures and test conditions, helping stakeholders such as consumers and regulators (ISO). Standard tests are worked out in so-called technical committees of independent bodies on an international level such as ISO, ASTM, CEN, or on a national level such as DIN (Germany), AFNOR (France). The technical committee appoints a working group, which then develops the standard during a multi-step procedure. The stage of the development of a standard is, in the best cases, visible online. The content is visible only to the members of the working group until publication of, for example, the Draft International Standard on an ISO level. Here, we present the currently available standard specifications and test methods for biodegradability and biodegradation of plastic in the context of the 'open environment'.

For the sake of understanding, we will briefly touch on the history of definitions and test development. The OECD made early efforts at developing tests for low molecular weight substances (e.g. in sewage treatment plant wastewater, etc.) and defined terms like 'primary' and 'ultimate' biodegradation, 'readily biodegradable' and 'inherently biodegradable' (OECD, 1992a). The focus is on the material potential to biodegrade and therefore the OECD test series 302 (A-C; OECD, 1981, 1992b, 2009) has the aim to test the biodegradability as such. Very recently, this aspect was discussed in respect of biodegradable polymers by Degli Innogenti and Brenton (2020). The authors use the term 'intrinsic biodegradability' and explain that 'it refers to an inherent quality, dependent on the chemical composition and structure of the material, prior to consideration of any 'extrinsic' properties'. They explain that the result is not related to environmental conditions of interest and cannot be transferred to them.[12] The influence of the environmental conditions on biodegradation rates needs to be assessed by other means, for example, by real tests or modelling.

The next step was to face the above-mentioned difficulty of balancing between an optimised screening test and the adequate representation of environmental conditions in the tests (see Section 4.2.1). From a questionnaire to 19 environmental protection agencies, a clear requirement was formulated: 'Standards for the 'open environment' must take up the conditions of the place of interest' (EPA Network, 2019). Assessing the potential for biodegradation in the open environment has been already subject to standard test method development and, in recent years, attempts to fulfil the need of the EPAs were already successfully completed in, for example, *ISO 9679:2016 Plastics — Determination of aerobic biodegradation of non-floating plastic materials in a seawater/sediment interface — Method by analysis of evolved carbon dioxide*. To respond to the need for assessing the disintegration behaviour in the field, an example such as *ISO 22766:2020 Plastics — Determination of the degree of disintegration of plastic materials in marine habitats under real field conditions* was developed. The recent focus on developing standard test methods for degradation in the sea is due to the fact that contamination by plastic in the sea is very strongly represented in the media. Land and freshwater pollution have also become increasingly evident in

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12   See also echa.europa.eu

recent times and will require the further development of test methods specific for these environments.

We do not evaluate the standards named here, and we do not claim that they are all suitable for the needs identified here. An evaluation based on clearly defined criteria should be done by a committee of interdisciplinary experts in a dedicated project.

4.4.1. Standard specification and standard test methods

Standards containing comprehensive information are also called 'specifications' (Suits, 2007). They are used as guidelines and are an explicit set of requirements to be satisfied by a material, product, system or service; as, for example, for the claim 'industrial compostable'. Such standards can also be set up as overarching or comprehensive standards, and are used as a baseline for certification programmes. Examples are *EN 10733:2018 Plastics – Biodegradable mulch films for use in agriculture and horticulture – Requirements and test methods* and *EN 13432 Packaging – Requirements for packaging recoverable through composting and biodegradation – Test scheme and evaluation criteria for the final acceptance of packaging*.

Overarching standards for the open environment, or for soil, freshwater and marine environments, are not available. Currently under development is *ISO/CD 24187 – Principles for the development of standards for investigation procedures of plastics in environmental media and related materials* (ISO/CD 24187). The status is visible as a Committee Draft on the ISO website, which means that the content is not yet public. The next status will be a Draft International Standard, then available online.

Standard test methods mostly provide detailed directions on performing specific tests, which produces a test result and the basis for accreditation programs (Suits, 2007). That way, results from different institutions are more comparable and assure a certain quality level. For assessing the biodegradability in the open environment, standard test methods are available at different stages. The tests for seawater are most advanced, then for soil; the least advanced tests are for freshwater. They are discussed in more detail below.

In general, it can be said that standards exist, but not all relevant environmental conditions are covered yet. For example, standard test methods with anaerobic conditions should be developed. For the open environment, the diversity of conditions that are crucial for degradation cannot be ignored. Biodegradation assessment at different conditions are not yet included, such as, for example, soil type, water content, sediment grain sizes, nutrients, and oxygen concentration. However, covering everything in a standard testing scheme would be too much. A solution could be to assess the influence of different environmental conditions (e.g. different soils, temperatures, sediment grain sizes, water content, etc.) on the biodegradation rates across several research projects as was done, for example, for temperatures in soil (Pischedda et al., 2019). The assessed variations of biodegradation in different soils, varying by a factor of five, could then serve to evaluate the uncertainty of the conducted standard tests. Such a dataset would allow us to take into account the

diversity of soils, freshwater and seawater habitats and to indicate the biodegradation rate as a 'from-to' rate or a range.

More extreme habitats — such as, for example, deserts, tundra, permafrost, cold surface waters, floating ice, and the deep sea — will almost certainly give rise to slow, possibly even very slow rates of plastic biodegradation. Testing for such habitats and conditions should only be required if a substantial input is expected or taking place. For a testing scheme, it is reasonable to select relevant conditions and habitats and only consider extreme ones in special cases. Determining which habitats and conditions should be included in standard test method development and specifications needs to be defined according to a cascade of decisions (see Section 4.3.1).

In summary, if needed, the existing standards should be adapted according to the relevant criteria and, if missing, be set up for the relevant environmental habitats and conditions for all three tiers: lab, field and mesocosm.

4.4.2. Available standards for soil

The existing laboratory standards for plastic biodegradation in soil are ASTM D5988-18 and ISO 17556:2019. Although focusing on soluble organic compounds, the standards and specifications ISO 16072:2002, 11266:2014, 14239:2017 (aerobic conditions) and 15473:2012 (anaerobic conditions) do include insoluble compounds.

Other habitats, such as grassland or forests, are not yet considered. They might be relevant for applications intentionally released and uncontrolled (e.g. shotgun shells) or intentionally used (e.g. tree-blight protection).

To our current knowledge, there are no standards for field or mesocosm tests nor specifications for the open environment soil. The latter is under discussion, because there is the specification EN 10733 'Plastics – Biodegradable mulch films for use in agriculture and horticulture – Requirements and test methods'(BS EN 17033:2018). It requires tests with a topsoil of an agricultural field or a forest. However, it is aimed at biodegradable mulch films for use in agriculture and horticulture. The testing requirements and criteria cover chemical composition, biodegradation in soil, ecotoxicity and physical characteristics, which can serve well as a baseline for specifications for open environment soil. A new specification (ISO/CD 24187), again focused on mulch film and including biodegradation, ecotoxicity and control of constituents, is under development at the ISO level.

4.4.3. Available standards for freshwater

Existing standards for freshwater lab tests originate from the operation of wastewater treatment plants: ISO 14851:2019, 14852:2018, 14853:2016. They are based on testing plastic biodegradation with activated sludge from wastewater treatment plants as inoculum, and do not exclude use also for freshwater. The disadvantages are that the inoculum of microbes comes from sewage treatment plants and is thus artificial; natural matrices (water and sediment) are not used to introduce microbes from the

open environment into the experiment. As far as we know, there are no standards for freshwater field and mesocosm tests, nor specifications. Habitats other than the water column, as an extension of the abovementioned standards, such as lake floor or riverbank scenarios, are not yet considered. The existing standards should be adapted according to the listed criteria, standards set up for relevant environmental habitats and conditions, and specifications formulated. *ISO 14853:2016 Plastics — Determination of the ultimate anaerobic biodegradation of plastic materials in an aqueous system — Method by measurement of biogas production* is a test focusing on anaerobic waste water treatment conditions and could be adapted for open environment freshwater and seawater scenarios.

4.4.4. Available standards for seawater

For the marine environment, some new ISO standards have been launched and some have been modified, based on existing ASTM standards in recent years. For lab tests, adaptations were under discussion and finalised in November 2020 (ISO/FDIS 23977-1; ISO/FDIS 23977-2). Tank and mesocosm testing methods are available or under review. Field tests are available for the sea surface, the sandy intertidal habitat (beach), the sandy shallow water seafloor and the water column. Specifications were available in ASTM D7081-05 and withdrawn in 2014. There is the new *ISO 22403:2020 Plastics — Assessment of the intrinsic biodegradability of materials exposed to marine inocula under mesophilic aerobic laboratory conditions — Test methods and requirements* for the intrinsic biodegradability of virgin (i.e. not pre-treated) plastic and polymers. It does not include ecotoxicity testing, nor disintegration under field conditions.

So far, several marine areas with special characteristics (e.g. without oxygen, low in nutrients and under high pressure (deep sea) are not considered in the test methods, despite their frequent occurrence and large share in the marine realm. A compilation of the currently available standards for testing biodegradation under marine conditions is shown below (Table 1). The existing standards should be adapted according to the listed criteria, and standards set up for the remaining relevant environmental habitats and conditions.

Table 1: Compilation of the current standard test methods and standard specifications for marine shallow water scenarios, according to the three-tier test scheme.

	Standard test methods: Pelagic zone (water column scenario)	Standard test methods: Benthic zone (seafloor scenario)	Standard test methods: Eulittoral zone (intertidal beach scenario)	Standards specifications
Laboratory tests	ASTM D6691-17		ASTM D7991-15	ASTM D7081-05; withdrawn 2014
	ASTM D6692-01; withdrawn 2010			ISO 22403:2020
	ISO/FDIS 23977-1	ISO 18830:2016, 2016	ISO 22404:2019	
	ISO/FDIS 23977-2	ISO 19679:2016,		
Field tests	ISO 15314:2018, 2018	ISO 22766:2020	(ISO 22766:2020, 2020	
Tank tests		ASTM D7473-12 & WK71923, 2020*		
	ISO/DIS 23832*	ISO/DIS 23832*	ISO/DIS 23832*	

ASTM = ASTM International (originally American Society for Testing and Materials)
ISO = International Organization for Standardization
* under development

4.4.5. Pass levels and duration times

A 'pass level' in this context is a specific percentage of biodegradation that needs to be reached over a pre-defined incubation time; plastic test material that falls short on this percentage fails the pass level. Meanwhile, 'duration time' defines the length a test should be run. Depending on the application and context, one or the other of these criteria should be used; neither is intrinsically better or worse.

Standard test methods usually specify test duration times, rather than pass levels. For example, in the soil test ISO 17556:2019, it is stated that the test time usually should not exceed six months. If a plateau (see Section 4.1.1.) has not yet been reached, the test can also be extended, but not to more than two years. In the water test ISO 14852:2018, it is stated that the test time should not exceed six months, and not more than 24 months for the seafloor test ISO 19679:2016. Here, a pass level is not stated. The test can be stopped as soon as a plateau in the measured values has been reached. The maximum test duration of two years reflects the difficulty of maintaining conditions in a closed incubations system and should not be considered a form of pass level. For marine field tests, it is stated that test results should be reported after three years or earlier, in cases where a disintegration of > 90% has been achieved (ISO 22766:2020). Still, in this test, the disintegration can be investigated beyond the three years. Being a field test, the conditions are not problematic to maintain, and the test duration could be considered as a form of threshold. However, the reasons for selecting the duration

of three years have not been specified. Eventually, it should be clarified whether pass levels belong in a standard test method and/or in standard specifications and/or certification schemes.

Standard specifications can contain specified pass levels. For example, EN 17033 (BS EN 17033:2018; mulch film in soil) requires a minimum of 90% conversion of the mulch film into CO_2 within two years using ISO 17556:2019. Furthermore, a minimum of 90% germination rate and plant growth (OECD, 2006), a difference in mortality rate and biomass of earthworms (ISO 11268-1:2012, 2018; ISO 11268-2:2012, 2018; ISO 11268-3:2014, 2014) of less than 10%, and a minimum of 80% nitrification of bacteria (ISO 15685:2012, 2017) relative to the blank is required. A disintegration test under field conditions is not required. EN 13432 (industrial compost) also requires a minimum of 90% conversion of the test material into CO_2. In contrast, a duration time is not stated but a disintegration test is required. Its duration is maximum twelve weeks and a minimum 10% of the original dry weight of test material should fail to pass through a >2 mm fraction sieve. Ecotoxicity is tested on higher plants with the OECD 208 (OECD, 2006; minimum 90% of germination rate and plant growth).

Certification schemes do have specified pass levels and usually rely on standard specifications.

From a societal perspective, it has not yet been determined when a product can be '*accepted*' as 'soil biodegradable', 'freshwater biodegradable' or 'marine biodegradable'. This is a challenge for further assessment, be it a risk assessment, a life cycle assessment, or in certification and regulation, as these usually depend on pass levels. The determination depends on many factors and should be treated with care by an interdisciplinary team of experts. For example, the effects on the environment of the plastic item, the location of the application, distribution routes, sinks, quantities used, social relevance, material properties and much more play a role.

It is important to understand that the assessment should be made on a case-by-case basis and that an appropriate test scheme is needed. A test scheme for a case-by-case assessment is certainly not easy to develop and is in danger of becoming too complicated and costly. It needs a good middle way, because simple generalisations would not exploit the full potential benefits and could leave loopholes for abuse. A good compromise is to define categories and criteria for several aspects, which can then be applied to the respective products.

As a first step, two categories would make sense and should be considered in the evaluation by an interdisciplinary team of experts:

Category 1: 'The requirement to biodegrade comparatively quickly for plastic objects with a short lifespan'

Category 2: 'The requirement to biodegrade more slowly for plastic objects with a longer lifespan'

Specifying the required pass levels would facilitate risk assessment, life cycle assessment, certification, regulation and legislation. Defining pass levels, be it in the form of a range or a minimum value, will be a balancing act and should be achieved under the guidance of a thorough catalogue of criteria and a decision tree.

4.4.6. Available standards for impact on organism level

Until recently, the focus of assessing the effects of biodegradation was on classical ecotoxicity tests. For testing the ecotoxicity of biodegrading materials, there are already a variety of standards available (see Table 2). Most have the scope to test low molecular weight molecules. So far, only ISO 11268-1:2012 and ISO 11268-2:2012, 2018 (for invertebrates in soil) and ASTM D7081-05 (withdrawn 2014; for marine systems) consider testing plastic materials. A new working draft to assess marine ecotoxicity is accepted for registration at ISO (ISO/WD 5430). The content is not yet public, and it remains to be seen what exactly it contains. The next logical step would be to evaluate the current standards and to define which ones should or must be applied to assess ecotoxicological impact for the environmental compartments soil, freshwater and seawater.

Table 2: Compilation of the current standard test methods and standard specifications for ecotoxicity tests on organisms such as plants, microbes, invertebrates and vertebrates. ASTM = ASTM International (originally American Society for Testing and Materials); ISO = International Organization for Standardization, Standards were made for soluble chemicals; In **bold**: Standards considering plastic as test materials.

Standard	*Test methods for* Plants	*Test methods for* Microbes	*Test methods for* Invertebrates	*Test methods for* Vertebrates	Specifications
Soil	ASTM E1963-09, 2014; ISO 11269-2:2012, 2017	ISO 15685:2012, 2017	ASTM E1676-12; ASTM E2172-01, 2014; ASTM E2591-07, 2013; **ISO 11268-1:2012, 2018; ISO 11268-2:2012, 2018**		ASTM WK45054; ISO 14238:2012, 2017; ISO 15799:2019; ISO 22030:2005, 2005
Freshwater	(ASTM E1218-04, 2012; ASTM E1415-91, 2012; ISO 8692:2012, 2017)		ASTM E1193-97, 2012; ASTM E2455-06, 2013; ISO 6341:2012, 2018	(ASTM E729-96, 2014)	
Marine	ASTM E1218-04, 2012; ASTM E1440-91, 2012; ISO 10253: 2016	ISO 11348-1/2/3:2007, 2007	ASTM E1563-98, 2012; ASTM E1611-00, 2013; ISO 16712:2005, 2019; ISO 14669:1999	ASTM E729-96, 2014; ASTM E1241-05, 2013; ASTM E1711-12	ASTM D7081-05 (withdrawn 2014) ISO/WD 5430 (unpublished data)

4.4.7. Available standards for impact on ecosystem level

To date, we are not aware of any standard test method on the impacts of biodegradation processes on an ecosystem level. Such standard test methods should be developed for the water column, sediment (fresh- and seawater) and soil. It is also important to measure the recovery time of the impacted system, in order to be able to include it in an LCIA.

4.4.8. Criteria to evaluate laboratory tests for biodegradability

This section focuses on laboratory tests in closed vessels. The criteria listed below should be understood in the context of Section 4.1.1. Biodegradation rate largely depends on the environmental conditions at the place where the plastic item passes through and finally ends up. These open environment conditions should be represented in lab tests to a certain degree, taking into account the principal biogeochemical processes occurring in nature. At the same time, the laboratory test should also be a screening test aimed at proving the claim 'biodegradable in …' and should thus be carried out under optimised conditions. Therefore, the proposed criteria reflect a mixture of a screening and a simulation test. The list below was developed by the authors of this report, based on available literature and personal experience in this field, and should be revised by a group of interdisciplinary experts in a dedicated project.

Matrices (environmental media for testing: water, sediment, soil)

- Matrices origin should be from the environment of interest (e.g. the location of application and/or expected sink).
- A combination or mixture of matrices could be allowed, as long as it reflects the environment of interest.
- Matrices pre-treatment, e.g. adapted sediment, should be possible to reduce the lag phase.
- Presence of other organic substances should be assessed and reported.

Inoculum of microbial degraders

- The inoculum should come with the matrices.
- The concentration of biodegrading microbes can be monitored and, if needed to improve the test, be diluted or concentrated.

Test substance

- The concentration of the test substance should be adjustable in order to reduce the duration of the test.
- The shape of the test substance (milled or sheet) should be adjustable in order to reduce the duration of the test.
- The physical and chemical properties and bioavailability of the test material (e.g. water solubility, adsorption on surfaces) should be reported.
- Measured residuals in the case of reporting relative results (biodegradation in relation to the positive control) should be reported.
- The toxic effects of the test substance under test conditions should be assessed (see below).

Physical and chemical conditions of the test system

- The ratio of the volume of matrices and test vessel should be specified.
- Maximum temperature of 30°C should be defined. A range of temperatures (e.g. 14–30°C) should be allowed and testing at the temperature of the environment of interest suggested.
- The availability and type of terminal electron acceptor for respiration, e.g. oxygen content: stable or decreasing, should be specified.
- Nutrient addition: stable, addition should be specified.
- Water content should be specified.
- Salinity should be specified.
- Metadata assessment should be specified (e.g. continuous temperature logging, regular pH measurement, nutrient concentration assessment, etc.).

Test conditions

- Mode of mixing: static or stirring, shaking, rotating, oscillating should be specified.
- Mode of aeration: batch or dynamic should be specified.

- Measurements of endpoints should be CO_2 (or CO_2 and CH_4) or respiration
- Duration should be specified and explained.
- What and how to validate the tests should be specified.
- What and how to report should be specified.
- Reporting should be specified.

Toxicity tests
- Organism size classes should be specified and explained.
- Trophic levels should be specified and explained.
- Toxicity levels should be specified and explained.
- Ecosystem impact assessment should be specified and explained.
- What and how to validate the tests should be specified.
- What and how to report should be specified.

Reference materials
- Positive control should be specified; a material similar to plastic would be best.
- Negative control should be specified, according to the test needs.

4.4.9. Good and problematic aspects explained using selected examples

Using examples, this section describes aspects that are important to consider when evaluating and selecting standards and when compiling a test scheme.

Examples of an inadequate standard

ASTM D6954:2018 Standard Guide for Exposing and Testing Plastics that Degrade in the Environment by a Combination of Oxidation and Biodegradation

This standard combines thermal and photooxidative treatment with subsequent biodegradation of a plastic material. It is a good example, in that the standard has to be read very carefully (and with good knowledge) in order to evaluate it. In principle, the procedures are well described, and it is clearly stated that oxidation is not an indicator of biodegradation and should not be presented in this way (Section 4.4.2). However, from an ecologist's point of view, the standard has a problematic part; it combines a technical procedure (pre-treatment) with subsequent testing in soil and water (Section 4.1). Typically, activation is done at temperatures and under light conditions that are not representative of the conditions in the open environment. This approach has been justified to achieve 'accelerated ageing' and it has been claimed that rates under enhanced activation can be used to extrapolate rates under environmental conditions. But this has not been demonstrated scientifically and therefore remains highly questionable. This means that, even if a test material has successfully passed the procedure defined in this standard, it may not produce the desired outcome in the reality of an open environment. This standard is inadequate and cannot be used for testing biodegradation in the open environment.

Because the conditions of pre-treatment in the environment do not occur in this way and cannot be planned, no controlled pre-treatment of the plastic material should be allowed for tests that assess the biodegradation of this plastic material in the open environment. A good example of this is the *ISO 22403:2020 Plastics – Assessment of the intrinsic biodegradability of materials exposed to marine inocula under mesophilic aerobic laboratory conditions – Test methods and requirements.*

PAS 9017:2020 Plastics – Biodegradation of polyolefins in an open-air terrestrial environment – Specifications.

This very new standard specifications require weathering at 60°C and further ecotoxicity and biodegradation measurements on the polyolefin wax created after weathering. Biodegradation and ecotoxicity tests on the original plastic item are not required. This is an example of an inadequate standard and can be seen as an illustration of finding ways to mislead about the biodegradation of polyolefins in the open environment (in this case, terrestrial). There is no scientific evidence that plastic material from polyolefins biodegrade in the open environment, as it is defined in this report.

Example of a current standard where a revision would be helpful

ASTM D6691-17 Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in the Marine Environment by a Defined Microbial Consortium of Natural Sea Water Inoculum.

According to this standard, the test should be performed at 30°C ± 1°C. Firstly, this temperature is not physiologically favourable for all microorganisms because it does not correspond to their optimum temperature. This means that the outcome could be less biodegradation than potentially possible. Secondly, this restriction makes it impossible to use the standard if you want to measure at cooler temperatures. This could be useful if one wants to adjust the test, for example, to marine conditions of temperate latitudes. This is an example in which an existing standard is rather limited, and a revision would be helpful to extend it, for example, to a temperature range of 14–30°C.

Example of a withdrawn standard and its potential use for a standard test method development

ASTM D6340-98 (2007) Standard Test Methods for Determining Aerobic Biodegradation of Radiolabeled Plastic Materials in an Aqueous or Compost Environment.

This standard was withdrawn in 2016. There are various reasons why a standard may not be continued: for example, this can happen if there is no initiative for a revision, or the revision indicates that the standard must be revised and the revision is not yet complete. Standards must be revised at regular intervals as, in this example, every 10 years, after which a committee of voluntary experts checks whether the standard still corresponds to the current status.

Experience shows that a revision usually does not change fundamental aspects. Therefore, it makes sense not to consider a withdrawn standard as invalid, but to consider it for the future development of standards and a test scheme, where appropriate.

Example for the need of a lab test to be combined with field and tank tests for environmental relevance

ISO 17556:2019 Plastics – Determination of the ultimate aerobic biodegradability of plastic materials in soil by measuring the oxygen demand in a respirometer.

This standard describes the method for achieving the optimum of biodegradation conditions by adjusting the humidity of the matrix (soil). By maintaining favourable soil moisture conditions, this test serves as a reliable screening test. However, favourable conditions in the open environment cannot be expected. Combining this lab standard test with field and tank standard tests covering additional environmentally relevant conditions would fill the gap and would provide specific degradation rates that can then be incorporated into LCA and LCIA. For more details see also Sections 4.2.2, 3 and 4.

Example of an existing standard adaptable for a testing scheme

ISO 15314:2018 Plastics – Methods for marine exposure (ISO 15314:2018, 2018).

This standard describes three methods for the exposure of plastic in the marine environment and states that the methodology can also be used with outdoor brackish water and freshwater exposures. The scope of this standard is to perform weathering tests and not to assess biodegradation. However, if combined with a biodegradation laboratory test (e.g. ASTM D6691-17) and the revision of some details (e.g. size of mesh used to protect the samples to be to 2 mm), the established standard can be used for the completion of a testing scheme for the 'open environment'. Building on existing standards will work as a way of setting up testing schemes for each 'open environment'.

> In summary, for the development of an efficient and economically feasible testing scheme for each open environment, the suggestions and ideas within this evidence report should be seen as a first step, to be further developed in an appointed project with a committee of interdisciplinary experts.

4.5 CERTIFICATION

Normalisation is essential for further development both of new biodegradable materials and for market introductions (De Wilde, 2020). For the survival of a product on the market, certification is helpful as a further step: it is a tool to verify independently that testing is correct and in accordance with test results and their interpretations (for example, in the form of claims), with the methods applied regarding materials tested and the suitability of the test methods. Generally speaking, a certifier is needed to judge the usually quite complex information and results, to translate specifications from theory into practice and to set up a certification programme. Demonstrating and eventually communicating that a product meets the requirements of a standard

specification leads to increased confidence from stakeholders. It also helps to ensure regulatory compliance.

4.5.1. Certification scheme and programme

In a certification scheme, the customer contacts a certifier and a recognised laboratory or institution to have the tests performed (Figure 6). The client and the certifier usually rely on independent testing facilities, mostly accredited according to BS EN ISO/IEC 17025:2017. They provide the test results and reports, which are then critically reviewed by the certifier's experts. Tests are done following standard methods and procedures. The clients themselves or external laboratories provide the chemical characterisation of the test material, and the certifier usually reserves the option to conduct additional analyses. The process is successfully completed with a certification. Subsequently, the corresponding label can be used on the plastic product, depending on the policy of the certifying agency and on the current state of legislation. As a rule, the validity of the certificate and the use of the label is limited in time and requires renewal after its expiry, or if changes are made in the tested material.
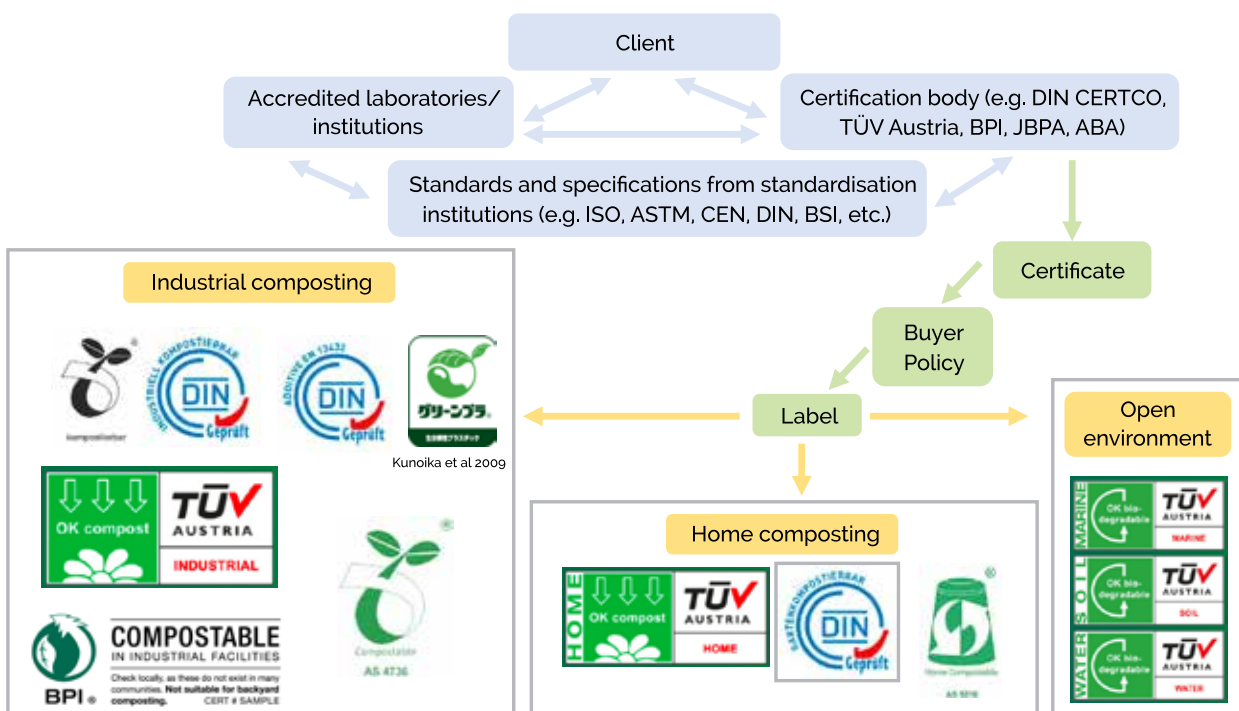
Figure 4.6:. Certification procedure and examples of currently available labels for industrial, home composting and biodegradable in soil, freshwater (water) and seawater (marine).

If there are standard test methods available, and usually also standard specifications that sufficiently cover a topic, a certifier might develop its certification programme. This includes, for example, what can be tested (pure polymers, products, natural materials, etc.), which test methods to apply, how many different tests to carry out, and any additional requirements from the certifier. Ideally, the criteria will be transparent and can be openly accessed, so it is clear on which basis the certificate is issued. The background data and test results, however, are usually confidential because they might affect proprietary information belonging to the client seeking a certification (e.g.

on material formulation). This certification service is usually offered on a commercial basis and the client pays a fee for certification and renewal.

4.5.2. Available certification programmes, including for the open environment

Currently available certification programmes for the biodegradation of plastic are offered by five institutions:

- TÜV Austria (branch office Belgium, ex-Vincotte) for industrial composting, home composting, soil, water and marine
- DIN CERTCO (Germany) for industrial composting, home composting, soil
- Biodegradable Products Institute (BPI; USA) for industrial composting
- Japan BioPlastics Association (JBPA) for industrial composting
- Australasian Bioplastics Association (ABA) for industrial composting and home composting

To our knowledge, there is no official reciprocal recognition of these various certificates.

TÜV Austria is the only institution offering a certification programme for three compartments of the open environment (TÜV Austria Times, 2019). This certifier takes into account that biodegradation in the open environment cannot be considered as such, and that soil, freshwater and marine compartments must be distinguished. They are described as follows (TÜV Austria):

- OK biodegradable SOIL: 'The OK biodegradable SOIL label is a guarantee a product will completely biodegrade in the soil without adversely affecting the environment.'
- OK biodegradable WATER: 'Products certified for OK biodegradable WATER guarantee biodegradation in a natural fresh water environment, and thus substantially contribute to the reduction of waste in rivers, lakes or any natural fresh water.'
- OK biodegradable MARINE: 'Considering the fact that most of the marine debris is land-based, marine biodegradability is an added value to any product, regardless of where it is consumed.'

It should be noted that there are as yet no explicit standard specifications that define these environmental compartments (see also Section 4.3). Setting up a catalogue of criteria and a testing scheme would be very helpful for the further development and improvement of certification schemes.

4.5.3. Scope, requirements and evaluation of current certification programmes for the open environment

The available certification programmes start with a description of their scope of application. For an evaluation of further requirements (e.g. marking/logo, references,

standard test methods, documents to be supplied, and chemical characterisation), it is crucial to understand precisely what the programme is meant for. The examples below are intended to show that the objectives of a certification programme can be quite specific, and that for an evaluation in the sense intended here, it is useful to examine the programmes more closely.

For example, the scope of DIN CERTCO for 'biodegradable in soil' is: "This certification program applies to materials, semi-finished products and mulch films that are manufactured entirely or partially from thermoplastics in accordance with DIN EN 17033 (2018). In addition, natural materials, such as jute, cellulose, paper, etc., can be used partially or completely for the same application. The certification program does not apply to packaging, bags or other applications. In conjunction with the test principles listed below, this certification program contains all the requirements for awarding the certification mark 'DIN Geprüft biodegradable in soil' and issuing certificates for materials, semi-finished products and mulch films."

As another example, the scope of TÜV Austria for all three 'OK biodegradable (soil, water and marine)' is that they are for raw materials, all components and constituents also known as intermediate products, as well as finished products. In the case of packaging, the primary packaging (the part which is in direct contact with the content) is accepted equal to the finished product. 'OK MARINE' specifies that it is for materials which are non-floating and tested in seawater only.

4.5.4. First suggestions and questions for certification programmes for plastic biodegradation in the open environment

A certification programme for a specific open environment could be based on the following aspects:

- Identification of where the plastic item is used (site of application e.g. terrestrial soil, marine seafloor, water column, etc.), distribution and transport routes, and sinks to guide the selection of the environments of interest.

- Identification of the relevant environmental conditions (e.g. with and without oxygen, etc.) of the environment of interest to guide in the selection of which biodegradation tests should be required.

- A four-tier test (including impact) approach to cover proof of biodegradability in the corresponding environment, determine the range of biodegradation rates and corresponding persistence times, and the impact assessment.

- The possibility to demand extra testing.

- The material datasheet (confidential, only for the certifier).

- Identification and characterisation of all material constituents (confidential, done by the certifier).

- The need for inspection test or re-evaluation on a regular basis.

- Possibilities to extend the certificate in a cost-effective way.

Questions to be addressed could be:

- Does a regulatory entity (e.g. the European Commission, national legislators) require certification (e.g. for exemptions from bans (see Plastic Directive)), or is the claim or self-declaration of the producer sufficient?

- In any case, what term is defined as appropriate to communicate biodegradability in the open environment? Does 'environmentally biodegradable' suffice, or does the receiving environment (e.g. soil, freshwater, marine) or even a receiving habitat (e.g. agricultural soil, marine water column, etc.) have to be specified?

- Should it be also communicated that 'non-receiving environments' are excluded, and that the validity of the certificate is limited?

- Would a product need to be certified in a potential receiving environment? For example, does disposable cutlery have to be certified, for example, as 'biodegradable soil' although it is meant to be disposed of in an industrial compost facility?

- Should the scope of regulation and certification be to test a product, or a single compound? How does one approach the possible effects on biodegradation rates of blending with other polymers or additives, glues, colorants, prints, etc?

- How does one take into account natural and non-modified materials when they are intentionally introduced or at a high risk of loss into the environment in large quantities? Should they then be subject to the same criteria to assess the biodegradation rate and impacts?

- How are non-biodegradable materials (e.g. conventional plastic, aluminium, glass, etc.) treated? Would they be treated in the same way and need to run through the testing scheme, or would they simply need to be labelled 'non-biodegradable'? If certification were mandatory for the biodegradable materials, resulting in higher costs, this could create an imbalance with competing products. The question is whether a certificate can turn this disadvantage into an advantage and thus justify the additional financial expenditure.

The topics addressed here are debated among stakeholders and we do not claim completeness. They must be understood as a basis for further discussion. Furthermore, we do not evaluate the certification programmes named here, or identify them as being suitable for the needs identified here. An evaluation based on clearly-defined criteria should be done by a committee of interdisciplinary experts in a dedicated project.

4.6 COMMUNICATION AND LABELLING

Labels are used to communicate a certain fact to consumers and commercial buyers. The communication about biodegradable plastics is complex; therefore, there are attempts to simplify and this can create misleading situations. For example, 'biodegradable EN 13432' means that the plastic item is compostable in an industrial facility. It does not mean that is it biodegradable in the open environment. However, a consumer may misperceive the claim and consider the plastic item is biodegradable in the open environment as well. This is not a desirable situation.

To solve this problem, there are different approaches. A survey has shown that 16 environmental protection agencies suggest that product labelling of biodegradable plastics must contain clear instructions on how to dispose of a product after use (EPA Network, 2019). Another approach is prohibition. The State of California acknowledges the complex nature of biodegradation and the fact that products might travel through multiple environments. Given these, and the constraints of potential harm to the environment, using the terms 'degradable', 'biodegradable', 'decomposable' or other similar terms is prohibited, without a thorough disclaimer with details, until the ASTM provides a standard specification approved by legislation (California Legislative Information, 2011). Also, standards are a way for improvement. ISO set up a series on 'environmental labels and declarations' as an international guideline. It covers self-declared claims (ISO 14021:2016), environmental labelling (ISO 14024:2018) and declarations (ISO 14024:2018). ISO 14063:2020 'Environmental Management – Environmental Communication', EN 16848 'Bio-based Products – Requirements for Business to Business Communication using a Data Sheet', and EN 16935 'Bio-based Products – Requirements for Business-to-Consumer Communication and Claims' could be used for the development of a specific standard specification for the communication and labelling of 'biodegradable in…' [to be specified].

As already stated in Chapter 2, using terms like 'primary', 'ultimate', 'readily', etc. in the context of biodegradation rates in the open environment can be problematic and lead to confusion. One needs to be very well informed to understand the differences between the terms, as well as knowing that they are restricted to optimised laboratory tests on biodegradability. With regard to communication, this is also not a desirable situation and such terms should be omitted or very well explained.

4.7 EXISTING GAPS

The topics addressed here are debated among stakeholders and we do not claim completeness. They must be understood as a basis for further discussion.

Single standard test methods
- Update lab tests for the criteria 'use of matrices', for 'measuring residuals in cases of reporting relative results (biodegradation in relation to the positive control)'
- Lab, tank and field tests to be extended to relevant environments that are not available (e.g. for anaerobic sand and mud for freshwater and seawater, forest soil, etc.)
- Deep sea test (for plastic items or abrasion of plastic items accumulating in the deep sea)
- Lab test to record the intermediate products, their persistence or degradation time

Environmental impact (needed for each environment)
- Ecotoxicity test scheme for organisms and ecosystems, including intermediate products and recovery time.

- Development of effect factors for the life cycle assessment of the ecotoxicological effects on organisms, potential effects on larger organisms, and effects on ecosystems.

Criteria

- Criteria for selecting the relevant habitats and conditions and therefore which test should be performed.
- Criteria for the biodegradation timeframes of different categories that are needed for a product (case-by-case approach) to be considered biodegradable.
- Criteria for the timeframes of different categories by when a product (case-by-case approach) should be disintegrated in each open environment.

Overarching standard specifications

- Evaluate currently available specifications and, if applicable, adapt according to the current needs:
  - **For soil**
  - **For freshwater**
  - **For the marine environment**
  - **For communication and labelling**

Catalogue of biodegradation rates and residence times of relevant environments

- A data catalogue of currently available blends and pure materials, as a reference for future regulation, certifications and innovation.

4.8 OPTIONS AND CHALLENGES FOR POLICY

In the literature on the topic of biodegradability in the open environment, one finds the call for improvement of the legal framework. At the same time, the challenges for such improvement are discussed. This section tries to summarise both, but we point out that we are not experts on evidence-based policy options and what follows does not claim to be complete.

In their report for the European Commission *Circular economy for plastics – Insights from research and innovation to inform policy and funding decisions*, Crippa et al. (2019) offer the latest compilation in terms of communication, certification, standards and risk analysis.

Communication and certification

The recommendations of Crippa et al. (2019) were that citizens and businesses should be informed whether a product is biodegradable through communication and education, and that information through standards, labels and life cycle impact assessment should be provided at the European level. Claims should be sufficiently specific, based on relevant information and validated by a third party. The need for harmonisation is mentioned several times. An OECD report in 2013 also points out

that the harmonisation of the different eco-labels used currently would be helpful in building consumer and business confidence (OECD, 2013).

Standards

In a broader sense, the harmonisation of standards among the different standards organisations is recommended (Crippa et al., 2019; Philp, Bartsev, Ritchie, Baucher, & Guy, 2013). The project HORIZONTAL could serve as an example to address this need (Gawlik et al., 2004). In this project, a team of experts advised on the development of horizontal CEN standards supporting the implementation of EU Directives on sludge, soil and biowaste, as well as linking them to international standards organisations.

On the level of standard test methods and specifications, the OECD (2013) states that it is not sufficient to do only one test to demonstrate biodegradability because this could lead to misinterpretations or even to incorrect labelling of products. Crippa et al. (2019) call for standards to be developed for different environments and, if feasible, to build on existing standards. Standards should be developed from the point of view of the respective open receiving environment, with the focus on the system property, in contrast to the previous focus on material and product categories. Additionally, standards and a holistic assessment method for the design of circular products should be developed.

Standards should be stringent because they make claims (e.g. on biodegradability) transparent for consumers, public waste authorities and legislators (OECD, 2013). ECOS (2019) explicitly calls for existing standards to be made stricter as well, and to ensure that the use of biodegradable polymers does not have any adverse effects on the environment. 'In order to do so, a minimum biodegradation pass level of 90% should be introduced in all standard specifications, as well as the requirement for the separate testing of added constituents present in a proportion of 1–15%' (ECOS, 2019).

Risk analysis

With regard to risk analyses, those with a systemic approach should be demanded and developed. The principles of the circular economy, including ecological, economic and societal costs and the benefits of political intervention, should be taken into account and compared with the costs of inaction (Crippa et al., 2019).

Links to legislation

In legislation, there are different approaches. For example, Ingram et al (2015) explain that the Endangered Species Act and Essential Fish Habitat (Magnuson-Stevens Fishery Conservation and Management Act) stipulate that environmental damage such as entanglement, ingestion or being covered by waste should be avoided or reduced, and that certain fishing lines made of biodegradable material should be used for Fish Attracting Devices. The EU's CleanSea project (2015) also concludes that bans (e.g. of polystyrene containers) and the use of natural materials or innovative alternatives based on harmless, biodegradable materials (especially for fishery products and cigarette filters) are policy options.

The State of California in its Waste Management Act goes as far as ruling that the term 'biodegradable' is not permitted until a standard specification approved by the legislature is in place. The law clearly states that the citation is misleading unless the claim contains a thorough disclaimer with the necessary qualifying details, including but not limited to the environments in which the claimed action will take place and the time periods covered. It further states that, there is no reasonable way to provide a proper disclaimer that qualifies the use of these and similar terms, given the complex nature of biodegradability and the fact that most plastic products pass through several environments from the time of manufacture to final disposal, without relying on an established standard scientific specification for the claimed action.

Shortly after the adoption of the law on microbead-free water in the USA, McDevitt et al. (2017) proposed the use of a standard called 'eco-cyclable'. They stated that future regulatory or legislative policy would be easier to write if there was a scientifically-informed standard that clearly distinguishes between environmentally-friendly plastic compositions and those that are persistent, bio-accumulative or toxic, arguing that it would help avoid the definitional and semantic issues that challenge microbead legislative efforts. They argue that to guide and facilitate future policymaking efforts, the scientific community should put in place a standard that defines the essential characteristics of environmentally benign materials. Given that there are no perfect and universal assays of degradation or toxicity, McDevitt et al argue that a balance must be struck between society's need for new and useful materials, and the requirements for efficient testing (measured in time and cost) to determine environmental safety.

This statement is in line with the conclusion of this evidence review report, adding that it is important to take into account the different environmental conditions of the open environment.

Challenges

- The implementation of standards, testing and certifying could take multiple forms. Assessments are a selection somewhere between high uncertainty and high costs (McDevitt et al., 2017).
- The high-cost approach requires comprehensive testing and certification; for example, an existing certifier, a government agency or a non-profit group could be entrusted with providing official certification. Regardless of who tests and certifies, the costs become comparatively high.

The high uncertainty, low cost approach would be a standard, without necessary certification but rather a self-declaration, and manufacturers are responsible for ensuring that their product meets the standard and the law. If companies mistakenly labelled a product as environmentally friendly, they would be subject to legal and market-based consequences.

Finally, it should be pointed out that the discussion on 'pass or fail' and legal implementation should also be conducted with regard to biodegradability in the open environment. It is important because the different environmental conditions lead to a lifetime range ('from-to') and not to a single value (see also Section 4.2.3), thereby

challenging a 'pass or fail' system. Dentzman & Goldberger (2020) provide an example from the USA where a national standard for controlling the labelling and quality of organic products became necessary. At the same time, it reduced certified organic agriculture by its restrictions because criteria were excluded that did not fit into a simplified 'pass or fail' system. It will be a challenge to consider this aspect in relation to the complexity of the open environment, and it could be tried in an application-specific approach if necessary.

Last, but not least, a common denominator for policymakers is that policy has to be kept flexible to facilitate development of innovative solutions (Philp, Bartsev, et al., 2013).

4.9 CONCEPTUAL FLOWCHART FOR THE ASSESSMENT OF BIODEGRADATION OF A PLASTIC ITEM IN THE OPEN ENVIRONMENT: THREE SCENARIOS

Here, we set out the possibilities for a testing scheme, showing three possible scenarios. The three scenarios are based on the delicate balance between high uncertainty or high costs, as described above by McDevitt et al. (2017) and other criteria, as described earlier in this Chapter. These conceptual flowchart schemes have not yet been evaluated by a committee of interdisciplinary experts and this should be done in a dedicated project.

Scenario 1 (Figure 7) includes proof of biodegradability in the form of a laboratory test, and the selection could be a simple screening test or a somewhat more demanding simulation test. If this test was completed successfully, proof of environmental safety must be provided by passing at least one ecotoxicity test or by passing three trophic levels (e.g. microbes, plants and invertebrates), which would increase environmental relevance.

The advantages of Scenario 1 are low costs. However, information for risk assessment remains minimal and the risk for waste accumulation is neither assessable, nor can it be estimated.

SCENARIO 1 – MOST SIMPLE = HIGH UNCERTAINTY FOR RISK ASSESSMENT & LOW COSTS

TEST MATERIAL = PLASTIC PRODUCT

Standard specifications of the relevant open environments*

Proof of Biodegradability

Screening test
Ideal matrices & conditions

?

Simulation test
100% natural matrices & semi-natural conditions

STM 1**

Complete conversion

yes

MUST

Proof of Environmental Safety

One exemplary test

?

Min. 3 trophic levels

STM 1

STM 1

STM 2

STM 3

pass

pass

yes

yes

ACCEPTED

ADVANTAGES
· **Costs** minimised
· Data for **LCIA from ecotoxicity tests**

DISADVANTAGES
· Information for **Risk Assessment** minimised
· **Risk of waste accumulation** cannot be evaluated and cannot be estimated

*To determine if ecosystem-specific only (soil, freshwater, marine), habitat-specific (benthic, pelagic, eulittoral) or also condition-specific (oxic, anoxic, warm, cold, nutrient-rich, nutrient-poor)

**STM#: Chose the standard test method according to the most relevant ecosystem, habitat and conditions

Figure 4.7: Scenario 1 to assess biodegradation of a plastic item in the open environment at low costs with resulting high uncertainty for risk assessment.

Scenario 2 (Figure 8) includes proof of biodegradability, as described for Scenario 1. If this test was completed successfully, the proof for environmental safety must be provided by covering at least three trophic levels and/or a test on the impact on ecosystem level, and so deliver even more environmentally relevant data. The main difference from Scenario 1 is the assessment of the range of lifetimes in the environments of interest, to be conducted in a combination of field and tank tests. The data on specific biodegradation rates of the tested plastic item then feed into the LCA and LCIA.

The advantages of Scenario 2 over Scenario 1 is an increase in information for risk assessment. The risk of accumulation of the plastic items can be estimated, and data for LCIA from ecotoxicity tests and an ecosystem level test, as well as data about the range of lifetimes, also become available. The disadvantages are increased costs,

and that the risk of accumulation of the plastic items cannot be evaluated. This could be done with a rating system (e.g. 0 kg / y, <10 kg / y, >10 kg / y accumulation).
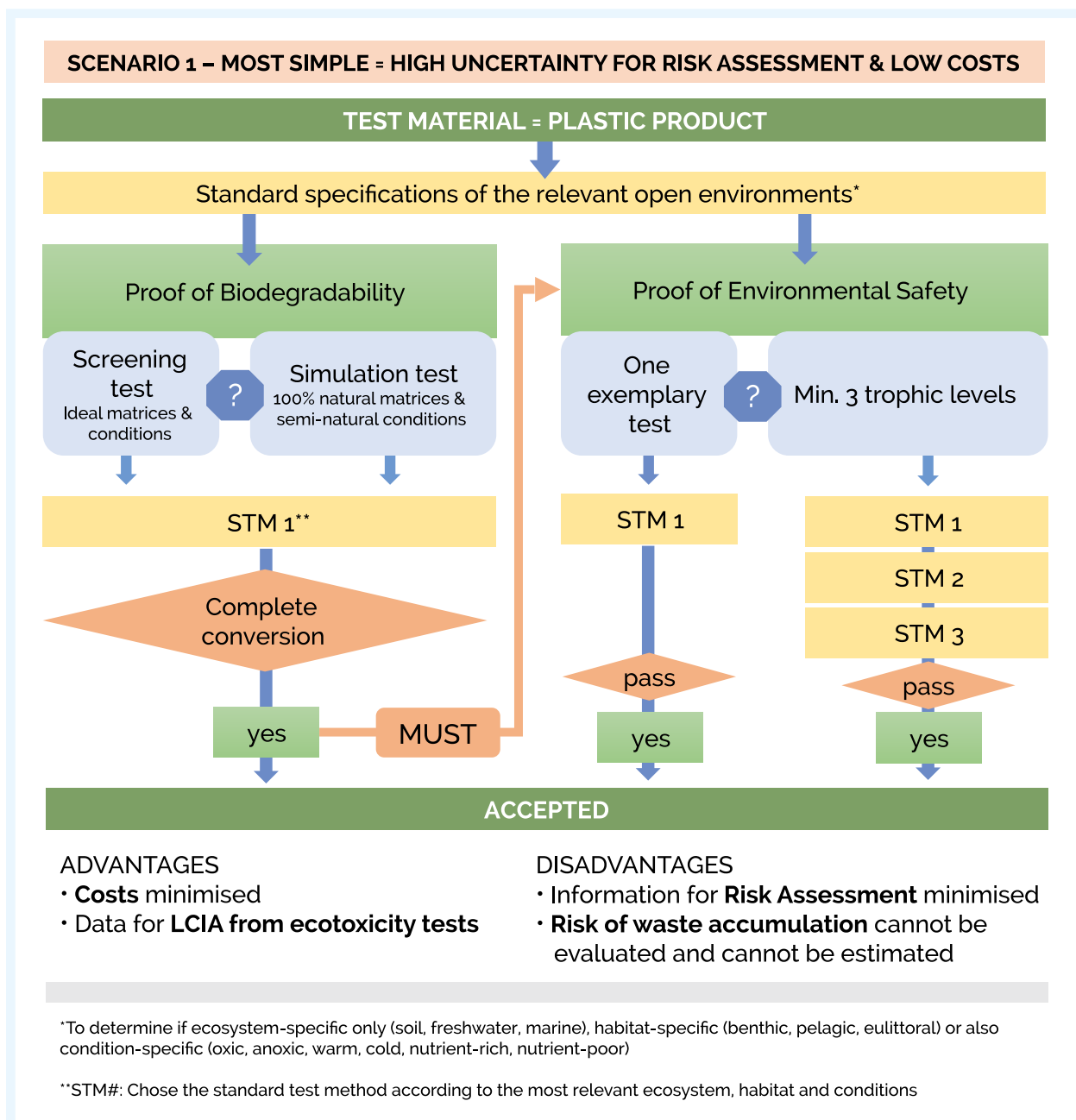

Figure 4.8: Scenario 2 to assess biodegradation of a plastic item in the open environment at increased costs and reduced uncertainty for risk assessment.

Scenario 3 (Figure 9) requires collection of additional data compared to Scenario 2, used for modelling scenarios with no accumulation. In models using the range of lifetimes and amounts of input or leakage into the environment, it thus becomes possible to rate the risk of accumulation in the environments of interest.

The advantages are similar to those in Scenario 2, with the addition of data on the risk of waste accumulation. This can now can be evaluated, for example, using a rating system

(e.g. 0 kg / y, <10 kg / y, >10 kg / y accumulation), and therefore minimised. Overall, information for risk assessment is increased and uncertainty further decreased. The disadvantages are higher costs compared to Scenarios 1 and 2; however, costs could be reduced through developing an economically feasible evaluation scheme, with a set of harmonised standard test methods and specifications and data catalogues.
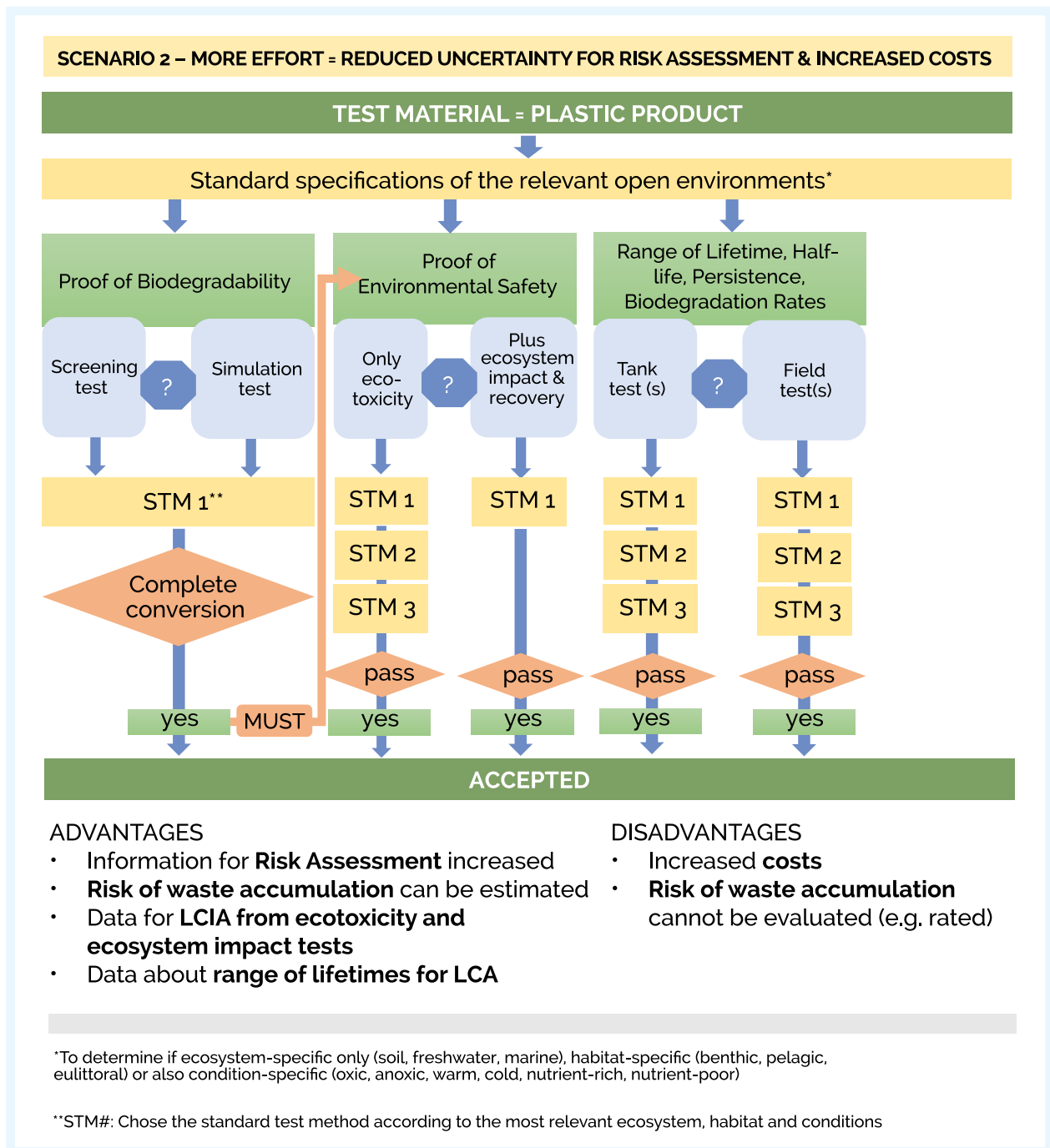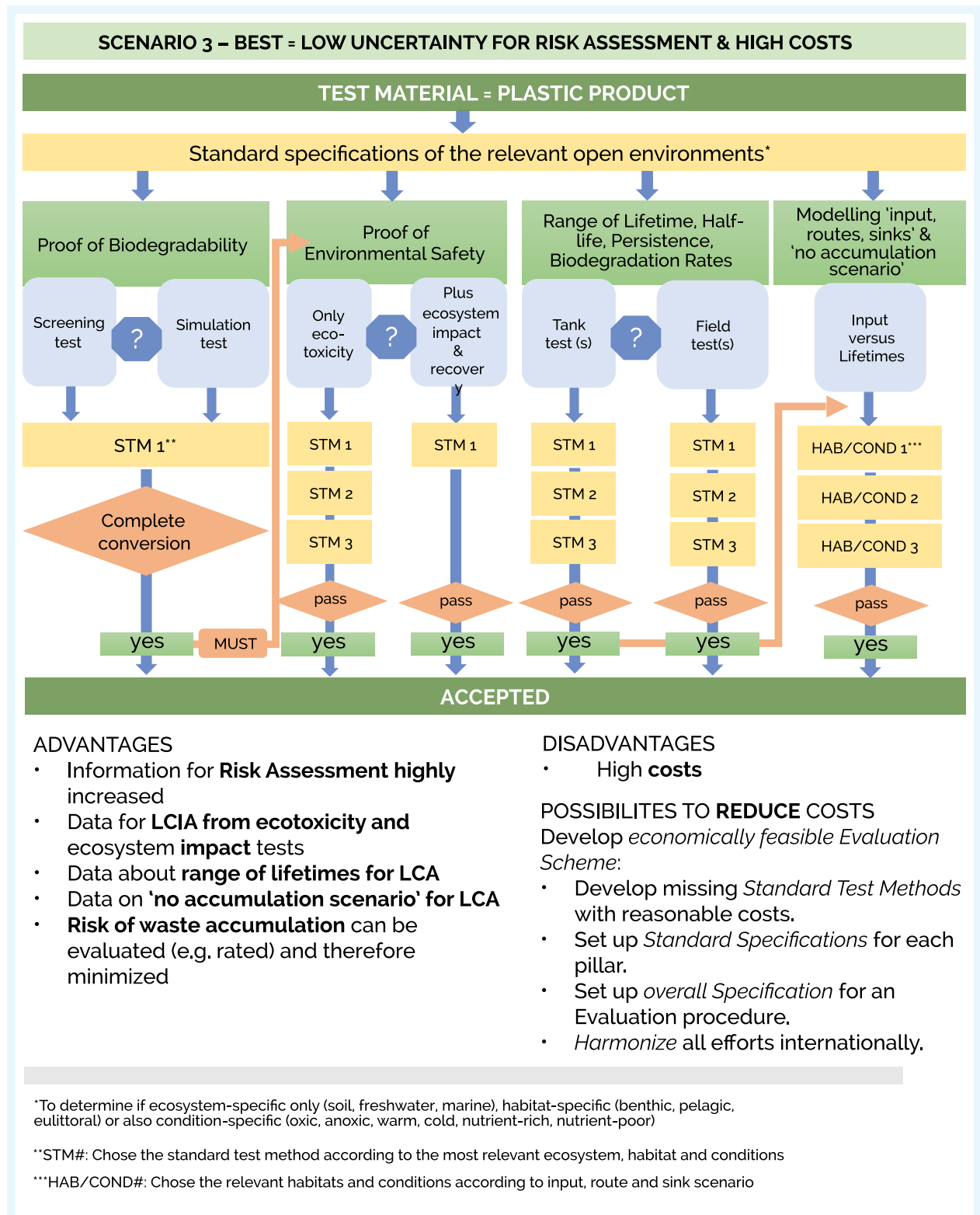

Figure 4.9: Scenario 3 to assess biodegradation of a plastic item in the open environment at high costs and low uncertainty for a risk assessment.

Summary

Substituting conventional with biodegradable plastics raises the political and societal question of how to assess the biodegradation of plastic items known to end up in the open environment. Standardisation is the means by which to achieve comparability, by defining the details of procedures and test conditions and thereby help stakeholders such as consumers and regulators. This Chapter summarises the development of tests, standards, and certification schemes for the biodegradation of plastic items and discusses the need to consider the interplay between the material and the environment of marketed plastics objects, rather than only the materials themselves.

Four requirements are introduced for testing and certifying a plastic item:

- the determination of **biodegradability**
- the assessment of the **biodegradation rates under environmentally relevant conditions**
- the modelling of the **lifetime/persistence** in the environments of interest
- the assessment of the **effects on the environment** at organism and ecosystem level

Standard test methods for lab tests measure the amount of end product over time using sediment and/or water from the environment of interest and hence the ability to prove (or not) the biodegradability of the product under these conditions. The biodegradation rate measurements under environmentally relevant conditions are assessed by adding field and tank tests (a three-tier approach), generating data for modelling the lifetime for LCA. Impacts assessed on an organism and ecosystem level (a four-tier approach) generate data for LCIA.

As not all plastic items can be tested everywhere and under all environmental conditions, a decision tree with criteria for each level of decision is suggested, for development by a team of interdisciplinary experts. We have made initial suggestions within this Chapter. Current standard test methods and standard specifications are summarised for the open environment soil, freshwater and marine, and examples of problematic and good standards are given. Specifying the pass levels is proposed, as it would facilitate risk assessment, life cycle assessment, certification, regulation and legislation. There is no time to lose in setting up a testing scheme with a holistic approach, which can be used efficiently (i.e. is economically feasible) and be environmentally relevant. The testing scheme should provide the basis for regulation and thus support innovation, market introductions and clear communication. It is designed to allow for a case-by-case approach, by applying a set of criteria and categories along a decision tree. As a first step, two categories are suggested; the requirement to biodegrade comparatively quickly for plastic objects with a short lifespan, and the requirement to biodegrade more slowly for plastic objects with a longer lifespan.

Existing gaps and needs are identified, including:

- Update the current and add further lab standard test methods for relevant environments not yet available (e.g. for anaerobic sand and mud for freshwater and seawater, forest soil, etc.).

- Develop a testing scheme for ecotoxicity on organisms and the impact on ecosystems, including impact factors for LCIA for each 'open environment'.

- Define criteria for a decision tree to guide the selection of relevant habitats and conditions in the environment of interest under which a plastic item should then be tested.

- Develop overarching standard specifications for each 'open environment'.

- Generate a catalogue of biodegradation rates and residence times for conventional and biodegradable plastic materials in open environments, as a baseline for comparative risk assessment in LCA and LCIA.

Three possible scenarios for the assessment of biodegradation of a plastic item in the open environment are explained at the end of the Chapter, ranging from a low cost/ high uncertainty to high cost/low uncertainty for a risk assessment scenario.

An important prerequisite for the testing scheme is that it has to be kept flexible enough to facilitate the development and implementation of innovative plastic materials. Although developing a reasonable testing scheme with a holistic approach will not be an easy task, it should be done soon to support decisions on the input of plastic into the open environment, and substituting biodegradable plastics for conventional plastics.

Key messages

- The substitution by plastic which is biodegradable in the open environment brings the possibility of reducing the accumulation of plastic in the environment. This is especially interesting for cases of intentional input, plastic items with high risk of loss and where loss is intrinsic to its use.

- Determining whether a plastic item is biodegradable in the open environment requires proof of its *biodegradability* under the conditions of interest (e.g. soil, freshwater, marine). With regard to its actual *biodegradation* in the open environment, it is necessary to measure the time taken to realise complete remineralisation under relevant environmental conditions and record its impact on the environment. Applying the precautionary principle there are four main requirements identified for testing and certifying of a plastic item:

  - **the determination of biodegradability**

  - **the assessment of the biodegradation rates under environmentally relevant conditions**

  - **the modelling of the lifetime/persistence in the environments of interest**

  - **the assessment of the effects on the environment on an organism and ecosystem level**

- Biodegradability should be assessed by applying standard laboratory tests under controlled conditions favourable for biodegradation of the plastic item of interest,

as well as the environmental conditions of interest. As proof of biodegradability, direct measurements of the end product(s) of the biodegradation process should be applied.

- Generally, there are two types of lab test – screening and simulation. In order to reach higher environmental relevance, the test should simulate the conditions of the environment of interest and use its matrices (soil, water, aquatic sediment), and still apply optimised conditions. Finding a balance between an optimal screening test and environmental representation is a difficult task and is under debate.

- Biodegradability is a system property and needs to be seen within the context of the prevailing environmental conditions. Therefore, from the environmental point of view, laboratory tests under controlled conditions are mandatory but, by themselves, give only a first indication of biodegradation rates for a plastic material in the open environment. Transferability into the environment is best validated by field and tank tests, and so achieve environmental relevance and assess biodegradation rates under *in-situ* conditions. These data are then used for modelling persistent times, which are crucial for LCA and LCIA. So far, there is no clear and mutually recognised testing scheme for the assessment of specific biodegradation rates.

- To assess the environmental effect and potential risk of biodegradable plastics, the question of how long a certain item remains in the environment is of central importance and should be answered again by tests and subsequent modelling. Also here, there is no clear and mutually recognised testing scheme for the assessment of impacts and effects.

- Standards are indispensable for such a test scheme. A range of standard test methods exist; however, many of them were developed quite specifically and for individual applications. For the open environment, the diversity of conditions that are crucial for degradation must be considered. The array of methods should be extended to the relevant conditions. The effect of more specific conditions such as soil type, water content, sediment grain sizes, nutrients, oxygen concentration, etc. should be addressed in specific research projects. Data from such projects should then be used for further modelling the range of biodegradation rates in the open environment.

- Standard specifications need to be improved for each open environment and should allow a case-to-case assessment to avoid needing to test all needs everywhere. Therefore, the test scheme must have a tool to identify the relevant tests case-by-case. Criteria by which to select the tests for biodegradability, the assessment of biodegradation rates, modelling persistent time and assessment of impacts are not yet available and should be defined by an interdisciplinary team of experts. Categories of degradation rates should be developed (as a minimum, a fast and slower category) to account for different lifetimes of a product.

- Currently, certification programmes are offered by five institutions worldwide. To our knowledge, there is no official reciprocal recognition of the various existing certificates. Our report puts forward initial suggestions and questions relating to standard test methods, standard specifications and certification programmes for the open environment; these and a testing scheme should be

further developed by an appointed committee of interdisciplinary experts and internationally harmonised.

- There is no time to lose in setting up a test scheme by a holistic approach, which can be used efficiently (it should be economically feasible) and which is environmentally relevant. The test scheme should provide the basis for regulation and thus support innovation, market introduction and clear communication. It should be designed to allow for a case-by-case approach by applying a set of criteria and categories along a decision tree. Its development will be a balancing act between costs and uncertainty.

Generally, we face a lack of observational and experimental data, both for conventional plastics and biodegradable plastics. A catalogue or comprehensive dataset of materials, with their performance described in a variety of ecological settings, expressed as a range of specific degradation rates, impacts and effects, is urgently needed but not currently available. A uniformly recognised test scheme with clear framework conditions can improve this situation.

Chapter 5: Ecological risk assessment

What is this Chapter about?

- This Chapter gives a general overview of the process of risk assessment, ecotoxicology and microbial ecotoxicology, as the foundation for describing the state of current knowledge and knowledge gaps concerning potential hazards and ecological risks associated with biodegradable plastics in the open environment.

- It describes identified and potential differences between biodegradable plastics and conventional plastics, as they relate to risk assessment. Based on this, specific criteria for an exposure assessment of biodegradable plastics are suggested.

- A preliminary conceptual model for an ecological risk assessment of biodegradable and compostable plastics is put forward to address the complex dependence and uncertainties of environmental biodegradation rates related to risks.

5.1 INTRODUCTION AND CHAPTER OUTLINE

A comparison of the ecological effects of biodegradable plastics with those of conventional plastics is made challenging by the many remaining knowledge gaps concerning the ecological risks of conventional plastics. There are, however, some identified and probable differences between biodegradable plastics and conventional plastics related to ecological risks:

- Quantities produced and intended applications
- Waste handling and potential for littering
- Knowledge of, and communication to, the public
- Their expected environmental persistence, as mediated by biodegradation rates
- Intermediate biodegradation products
- Release rate and fate of additives
- Influence of bioavailable carbon on biogeochemical cycles
- Recovery after exposure
- Remaining uncertainties (unknowns)

The final point includes uncertainties related to variations in environmental biodegradation rates, and how biodegradation may influence the transport and sinks of biodegradable plastics.

Based on the identified and probable differences, we suggest in this Chapter specific criteria for an exposure assessment of biodegradable plastics. Among the criteria are quantities released, how abiotic and biotic transformation may influence their transport, translocation between environments and compartments of environments, and final receiving environments.

As all risk assessment is dependent on dosage and exposure time, there is a need to address current and future quantities of biodegradable plastic production, their applications, release rates, and the potential receiving environments.

5.2 RISK ASSESSMENT

Risk assessment is the process of estimating the likelihood that an event will occur under a given set of circumstances (Maltby, 2006). Environmental risk assessment involves an analysis of information on the environmental fate and behaviour of chemicals or stressors (agents that exert stress), integrated with an analysis of information on their effect on human beings and ecological systems (Ishaque & Aighewi, 2014; van Leeuwen, 2007). Ecological risk assessment is a part of environmental risk assessment and concerns the effects on non-human populations, communities and ecosystems (Suter II, 2006).

Risk assessment is an important decision-making tool that can be used to identify existing problems and to predict potential risks of planned actions. The following description of principles and definitions involved in risk assessment is largely based on text by Maltby (2006), and here represents the generic process of risk assessment.

Central to any risk assessment process is the distinction between hazard and risk. Whereas hazard is the ability of a chemical or component (hereafter referred to as 'stressor') to harm organisms or cause harm to an ecosystem, risk is the probability that harm will occur under a set of circumstances.

- **Prospective risk assessment** predicts the likely consequences of releasing a stressor into the environment and is usually generic rather than site-specific. Consequently, it requires the identification of the potential effects of a stressor on organisms in a variety of ecosystems.

- **Retrospective risk assessment** considers the risk of stressors after release into the environment, and the focus usually is on a single stressor and its effects on selected ecosystem components. However, ecosystems are comprised of a vast number of interacting species and the structure and functioning of ecosystems are the consequence of a variety of physical, chemical and biological factors acting sequentially and concurrently. Isolating the effect of one single stressor from the multiple natural and other anthropogenic stressors operating on ecosystems is one of the major challenges of retrospective risk assessment.

Assessing the risk that stressors pose to the environment is a three-phase process (Figure 5.1), which starts with a problem formulation, where the hazard is identified and a study is planned (Phase 1). This is followed by an analysis phase (Phase 2), in which the exposure to, and effects of, the stressors are assessed. In the final phase (Phase

3), information on exposure and effects are evaluated together to characterise risk. Risk assessments are made for different environmental compartments (e.g. terrestrial, aquatic, atmospheric), usually by a tiered approach. Lower-tier risk assessment is based on limited data and reasonable worst-case assumptions, whereas higher-tier assessments are based on more realistic but complex datasets. Moving through the tiers refines the assessment of exposure and effects and hence reduces uncertainties of the risk characterisation.
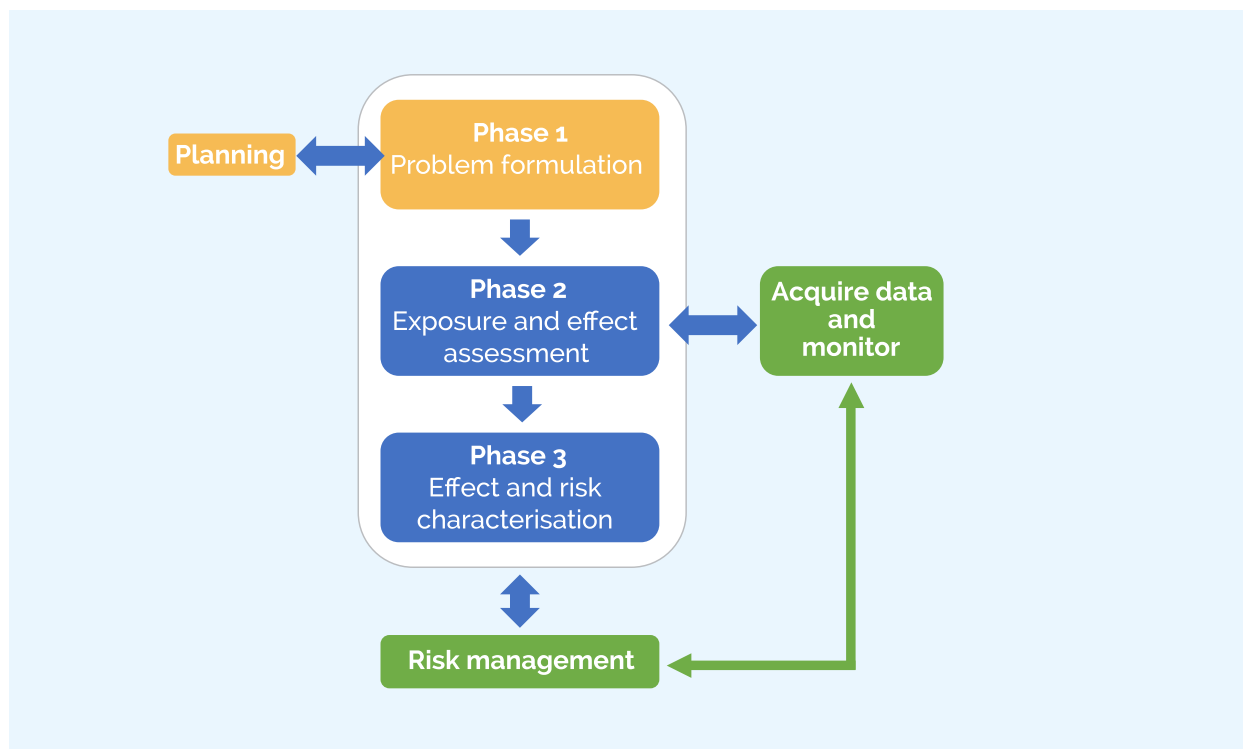
Figure 5.1: The three-phase process of risk assessment.

5.2.1 Problem formulation (Phase 1)

The purpose of the first phase is to determine whether a hazard exists, and if so, whether the effects warrant further study or action. If further studies are necessary, the type of data required to characterise the risk are identified, and appropriate assessment and measurement endpoints selected. Hazard identification may include short-term tests and screening, as well as reviews of existing information that characterise the potentially affected ecosystems and stressors in question. This phase should include the development of a conceptual model that identifies contaminant sources, biological receptors and the processes that link them.

In Section 5.5, we present current knowledge on the potential ecological effects of biodegradable plastics. We focus on marine systems and agricultural soils but acknowledge that studies in other environments may show similar effects.

5.2.2 Exposure and effect assessments (Phase 2)

This phase includes the measurement or prediction of emission, transport, fate, and behaviour of the stressor in the environment. The purpose of exposure assessment

is to determine exposure concentrations (dose) and identify key environmental components for assessing risk (endpoints).

Prospective risk assessment predicts environmental concentrations (PECs; e.g. predictions of biodegradable plastics release by mathematical modelling), while retrospective risk assessment consists of analyses of environmental media or ecological receptors (e.g. ecotoxicological studies on biodegradable plastic from the literature), and may also include mathematical modelling.

In addition to exposure assessment, this phase characterises the relationship between exposure and effects to derive dosages at which no adverse ecological effects occur (predicted no effect dosage, or PNEC).

Effect assessments can be based on single-species toxicity tests, microcosm or mesocosm studies, field studies or surveys, or population and ecosystem modelling. Assessments of lower-tier effects involve acute and chronic toxicity tests with standard species, while assessments of higher-tier effects include acute and chronic toxicity and go beyond studies of individual species to consider population-level and community-level effects, including indirect toxic or harmful effects due to change in trophic interactions and secondary poisoning.

Related to plastics in the open environment, higher-tier approaches should be applied to study multiscale effects associated with, for example, macro-plastic accumulation and landscape change, transfer of microplastics through trophic levels, and impact of plastics on soil and sediment microbiology and biogeochemical cycles. The multidimensionality of potential ecological effects is relevant for all plastics and will be addressed specifically for biodegradable plastics later in this Chapter.

5.2.3 Evaluation and risk characterisation (Phase 3)

The information from the exposure and effects assessment are combined to describe the nature and magnitude of risks posed by a stressor. Risk may be expressed as a quotient or as a probability and should include a consideration of the uncertainties inherent in the risk assessment process.

5.2.4 Exposure: Dose-response principle and volumes of input

Dose is defined as the quantity of stressors. In the context of this report, these are biodegradable plastics and their additives. In an ecological context, a dose refers to the quantity of a stressor received by an environmental entity (species, population, community or an ecosystem; Ishaque & Aighewi, 2014). The dose can relate to the amount of a stressor in the environment (exposed dose) or the amount of the exposed dose that enters an organism (absorbed dose). The frequency of exposure to a stressor may depend on whether the exposure is regular or irregular but may also depend on seasonal variations. In the case of biodegradable plastics, seasonal factors such as temperature may influence their biodegradation rate. A low biodegradation rate may

increase the biodegradable plastics physical residence time (physical exposure time), while a high biodegradation rate reduces its physical residence time.

Harmful or unfavourable ecological effects of exposure to stressors are called 'response'. Response may relate to toxic reactions or change in function or health at any entity level (Ishaque & Aighewi, 2014). Endpoints could be, for example, large mammals, microbial communities or soil health, including biogeochemical cycling (for further examples of possible endpoints, see Table 5.1). The potential for multiple endpoints in ecological risk assessment puts the emphasis on the problem formulation, which defines the relevant endpoints for the ecosystems or environments under consideration for specific stressors. The relationship between the exposure dose to a stressor and the response from an entity receiving the stressor is described by stressor dose-response models (Ishaque & Aighewi, 2014). Some of the challenges related to stressors' dose-response assessment is to distinguish ecosystem response to natural processes from those caused by stressors, as well as the quantification of indirect effects. This is especially relevant for the biodegradation aspect of biodegradable plastics, as microbial communities will metabolise and thus include carbon derived from the polymers into the biogeochemical cycles of the receiving environments.

We conclude that, based on the different stages outlined above, the risk assessment of biodegradable plastics in the open environment is currently at Phase 1, the problem formulation phase. Here, the objectives of the risk assessment should be clearly expressed with defined goals. The topic to be risk-assessed, biodegradable plastics, is evaluated and a plan for analysing data and characterising risks is developed in the following sections.

The objectives of the current ecological risk assessment are:

1. Evaluate the current literature on the ecological effects and hazards of biodegradable plastics and identify knowledge gaps and needs (Chapter 5).
2. Describe endpoints that cover known risks as well as potential risks identified so far (Chapter 4 and Chapter 5).
3. Define and describe available testing and certification schemes and the current knowledge gaps (Chapter 4).
4. Consider and identify current and potential future sources of exposure (Chapter 3).
5. Develop a conceptual model for ecological risk assessment of biodegradable plastics (Chapter 5).

5.3 ECOTOXICOLOGY

Ecotoxicology is defined as a branch of toxicology that concerns the study of the harmful effects caused by natural and synthetic pollutants (stressors) to biota in aquatic and terrestrial ecosystems (Devillers, 2009). It involves the investigation of how and to what level wildlife and humans are exposed to pollutants, and the manner in which pollutants are released into the environment, transported between different compartments of the biosphere, and are transformed by abiotic and biotic processes.

Microbial ecotoxicology is an interdisciplinary area of research that investigates the impact of human activities on the diversity, abundance and activity of microorganisms (Ghiglione et al., 2014). While microbial toxicology looks at the toxic effects of compounds on a certain microorganism and draws conclusions on the toxicity to the whole community, microbial ecotoxicology aims to compile different analytical approaches that are applied within microbial ecology, microbial toxicology, chemistry and physics, in order to have a more accurate assessment of the effects of a pollutant on the whole community (Shahsavari, Aburto-Medina, Khudur, Taha, & Ball, 2017). The focus is not only the effects of pollutants on microorganisms, but also on the role of microorganisms in the fate of pollutants (Cravo-Laureau, Cagnon, Lauga, & Duran, 2017). In a wider ecological frame, microbial ecotoxicological investigations provide a sensitive way of assessing the impact of various environmental disturbances or pollutants and subsequent ecosystem responses (Ghiglione, Martin-Laurent, Stachowski-Haberkorn, Pesce, & Vuilleumier, 2014).

5.4 PLASTICS IN THE ENVIRONMENT AND RELATED RISKS

Listed below are four categories of plastic that are defined for the current report and nowadays found in the open environment. In addition to the certified compostable and environmentally biodegradable plastics, there are plastics that are marketed as biodegradable but do not fulfil the test requirements for compostability or biodegradability in the environment, and plastics that are considered non-biodegradable due to lack of biodegradability or slow biodegradation rate.

- Certified biodegradable plastic in an environment other than that for which it was intended (e.g. compostable bags in the ocean, mulch films in aquatic environments).

- Biodegradable plastic in the environment for which it was certified (e.g. soil, water, marine environments).

- Supposedly biodegradable plastics that are marketed as biodegradable but do not fulfil the stated test requirements (e.g. oxo-degradable, blends or unknown compositions).

- Conventional plastics that do not biodegrade, or that biodegrade so slowly that they are effectively non-biodegradable (PE, PP, PET, PS).

5.4.1 Plastic pollution in EU

According to the EU Directive of 5 June 2019 on the reduction of the impact of certain plastic products on the environment, 80–85% of marine litter from recent beach counts is plastic, of which 50% falls into the category of single-use plastic, and 27% is fishing-related items (Official Journal of the European Union, 2019). Based on their dominance as plastic litter in the environment, these products are a high-priority focus in the EU's strategy on prevention of plastic littering, which includes requirements for future items to be reusable or easily recyclable by 2030. According to the EU Directive, single-use plastic products are products intended for use just once or for a short period of time before disposal, and include fast-food and meal containers,

sandwich wrappers and salad boxes as well as food containers for fruits, vegetables and desserts. Tobacco-product filters are the second most frequently found single-use plastic item on beaches in the EU and are a product that is discarded directly into the environment. Here, measures to accelerate innovation and product development are expected by extending producer responsibilities.

According to this Directive, all products that are likely to be discarded directly into the environment are within the scope of the current report, including single-use biodegradable plastic products that are aimed for recovery in industrial composting, as well as biodegradable plastics targeted at replacing conventional plastics in products like tobacco filters, fireworks, and lawn trimmer ribbons.

5.4.2 Release, transport, transformation, and translocation of plastics in the environment

The environmental risks of conventional plastics are largely associated with the yearly volumes released into the environment, and their persistence in it, which leads to their accumulation and integration into exposed environments (Figure 5.2; Barnes, Galgani et al., 2009). As previously stated, in 2018, global plastic production almost reached 360 million tonnes, to which European plastic production contributed almost 62 million tonnes (PlasticsEurope, 2019). Recent estimates suggest that around 9% is recycled, 12% incinerated, and 79% accumulates in landfills or in the open environment (Geyer et al., 2017). Another study estimated that of the 275 million tonnes of land-based plastics waste generated in 192 costal countries in 2010, 4.8 to 12.7 million tonnes entered the ocean (Jambeck et al., 2015).

The release of plastics into the environment may be caused by mismanaged waste handling, littering, accidental disposal, and wastewater or sewage containing microplastics from cosmetics (primary microplastics), washing of clothes (secondary microplastics), or other consumer plastic products released into wastewater and sewage systems (Barnes et al., 2009; Carr, Liu, & Tesoro, 2016; Guo et al., 2019; SAPEA, 2019; Zitko & Hanlon, 1991). The discharge routes may be irregular (accidental) or regular (e.g. wastewater/sewage). Despite available systems for waste management, littering is still one of the basic causes of environmental pollution (Haider et al., 2019). It is a relevant concern that consumers perceive the biodegradability of biodegradable plastic products as an excuse for incorrect waste handling, and that this mindset may increase the risk of littering of biodegradable plastics (see Chapter 6). Carrier bags were the main application of biodegradable plastics in 2019, and release into the environment through mismanaged waste and consumer behaviour are documented on coastlines, deep seafloor, rivers, lakes, and terrestrial environments (see Chapter 3). Plastics may be transported by wind and ocean currents and accumulate in distant locations (Barnes et al., 2009). Herein lies the challenge of plastic pollution: locally mismanaged waste has worldwide ramifications, making plastic pollution a global challenge.

When entering the open environment, plastics are exposed to environmental conditions and weathered by physical, chemical, and biological factors. This transforms the characteristics of the plastics (e.g. size by fragmentation, weight by biofouling, structure and surface properties) which again influence their interactions with, and fate in, the receiving environments (Chamas et al., 2020; Napper & Thompson, 2019; Summers et al., 2018). A recent study aiming to give a global framework of plastic transport and accumulation in aquatic environments shows that packaging and consumer products were most frequently encountered in rivers, and fishery/aquaculture items in ocean environments (Schwarz et al., 2019). Not surprisingly, polyethylene and polypropylene were the most frequent plastic pollutant in all environments. The highest diversity of polymers was found in ocean and freshwater sediments, suggesting that a large proportion of plastic waste accumulates in these environmental compartments. The study demonstrates that transport and accumulation patterns of plastics are most affected by density, surface area, and the size of plastic items. It is therefore important to implement knowledge about transport patterns and final environmental sinks of plastic litter into an ecological and environmental risk assessment of plastics in general. In the case of biodegradable plastics, efforts should be made to predict how products are transported in the open environment, considering not only initial density, surface area, and size, but also how environmental transformation, including biodegradation, may influence their transport, translocation, accumulation and final sinks. In this context, residual microplastics from industrial compost and fragments from agricultural biodegradable mulch films are examples of new sources of environmental microplastics, with the potential for translocation from soil to aquatic environments and sediments.

Industrial composting (at 58°C) allows up to 10% residual fragments of biodegradable plastics with a size of >2mm within 3 months, in combination with at least 90% mineralisation, as measured against a positive control (generally cellulose; DIN EN 13432; Pagga, 1998; Ruggero et al., 2019; see also Chapter 4 of this report). When transferred to the environment via compost for the purpose of soil improvement, the further biodegradation rate of residual fragments of compostable plastics is expected to be much slower. Compostable PLA showed first signs of fragmentation and disintegration after 7 months in Mediterranean soil, while the positive cellulose control was completely degraded after 1 month (Rudnik & Briassoulis, 2011). Results obtained in a parallel laboratory study at room temperature showed similar results after 11 months' incubation. In another study, PLA showed no sign of weight loss after 6 months incubated in leaf mould/garden soil at 25-30°C (Teramoto et al., 2004). If compostable plastics are introduced into the open environment or if biodegradable mulch films certified for biodegradation in agricultural soils relocate to an aquatic environment, their certifications do no longer apply. The 'new' biodegradation rate will be unknown, as will the associated ecological risks.

The transport of plastic pollution is not limited to relocation between environments, but also translocation within compartments and between trophic levels of biospheres. An example of the latter is the transfer of microplastics via filter-feeding organisms to fish and further to mammals (secondary ingestion; Kühn et al., 2015; Lusher, 2015).

Furthermore, wildlife, for instance birds, may accidentally contribute to the transport and transformation of plastic pollution by ingesting and grinding plastics in their gizzard, followed by excreting smaller plastic fragments associated with relocation (Kühn et al., 2015).

Microplastics have been detected in all environments, including the Alps, Arctic, and deep marine environments (Bergmann et al., 2019; Courtene-Jones, Quinn, Ewins, Gary, & Narayanaswamy, 2019; Kane & Clare, 2019; SAPEA, 2019). Because of their potential for widespread environmental distribution, the ecological risks of micro- and nano-sized biodegradable plastics should be subjected to special consideration. Compost is one source of compostable and biodegradable micro- and nanoplastics that is expected to increase with increased application of compostable and biodegradable plastic products in the future.

5.4.3 Environmental risks of conventional plastics

Conventional plastics have accumulated in natural environments over the last 70 years. In locations receiving high yearly dosages, the physical consequences are especially apparent by plastic of all sizes interfering with nature (Figure 5.2). The potential risks from plastic pollution can be related to their size, shape, polymer type, and additives. Size-related hazards related to ingestion of macro-, meso- and microplastics have been identified for all trophic levels (Kühn et al., 2015; Figure 5.2). Entanglement is a structural hazard mostly involving mega- and meso-plastics, trapping and/or seriously harming aquatic and terrestrial animals and birds (Kühn et al., 2015). Structural hazards may also include macro-plastics acting as physical barriers, hindering the transport of gases, water and nutrients, or fragments of plastics affecting soil structure. Studies show that the accumulation of mulch film in agricultural soil may have negative effects on soil health and productivity (Gao et al., 2019; Guo et al., 2019; Liu, He, & Yan, 2014; R. M. Qi, Jones, Li, Liu, & Yan, 2020). Chemical hazards are related to polymer degradation products, release of additives and heavy metals, and chemicals absorbing/desorbing at the surface of plastics (Munier & Bendell, 2018; R. M. Qi et al., 2020; Zimmermann et al., 2019; Zimmermann, Dombrowski, Volker, & Wagner, 2020). Biological hazards are related to biofilm growth on the surface of plastics in the environment (biofouling), including selecting and being vectors for pathogens (Jacquin et al., 2019; Zettler et al., 2013).

Plastics are the most abundant debris in the marine environment and have become a new ecological habitat for marine microorganisms, named the 'plastisphere' (Zettler et al., 2013). DNA-based studies have shown that the plastisphere is distinct from the surrounding environment and includes both putative conventional plastic degraders and putative animal and human pathogens (Jacquin et al., 2019; Zettler et al., 2013; Wright et al., 2020). Plastics debris as a vector for the enrichment and transport of pathogens, heavy metals, toxins, and antibiotic and metal resistant genes are examples of current environmental concerns and topics of research in both aquatic and terrestrial environments (Guo et al., 2019; Jacquin et al., 2019; Zettler et al., 2013). Furthermore, the plastisphere's interactions with, and possible effects on,

biogeochemical cycles are another relevant ecological concern (Jacquin et al., 2019). The ecological consequences of the plastisphere's unique community composition compared to surrounding water and soil in natural habitats are still poorly understood, as are the long-term consequences of mega/macro-plastics as physical barriers disturbing the transport of gas, water and nutrients in soil and sediments. However, the accumulation of mulch films in agricultural soils have been observed to have a detrimental effect on soil structure, water and nutrient transport, crop yield, and to threaten soil health through the absorption and desorption interactions of heavy metals and organic contaminants with plastic surfaces (Gao et al., 2019; Guo et al., 2019; Liu et al., 2014; Qi et al., 2020).

Records from 2012 and 2015 show that, in the marine environment alone, a range of 580-663 species suffer from the effects of plastic pollution (Avio, Gorbi, & Regoli, 2017; Kühn et al., 2015). These include harmful effects from entanglement and ingestion. The consequences of ingesting large plastic items may be starvation and death, while microplastics may enter food webs from soil and aquatic environments, posing a potential risk to higher animals and humans (Alexiadou et al., 2019; Axworthy & Padilla-Gamino, 2019; Lusher et al., 2015; SAPEA, 2019; Yong et al., 2020). Studies show that zooplankton is adversely affected by microplastics, interfering with not only predator-prey interactions and feeding, but also by adhering to the external carapace (Cole et al., 2013; Van Colen et al., 2020). Recent findings show that nanoplastics interact with biopolymers in marine conditions by forming aggregates resembling marine snow (Summers et al., 2018; Figure 5.2). It is hypothesised that nanoplastics may affect the buoyancy of organic matter in oceans and potentially influence ocean food chains and especially deep-sea ecosystems (The Maritime Executive, 2019).
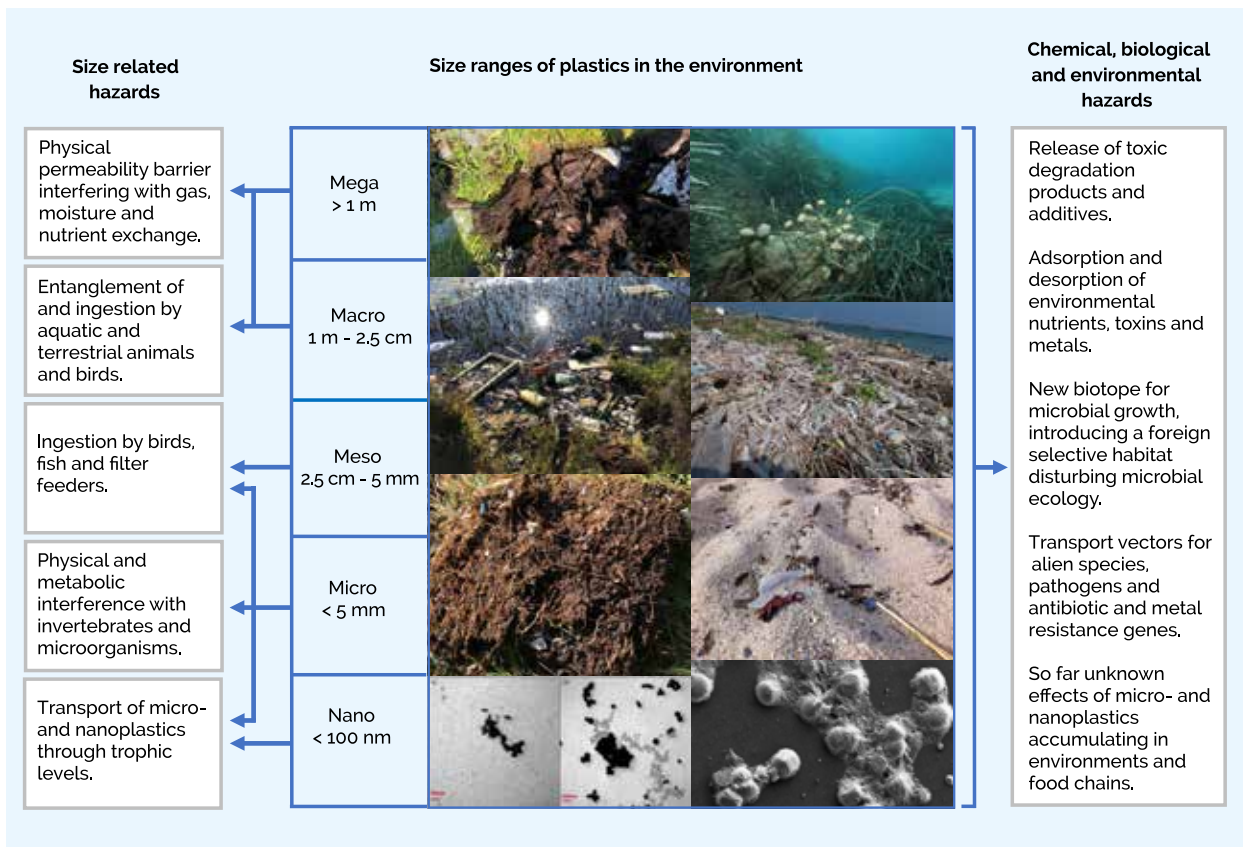
Figure 5.2: Overview of known and potential hazards of conventional plastics pollution related to size (GESAMP, 2019) as well as chemical, biological and environmental hazards. The top three pictures at the left are from Lisle Lyngøyna, an isle in the archipelago Øygarden in the North Sea on the western coast of Norway, showing plastics of various sizes accumulated in soil and water (photos Gunhild Bødtker, NORCE http://creativecommons.org/licenses/by-nc-nd/4.0/). The three top pictures to the right show fishing and mussel nets in and around the Mediterranean Sea and plastic fragments accumulating on a sandy Mediterranean beach (photos: fishing net, beach © HYDRA Marine Sciences/Lott, mussels © Gianfranco Rossi). The three bottom pictures are from transmission electronic microscopy of environmentally relevant polyethylene nanoplastics (left) and a mixture of polystyrene standard latex (middle; photographs from Gigault et al.(2018), while the pictures to the right show nanoplastic agglomerates that are formed at marine conditions (photo from Maritime Executive, 2019).

5.5 POTENTIAL RISKS OF BIODEGRADABLE PLASTICS IN THE ENVIRONMENT

Based on current knowledge, is it possible to foresee any potential benefits of biodegradable plastics over conventional plastics? This section presents studies assessing the ecological effects observed after exposure of biodegradable plastics to different environments. We discuss the potential ecological consequences, compared to what is currently known for conventional plastics.

When considering the potential environmental consequences of biodegradable plastics litter compared to conventional plastics, it is fruitful to base the comparison on what ecological risks of conventional plastics are already known. In the context of this report, the most significant difference between conventional plastics and biodegradable plastics is their potential to biodegrade. Although conventional plastics have been shown to be biodegraded by some microbes, the rates are so slow that they are, in environmental terms, effectively non-biodegradable (Ahmed et al., 2018).

Dosage is an important factor when assessing environmental consequences. Currently, biodegradable plastics constitutes only 0.3% of plastics produced, as we have already mentioned in this report. As a result, the amount of biodegradable plastics that currently reach the open environment across all settings is considerably lower than conventional plastics. If the production of biodegradable plastics increases, then we can expect the input (dosage) into the open environment to increase, including micro- and nanoplastic residues from industrial composting.

The physical exposure time of biodegradable plastics to the environment is dependent on their biodegradation rate in the receiving environment. Studies show that putative environmental biodegradation rates of the same plastic polymer vary with the type of environment (aquatic and terrestrial), the season (where temperature is a significant factor), and ecological variations (Dilkes-Hoffman et al., 2019; Haider et al., 2019; Napper & Thompson, 2019; O'Brine & Thompson, 2010; Rudnik & Briassoulis, 2011; Teramoto et al., 2004; Volova et al., 2007). Biodegradation is a system property, determined not only by the biodegradability of polymers but also by the environmental conditions that determine the extent to which biodegradation can take place (see Chapter 2). When assessing the ecological risks of biodegradable plastics, products intended for composting (~58°C) should therefore be differentiated from plastics that are intended to biodegrade in the open environment. As the biodegradation rate of biodegradable plastics varies between different environments, any risk assessment needs to be specific to those environments, for example, marine, freshwater and soil. The challenge for a risk assessment of biodegradable plastics is illustrated by differentiating further between specific compartments of environments (e.g. surface, water column or seafloor/sediment for the marine environment).

If biodegradable plastics persist in the environment for a substantial time before biodegrading, some of the risks of biodegradable plastics are likely to be the same as for conventional plastics. In this regard, it is particularly important to differentiate between biodegradable products intended for biodegradation in the open environment, and the biodegradable products intended for industrial composting. The former category includes agricultural plastics, such as mulch films that may be ploughed into the soil after use (Sander, 2019) and fishery plastic products with a high risk of loss to the open environment (Kim, Park, & Lee, 2014). Industrial composting differs from environmental conditions by providing stable and optimal conditions for biodegradation (see Chapter 4). The certification of compostable plastic products thus refers to biodegradation in controlled conditions, and not to the open environment. Biodegradable plastic products intended for biodegradation in the open environment may be certified for an environment such as soil, but end up in a different environment, such as freshwater or the marine environment. In such cases, the certification does not apply to the receiving environment and the consequence is a deviation of the expected biodegradation rate and uncertainties associated with the actual turnover rate or half-life of the product in the environment. The uncertainties are associated with factors that influence biodegradation rate, such as temperature, moisture, the availability of nutrients and electron acceptors, the presence of plastic degraders,

and physical or structural characteristics that may affect the biodegradation rate (see Chapter 2).

Biodegradable plastics may be considered as additional organic carbon input to environments. The significance of this input in terms of effect is expected to be dosage-dependent but may also depend on the nutrient conditions of the receiving environment and the effect on the microbial ecology. The biodegradation rate of biodegradable plastic products may also influence the release of additives into the environment. The possible difference in the biodegradation rate of a polymer versus additives suggests the need for separate consideration of the potential environmental hazard and effect of additives. Also, together with the biodegradation rate, the rate of physical and mechanical degradation of biodegradable plastics may influence the risk of entanglement by animals, and potential risks associated with the accumulation of microplastics.

One of the main challenges when considering the potential ecological consequences of plastic exposure to natural environments is the limited studies performed so far that focus on ecological risks, and this is especially true for biodegradable plastics (Haider et al., 2019).

5.5.1 Risks on ecological and ecosystem level, impacts on element cycles

Microorganisms are omnipresent and play a crucial role in the biogeochemical cycling of elements in the environment, and any perturbations in the activity and diversity of the microbial community are likely to lead to significant impacts on the cycling of elements and ecosystem resilience (Jacquin et al., 2019; Shahsavari et al., 2017). Biodegradable plastics are portrayed as part of the solution to combating conventional plastic pollution, due to their biodegradability and hence reduced risk of persistence in the natural environment. However, their biodegradability may cause new ecological effects that need to be assessed.

Studies in soil environments

Weathering and fragmentation of non-biodegradable PE mulch films leads to their accumulation in agricultural soils, raising concerns about interference with water infiltration and gas exchange, root growth and soil microbial community composition (Sander, 2019). Biodegradable mulch films are promising alternatives to PE films as they offer the same qualities and purpose, while their biodegradability in soil suggests reduced concern of accumulation. The application of biodegradable mulch offers the possibility of ploughing them into the soil after use. By this practice, biodegradable mulch may influence the soil in two ways; firstly, as a physical barrier affecting soil microclimate and atmosphere (similar to conventional mulch film); and secondly, by adding carbon, additives and adherent chemicals and microorganisms to the soil (Bandopadhyay et al., 2018). Although the carbon input is small, taking into account the volume of soil they are incorporated into, agricultural soils are generally carbon-limited (Bandopadhyay et al., 2018). Studies have shown an increase in microbial biomass and enzyme activity, and changes in soil microbial communities involving enrichment

of specific genera of fungi or bacteria (Bandopadhyay et al., 2018; Koitabashi et al., 2012; Li et al., 2014a; Li et al., 2014b; Muroi et al., 2016; Yamamoto-Tamura et al., 2015). The biodegradation of biodegradable mulch films in soil seems to be dominated by fungi (Koitabashi et al., 2012; Muroi et al., 2016), probably because fungal cells have a higher carbon-to-nitrogen ratio (~15:1) than bacteria (~5:1) and are thus better at taking up carbon from the carbon-rich polymers, particularly if only limited nitrogen is available from the degrading mulch films and/or associated soils (Sander, 2019). The shifts observed in the soil microbial community have also been predominantly associated with the fungal community, although some studies also report on shifts in bacterial composition and in omnivore unicellular predators (Koitabashi et al., 2012; Muroi et al., 2016). A study observing only a minimal degradation of mulches (labelled biodegradable) in soil detected no significant change in either the fungal or bacterial composition of bulk soil (Moore-Kucera et al., 2014). The above-mentioned studies were inconclusive on the negative impacts of biodegradable mulch film on associated plant growth and soil quality.

Studies from China show that the accumulation of conventional mulch films in agricultural soil has negative effects on crop yield when >240 kg/ha (Gao et al., 2019). Biodegradable mulch film biodegrades at a varying rate in different geographical locations, with remaining fractions varying between 2% and 89% in some studies (Li et al., 2014b). Studies show that complete biodegradation generally takes more than one year, which suggests an accumulation in soil by repeated yearly application (Li et al., 2014b; Sintim et al., 2020). Recent estimates of accumulation rates, with temperature and fallow year as variables, suggest that biodegradable mulch films have a higher risk of accumulation in cold climates, but that this may be mitigated by including a fallow year every three years for thin films (15μm; Eunomia, 2020). Under conditions of higher film thickness and cold soil temperatures (5°C), even the inclusion of fallow years may not prevent accumulation and, under those conditions, even biodegradable mulch films may surpass the negative-impact threshold identified for conventional mulch films. Based on single studies, reviews and recent estimates, there seems to be a consensus that biodegradation rates of biodegradable mulch films vary with soil and environmental factors (importantly, temperature), and that accumulation is a relevant concern. Negative consequences on crop yield are postulated, based on findings for conventional mulch films, and there is a need for dedicated research to assess the long-term ecological effects of biodegradable mulch films on soil microorganisms and soil health.

Other agricultural applications of biodegradable plastics may include seedling trays, protective coatings for seeds, and coatings for controlled release of fertilisers (Harmaen et al., 2015; Majeed, Ramli, Mansor, & Man, 2015; Meng et al., 2019; Vercelheze, Marim, Oliveira, & Mali, 2019). Incubation studies with biodegradable seedling trays in different types of rice-paddy soil showed that the microbial response was both soil type- and time-dependent (Meng et al., 2019). A significant temporary increase in microbial activity and a concomitant reduction in functional diversity was observed in black soil, in addition to an increase in the relative abundance of some specific

bacterial genera. The authors' suggested explanation of results is that starches and degradation intermediates were released into the soil and utilised as carbon sources.

Biodegradation and complete mineralisation of plastic in natural environments may, in some locations, significantly increase the total organic carbon load if biodegradable plastics are disposed of into the open environment in the same manner and volumes as conventional plastics. The reduced environmental persistence of biodegradable plastics is traded for an increased organic carbon input to natural environments. This poses a potential risk of a local imbalance of nutrient ratios (C:N:P), saprobiation or change in the natural ecology in the short-term (if irregular input) or long-term (if regular input). It should be stressed that this potential risk is dosage-dependent. Future production volumes and the public response to waste schemes for biodegradable and compostable plastics will determine the future release rates into the environment. However, as even minor carbon inputs may disturb the natural ecology (Bandopadhyay et al., 2018), care should be taken to avoid unnecessary or large-scale disposal of biodegradable plastics to the open environment.

5.5.1.2 Studies in marine environments

Studies have shown that the microbial community composition found on biodegradable plastics differs from that of non-biodegradable plastics (Pinnell & Turner, 2019). Dussud et al. (2018) found a higher degree of colonisation and activity on biodegradable plastics compared to non-biodegradable PE, and also a distinct microbial community structure on biodegradable PHBV, compared to the other plastics tested. A molecular assessment of the community composition of plastic surfaces showed that the biofilm on biodegradable PHA differed from that of non-biodegradable PET and a ceramic surface used as a control, after incubation at a sediment-sea water interface for 28 days (Pinnell & Turner, 2019). The PHA biofilm was dominated by sulphate-reducing bacteria, which were enriched to a larger extent on PHA compared to PET and the ceramic control. The authors of the study claim that, if conventional plastic pollution were traded for biodegradable plastic pollution and inputs to marine sediments were large, the microbial response may affect the benthic biogeochemical environment by enrichment and increased activity of sulphate-reducing bacteria (increased H_2S production). The study did not include recovery time, i.e. how long the biogeochemistry was affected.

Early diatom colonisation on PE plastic bags compared to a biodegradable compostable bag (Mater-Bi N°014) in shallow benthic and pelagic locations in the Mediterranean showed that diatom composition varied with location as well as by plastic type (Eich, Mildenberger, Laforsch, & Weber, 2015). The abundance of diatoms was lower on the surface of the biodegradable compostable plastic compared to PE, and oxygen consumption was larger, probably due to bacteria metabolising the biodegradable plastic. A similar study showed increased biofouling over time for both PE and biodegradable bags, which in time affected the bags' buoyancy, causing them to sink (Pauli, Petermann, Lott, & Weber, 2017). The biodegradable plastic bags disintegrated at a higher rate compared to the PE plastic, and the biofilm on the

biodegradable bags had a higher net oxygen consumption compared to the biofilm on the PE bags. Overall, a positive net oxygen production was observed for biofilms on both bag types when in the pelagic zone, and negative in the benthic zone. Both studies suggest that the biodegradation of the biodegradable plastic bags was contributing to a larger oxygen consumption compared to the PE bags. Another study compared the ecological effects of HDPE bags and compostable bags on intertidal shore sediment (Green, Boots, Blockley, Rocha, & Thompson, 2015). After 9 weeks, the presence of both bag types created anoxic conditions within the sediment, along with reduced primary productivity and organic matter, and significantly lower abundances of infaunal invertebrates. This indicates that both conventional and compostable bags can rapidly alter marine assemblages and the ecosystem services they provide (Green et al., 2015). A study assessing the effect of biodegradable bags on sediment seagrass of the Mediterranean showed reduced sediment oxygen and pH levels, as well as a change in the spatial segregation of seagrass and coexistence with other species (Balestri et al., 2017). Microplastic from compostable plastics, as well as microplastics from conventional plastics, was observed to have a negative effect on sediment lugworms and associated microalgae (Green et al., 2016).

In conclusion, the potential new hazards and effects of biodegradable plastics, compared to conventional plastics, are linked to their biodegradability. This emphasises the importance and need to design and conduct specific risk assessments that include environmental biodegradation rates, the associated ecological effects of biodegradation, and the consequences on cycling of elements. It is also important to assess whether the ecological effects are transient or permanent related to dosage (dose-response; a relevant example is irregular versus regular input).

5.5.2 Toxicological risk of additives

One of the concerns related to biodegradable plastics in the open environment is that they may leach additives and absorbed metals and toxins if persisting in environments over a period of time before complete biodegradation (Balestri et al., 2019). Furthermore, it is not known to what extent additives will persist in the environment after the plastic polymer is completely biodegraded. Recent studies show that plastics products made from biodegradable polymers have similar toxicity as conventional plastics, and that chemical and toxicological signatures are more related to product type than polymer material (Zimmermann et al., 2019). In the most recent study, six out of ten samples of the biodegradable polymer PLA, as well as pellets of one type of the biodegradable polymer PHA, induced baseline toxicity, while one PLA product also showed a potent effect on oxidative stress (Zimmermann et al., 2020). Most samples tested in these studies, which included petroleum-based, bio-based and biodegradable plastics, contained several thousand chemical compounds, illustrating the challenge of chemical safety and risk assessment of biodegradable plastic products, as well as conventional plastics.

Another study on the phytotoxicity of conventional (HDPE) and biodegradable (Mater-bi®, MB) plastic bags, which simulated leaching of additives from bags deposited in

natural environments, showed that leachates from both types of bags had effects on water quality and seedlings (Balestri et al., 2019). The bags affected water chemistry relevant to plants, where leaching from MB bags reduced pH (while HDPE increased pH somewhat), and both bags caused an increase in salinity and the concentration of total dissolved solids of exposed water. Also, phytotoxic substances including bisphenol A were released into the water. Although no effect was observed on germination, the development of abnormalities and reduced growth was observed for both bag types. The authors of the study conclude that these findings indicate that plastic bags, including those that meet biodegradability and composability standards, represent a potential hazard to plants if left in natural environments (Balestri et al., 2019). Furthermore, they stress that users should be adequately informed about the potential environmental impact of incorrect bag disposal. Another study, where biodegradable seedling trays (a blend of PLA, PBAT and starch) were incubated in different types of paddy soil, found no significant increase in phthalic acid ester (PAE) over time and with increasing amounts of biodegradable seedling trays added (Meng et al., 2019).

When disposed of as intended for industrial composting, the final compost product must meet ecotoxicity safety requirements (OECD standard 208 (OECD, 2006), see Chapter 4). Similar standard toxicity tests should be developed for biodegradable plastics intended for biodegradation in open environments. A review of ecotoxicological studies performed with biodegradable plastic products shows that results vary not only between products of different polymers, but also between products of the same polymer (Haider et al., 2019). Furthermore, both test media and test systems vary between studies, underlining that general conclusions are not possible. The complexity of an ecotoxicological assessment of biodegradable polymers needs to be addressed, including whether the cause of effects is due to additives, the accumulation of degradation products, or metabolites from microbial activity – or combinations of these. A still highly relevant study by Fritz et al. (2003) shows that microbial activity associated with the biodegradation of natural polymers had negative effects on plant growth and on some occasion also on *Daphnia* (water fleas) and bacteria (Fritz et al., 2003). The authors stress the need for repeated measurements during long-term testing, as well as the need to differentiate between indirect effects caused by microbial activity and the chemical toxicity of degradation products and additives. Based on recent reviews on the environmental performance of biodegradable plastics, ecotoxicological data for biodegradable polymers are still scarce (Haider et al., 2019; Lambert & Wagner, 2017). Arguments for testing methods addressing different environments and variations within these, as well as for testing plastic products specifically and not merely the pure components, are relevant not only for assessing realistic environmental biodegradation rates, but also for assessing the actual toxicological effects.

In conclusion, based on the current literature, the ecological risks of additives of biodegradable and compostable plastics are still not clear and need to be further studied under conditions relevant for different natural environments.

5.5.3 Microplastics from biodegradable plastics

The fate and timing of degradation of microplastics deriving from biodegradable plastics are mostly unknown, thus making them potentially as hazardous as the microplastics of conventional polymers (Alvarez-Chavez, Edwards, Moure-Eraso, & Geiser, 2012; Emadian, Onay, & Demirel, 2017; Ruggero et al., 2019). A study by Napper and Thompson (2019) showed that compostable plastic bags disintegrated into microplastic in the open air, as did oxo-degradable and standard polyethylene plastics bags. Some biodegradable plastics intended for biodegradation by composting (e.g. PLA) may contribute to microplastic debris if not fully biodegraded in environmental conditions (Lambert & Wagner, 2017). This concern also applies to microplastic residues in compost used for soil fertilisation and amendment (Markowicz & Szymanska-Pulikowska, 2019; Ruggero et al., 2019). Mesocosm studies assessing the effects of microplastics on filter-feeding molluscs show that both conventional and biodegradable plastics may interfere with filtration and cause alterations in the associated ecosystem functioning and diversity (Green, Boots, O'Connor, & Thompson, 2017). Blue mussels showed reduced tenacity and attachment strength after exposure to polyethylene microplastic, but no negative effect was observed for PLA (Green, Colgan, Thompson, & Carolan, 2019). However, exposure to both types of microplastics altered the haemolymph proteome (including proteins involved in vital biological processes), although the response to PLA was less pronounced.

In general, a significant reduction in the biodegradation rate of compostable plastics such as PLA is expected in environmental conditions, as compared to composting conditions (Haider et al., 2019). Therefore, labelling of plastic items intended for industrial composting should not include 'biodegradable', but only 'compostable' so not to confuse public waste handling. It should be stressed that microplastics from biodegradable plastics are to be considered transient in the open environment, but as they are easily transported between environments, their residence time in the open environment may vary. However, micro- and nanoplastics from biodegradable plastics are expected to biodegrade at a higher rate than larger items, due to their higher surface-to-volume ratio (Chinaglia et al., 2018a; Chapter 2 of this report). Their biodegradability also suggests that their hazardous effects after ingestion may be less in organisms with gut microorganisms able to biodegrade the polymer, as compared to the effect of non-biodegradable conventional microplastics. Microplastics are the most widespread form of plastic pollution, and the most difficult to clean from the environment, and they are shown to be ingested by organisms at all trophic levels. In this context, biodegradable microplastics may potentially be less harmful overall than conventional microplastics. However, at this stage, this reasoning is based on a limited number of studies and general assumptions. More dedicated research is needed to elaborate and conclude on this important environmental question.

In conclusion, microplastics originating from biodegradable and compostable plastics may temporarily contribute to the negative effects known for microplastics in general. However, the level of contribution (exposure time) is dependent on their biodegradation rate in the receiving environments, and in organisms that ingest them.

5.5.4 Risks of entanglement and ingestion

Large biodegradable plastic structures (mega/macro), with a risk of a low biodegradation rate in the receiving environment, may pose a structural hazard for marine and terrestrial animals. In addition, plastics in this size range may have impacts as physical barriers interfering with the ecology of soil and aquatic habitats. Again, the level of exposure is dependent on the degree of disposal and (bio)degradation rate in receiving environments.

In conclusion, while persisting in the environment, large items of biodegradable plastics pose a risk of entanglement and ingestion by terrestrial and aquatic wildlife.

5.5.5 Aesthetic damage

Plastic litter is not only a cause of ecological harm, but it also imposes visual harm by deteriorating natural environments and public recreation areas. If not biodegraded in the environment, biodegradable plastics will need to be cleaned up in the same manner as conventional plastics. The fate of biodegradable plastics and their biodegradation rate, if mixed with conventional plastic debris and accumulated in the open environment, is not known, but barriers inflicted by conventional plastics may promote anaerobic decomposition of biodegradable plastics.

In conclusion, increasing fractions of biodegradable plastics in environmental plastic debris may potentially add to environmental plastic accumulation and aggravate the damage by the odour of anaerobic decomposition and toxic gas production (H_2S).

5.6 RISK ASSESSMENT OF BIODEGRADABLE PLASTICS, PROBLEM FORMULATION (PHASE 1)

Central to the risk assessment of biodegradable plastics in the open environment is the identification of potential ecological hazards, current exposure, and future exposure predictions. For all plastics, if waste systems are well managed (e.g. reclaiming and recycling is working as intended), release to the environment may be limited, and thus ecological risks are expected to be low. However, in the case of poorly managed waste handling of, for example, compostable plastics, similar risks may arise as from conventional plastics, particularly if biodegradation rates are low, until the plastics are eventually mineralised. The biodegradation rates of biodegradable plastics in the receiving environment influence both their physical residence time (and thus physical exposure to the environment) and their input as bioavailable carbon (element exposure). It is thus crucial to understand and correctly measure biodegradation rates in environmental conditions. As biodegradation rates are strongly dependent on environmental factors, the type of receiving environment also influences the risks associated with biodegradable plastics. The overall dosage of biodegradable plastics waste received by a given environment is determined by both application, waste handling and environmental transport.

The risk-benefit ratio of biodegradable plastics thus depends on the following, interacting factors:

- The environment, in terms of the diversity of plastics waste it receives (ranging from narrow-range environments like agricultural soils where mulch films are used, to the wide range of environments that receive plastic bags and fireworks components).

- The fate of the plastics products in the receiving environment (the time of mineralisation through biodegradation versus the time of physical persistence).

- The rate at which environments receive plastics wastes, which determines the dosage of plastics waste exposure to the environment.

While quantitative risk-benefit assessments are still lacking, these general considerations imply a range of scenarios related to physical harm, ranging from high risk and little benefits in environments receiving high dosages of biodegradable plastics that are subjected to low biodegradation rates (high persistence in the environment), to high benefit at low risk in open environments where the biodegradation rates of plastics occurs within an acceptable timeframe. Another aspect of risk-benefit assessment is the potential harm associated with the biodegradation process such as, for example, increased carbon input that may affect microbial ecology and biogeochemical cycles. These biodegradation-associated risks are also influenced by dosage, but highly dependent on the environmental biodegradation rates. For example, if no biodegradation occurs, the risks associated with the biodegradation process do not apply.

In all scenarios, the physical risks posed by biodegradable plastics are significantly increased by two factors, namely low biodegradation rate and increasing dosage received by a given environment. With a high biodegradation rate, the benefits of biodegradable plastics could outweigh or balance the physical risks compared to conventional plastics, due to a lower residence time, while the potential stress from carbon input and the release rate of additives is increased. There are significant knowledge gaps on the potential benefits and risks. Negative effects of the accumulation of conventional plastics have been documented, but more studies are needed on the ecological effects of biodegradable plastic accumulation. The acceptable timespan for persistence needs to be determined by exposure and effect assessments for the relevant environments (Phase 2 of risk assessment).

If the release rate of biodegradable plastics (for example, yearly) exceeds their biodegradation rates, the consequence will be their accumulation in the open environment, likely resulting in similar risks to the environment as conventional plastics, until their eventual mineralisation. Based on knowledge from conventional plastic litter, the dosage received by individual environments is influenced by transport between environments and compartments by ocean currents and geographical factors (Galgani, Hanke, & Maes, 2015; Schwarz et al., 2019). This means that some environments may receive significantly higher yearly dosages than others. Thus, the mathematical modelling of yearly inputs of biodegradable and compostable plastics into receiving environments is advised.

The transport/translocation, fate, as well as impact (physical, chemical, and biological) of biodegradable plastics may be affected by their transformation due to environmental abiotic and biotic factors (surface erosion, fragmentation, biofouling, and biodegradation). Based on their biodegradability, it is reasonable to assume that biodegradable plastics will behave and transport differently in the open environment compared to conventional plastics, influencing their final sink. Furthermore, it may be hypothesised that the leaching or release rate of additives from biodegradable plastics are linked to the biodegradation rate of the polymer. Thus, the release and (bio)degradation rates of additives should also be a part of the risk assessment of biodegradable plastics.

In conclusion, the scientific literature documents the potential negative ecological effects of biodegradable plastics that are related to their biodegradability, including responses to the increased carbon input that manifest in increases in microbial activity and abundance, and changes in microbial community composition. There are significant knowledge gaps related to dosage/exposure, recovery, and possible long-term ecological consequences (e.g. microbial community composition, cycling of elements and level of impact on other trophic levels). Biodegradable mulch films are an example of applications that should be assessed for long-term ecological consequences. The practice of ploughing used mulch films into the soil after use, combined with incomplete biodegradation before new mulch-film application, may lead to the accumulation of biodegradable mulch-film residues in agricultural soils over time (Bandopadhyay et al., 2018; Sintim & Flury, 2017). The long-term ecological implications of the effects observed so far are not known and need to be studied and included in ecological risk assessments of biodegradable mulch films (Bandopadhyay et al., 2018).

The accumulation of plastics in exposed environments represents a similar scenario, whereby the regular dosage of biodegradable plastics may be significant. The recovery rate from biodegradable plastics input is a relevant factor to include in the assessment of long-term ecological risks. Potential environmental risks from the release of greenhouse gases may be relevant to consider in cases of the large-scale disposal of biodegradable plastics into landfills, with the subsequent risk of anaerobic biodegradation coupled to methane production (Chidambarampadmavathy et al., 2017). If substituting conventional plastic with biodegradable alternatives, waste handling and societal relevance should be addressed to avoid the unnecessary future accumulation of biodegradable plastics in the open environment (e.g. agricultural soils, landfills, permanent aquaculture installations with a risk of release in the near environment).

5.6.1 Criteria for exposure, effects, and endpoints

Exposure assessment considers global, regional, and local inputs, and how they are influenced by transport, translocation, and transformation, all of which may determine the final receiving environment (sink). Effect assessment is based on ecological responses and effects already described in the literature and/or observed through

specific studies. Assessment endpoints refer to the environmental values that are to be protected, the societal relevance of these values should be understood and valued by the public and decision makers (Suter II, 1990). Measurement endpoints must be appropriate to the route of exposure, which means that the exposure should be relevant and equal to that encountered by organisms in the environment (assessment endpoint organisms; Suter II, 1990). If this is not possible, the organisms that have the highest exposure should be tested. In the risk assessment of biodegradable plastics, significant assessment endpoints include environmental biodegradation rates and microbial communities. The measurement endpoints include CO_2 and CH_4 production rates, quantifying mineralisation of carbon in polymers (Chapter 4). Initial criteria for a risk assessment of biodegradable plastics are given in Table 5.1 below.

Table 5.1: Criteria for risk assessment of biodegradable plastics.

	Exposure assessment (input, dosage, and exposure)	Effect assessment (hazard or effect)	Assessment endpoints (environmental value)	Measurement endpoint (methodology)
Input volumes	Global Regional Local Site specific	Geographical distribution Exposed environments as sinks Vectors for transport of foreign species, pathogens, heavy metals, and toxins	Global environmental health	Modelling of inputs from individual studies
Transport, transformation and receiving environments/Effects, assessment, and endpoint measurements	Transport Translocation Residence times • Sinks • Ocean • Marine environments • Freshwater • Rivers • Sediments • Coastlines • Environmental soil • Agricultural soil	Entanglement	Terrestrial and aquatic animals, birds	Frequency of observations
		Ingestion	Terrestrial and aquatic animals, birds, fish, invertebrates, microorganisms	Frequency of observations
		Physical barrier	Impact on ecological entities: • Microbial ecology • (Bio)geochemical cycles • Botany • Soil and sediment invertebrates	Metagenome, Next-Generation Sequencing (NGS) Oxygen and redox levels Microbial biogases (CO_2, CH_4, N_2, H_2S) Response assessment (species counts over time)
		Accumulation	Aesthetic degradation of nature Alterations of nature type Soil health and function Biogas production (CO_2, CH_4, H_2S) Impact on systems ecology	Mapping of geography, system ecology with endpoints including e.g. hydrology, botany, fauna, microbiology, biogeochemical cycles.

Transport, transformation and receiving environments/Effects, assessment, and endpoint measurements				
	Size transformation by abiotic and biotic factors: • Degradation rate • Fragmentation rate • Biodegradation rate • Intermediates • Leaching rate of additives	Ingestion (all size categories) Transport via and/or through trophic levels	Terrestrial and aquatic animals, birds, fish, invertebrates, microorganisms	Frequency of observations and effects at different trophic levels
		Biodegradation rate in different environments and compartments of environments.	Physical persistence. Carbon source influencing microbial activity, biogeochemical cycles, species abundances and community compositions in: • Ocean • Marine environments • Freshwater • Rivers • Sediments • Environmental soil • Agricultural soil	Mineralisation (CO_2/CH_4 production) Mass loss of plastic (%) Metagenome, NGS Oxygen and redox levels Microbial biogases (CO_2, CH_4, N_2, H_2S). Response assessment (species, populations, and community counts and composition)
	Size transformation by abiotic and biotic factors: • Degradation rate • Fragmentation rate • Biodegradation rate • Intermediates • Leaching of additives • Recovery • Fast • Slow • Never	Toxicity • Lethal • Sub-lethal • Acute • Chronic	Species specific Community specific Ecological impacts	Ecotoxicity tests Specific species/population studies Community studies
		Species or ecological impacts • Lethal • Sub-lethal • Acute • Chronic	Short- or long-term effects on species/populations, communities, or biogeochemical cycling.	Before exposure During exposure After exposure (endpoints given above)

5.6.2 Conceptual model for ecological risk assessment of biodegradable plastics

The basis for developing a conceptual model depends on the stage of the assessment and the amount of prior assessment that has been done at that stage (Suter II, 1996). The initial conceptual model is based on a qualitative evaluation of existing information and expert judgment. It should be conservative in the sense that sources, pathways, and receptors should be deleted only if they are clearly not applicable to the site.

A conceptual model for an ecological risk assessment of biodegradable plastics is outlined in Figure 5.3. The contaminant source includes products both certified and labelled as compostable and biodegradable, respectively.
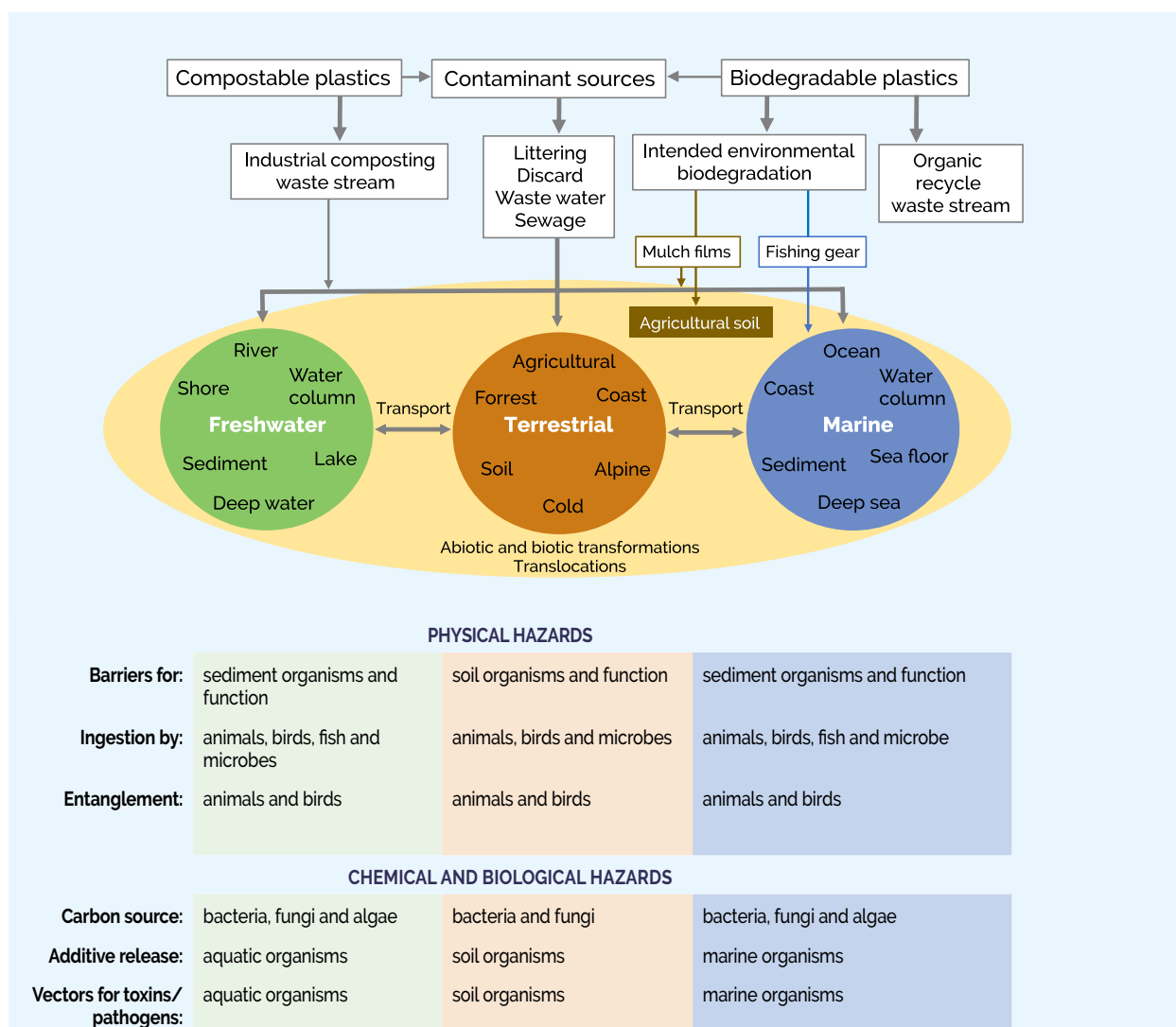
Figure 5.3: Conceptual model for risk assessment of biodegradable plastics. The endpoint effects and endpoint measurements are given in more detail in Table 5.1.

Compostable products are intended to be reclaimed and composted in industrial facilities (e.g. single-use items), while biodegradable plastics products may enter an organic recycling waste stream or be subjected to environmental biodegradation (e.g. mulch film, fishing gear). Mismanaged waste handling and accidental discharge are examples of non-intended release routes into the open environment. The open

environment is represented by freshwater, terrestrial and marine environments. The biodegradable and compostable plastics may be transported between environments, or within compartments of each environment. The plastics will be subjected to abiotic and biotic environmental factors, which may transform them physically (e.g. size, biofouling, biodegradation) and physiochemically (surface properties, biofouling, absorption, biodegradation). The plastics may influence the environment physically, chemically or through element availability, causing structural effects/harm (e.g. entanglement, ingestion, barriers in soil and sediments), toxic effects/harm (leaching of additives, chemical/heavy metal absorption/desorption) or disturb natural ecology by interfering with biogeochemical cycles (utilisation as carbon source, inflicting barriers for gas- and nutrient transport).

The persistence of biodegradable plastics is dependent on their biodegradability in the relevant environmental conditions. Thus, the uncertainties around their fate in the open environment are highly dependent on their in situ biodegradation rate in receiving environments. Even when certified to biodegrade in a particular environment, seasonal and microbiological variations in nature mean that we need to accept uncertainties around actual biodegradation rates, even if the receiving environment matches the certification. If biodegradable plastics are translocated to an environment they are not certified for, their persistence and associated risks are unknown. Therefore, risk assessment is needed for the likelihood of translocation of biodegradable plastics intended for environmental biodegradation (e.g. agricultural mulch), and the ecological risks in potential receiving environments (e.g. rivers, freshwater). Furthermore, compostable, and biodegradable plastic products intended for industrial composting and organic recycling, respectively, should be risk-assessed for their likelihood of ending up in the open environment, and for ecological risks if they so do.

Biodegradable plastics are a good example not only of a contaminant influencing the environment, but also of the environment influencing and transforming the contaminant, and by that process introducing new ecological effects. Besides environmental biodegradation rates and knowledge gaps regarding the ecological consequences of biodegradable plastics, identified uncertainties concern future waste handling, production volumes, and applications of biodegradable and compostable plastics.

Input to the development of ecological risk assessment of biodegradable plastics

As stated at the beginning of this Chapter, ecological risks are linked to dosages. The volumes of biodegradable plastics reaching the open environment are dependent on production volumes, available products and their application, systems for waste handling, and public knowledge, awareness, and behaviour (Chapter 6). Future production volumes and applications should be weighed up against ecological risks and effects. An important part of the risk assessment of biodegradable plastics is consumer behaviour and responsible waste handling, which should be addressed through public education and awareness campaigns.

This Chapter describes the potential risks of biodegradable plastics related to open environments, and ecological effects. We have described the multidimensionality of potential ecological risks, how receiving environments significantly influence risks and exposure time, and how transport, transformation and translocation add to the uncertainties for all size ranges of biodegradable plastics. The future ecological risk assessment of biodegradable plastics should be capable of addressing and including all these aspects. This may involve new study designs (Chapter 4) and the development of mathematical models capable of incorporating all essential and determining factors and variables related to environmental transport, translocation, final sinks, and environmental biodegradation.

This Chapter has only considered ecological risks in open environments, but environmental risks, including the effects on human society, should be part of a future risk assessment through life cycle assessment (LCA) or life cycle impact assessment (LCIA). The use of biodegradable plastics in agriculture is one specific concern, by not only potentially affecting soil ecology and soil health, but also food production and human health.

Risk assessment should include both short-term and long-term effects of irregular exposure, as well as regular exposure. The main identified knowledge needs are:

- Biodegradation rates for different biodegradable plastic polymers and/or products in different environments and compartments of environments. Seasonal factors should be included as variables, the most important is probably temperature.

- Transport, transformation, and translocation of biodegradable plastics in the environment is believed to be different compared to conventional plastics, as biodegradation influences the transformation of structure, size, and buoyancy.

- Short- and long-term consequences of irregular and regular exposure to biodegradable plastics related to current and predicted future exposure.

- Biodegradable plastics influence microbial communities by being an available surface and carbon source, thus their effects on biogeochemical cycles and associated ecosystems need to be studied for long-term effects and recovery time.

- The ecological risks of additives of biodegradable and compostable plastics are not clear and need to be studied further under environmental conditions, as should their release rates relative to the environmental biodegradation rates of the polymers. The effect of additives should be differentiated from the effects of intermediate degradation products and/or metabolites from the biodegradation process of the polymer.

- Residual microplastics from industrial and home composting are a new potential risk. Used for soil improvement, compost represents a future increasing source of microplastics for agricultural and natural soils. The concerns are related to effects on soil structure and health, physical harms to organisms, and effects on microbial ecology. Translocation into aquatic environments, where persistence may increase due to reduced biodegradation rate, is a special concern.

The potential hazards of biodegradable plastics in the open environment have been described, based on studies performed in soil and marine environments. The potential harmful effects may relate to their physical persistence in the environment before biodegradation, the toxic effects of additives, or the input of bioavailable carbon affecting microbial ecology and biogeochemical cycles. Observed responses to carbon input are shifts in microbial biomass, community composition and activity, but the long-term effects and consequences related to dose are not known. Neither is recovery rate, and how it may relate to irregular and regular exposures. More knowledge is needed on the potentially toxic effects of additives, their release rate during biodegradation of the polymer and recovery rates after exposure. The effects of additives should be distinguished from those of microbial activity.

The long-term effects and risks of biodegradable mulch film application on agricultural soil microbiology and soil health are a special concern, as the practice of ploughing them in after use, combined with incomplete biodegradation, may lead to the accumulation of biodegradable mulch films in agricultural soils. The accumulation of conventional agricultural mulch films has adverse effects on plant growth and soil health but, to date, similar effects from the use of biodegradable mulch films have not been shown. However, current estimates suggest that harmful accumulation may occur, particularly in cold climates, which supports the need for dedicated research assessing long-term ecological effects as well as effects on crop yield, from the use of biodegradable mulch films.

Figure 5.4 summarises the current input to ecological risk assessment of biodegradable plastics (yellow boxes) and the future ecological risk assessment (blue boxes) and monitoring and risk management (green boxes) that need to be conducted.
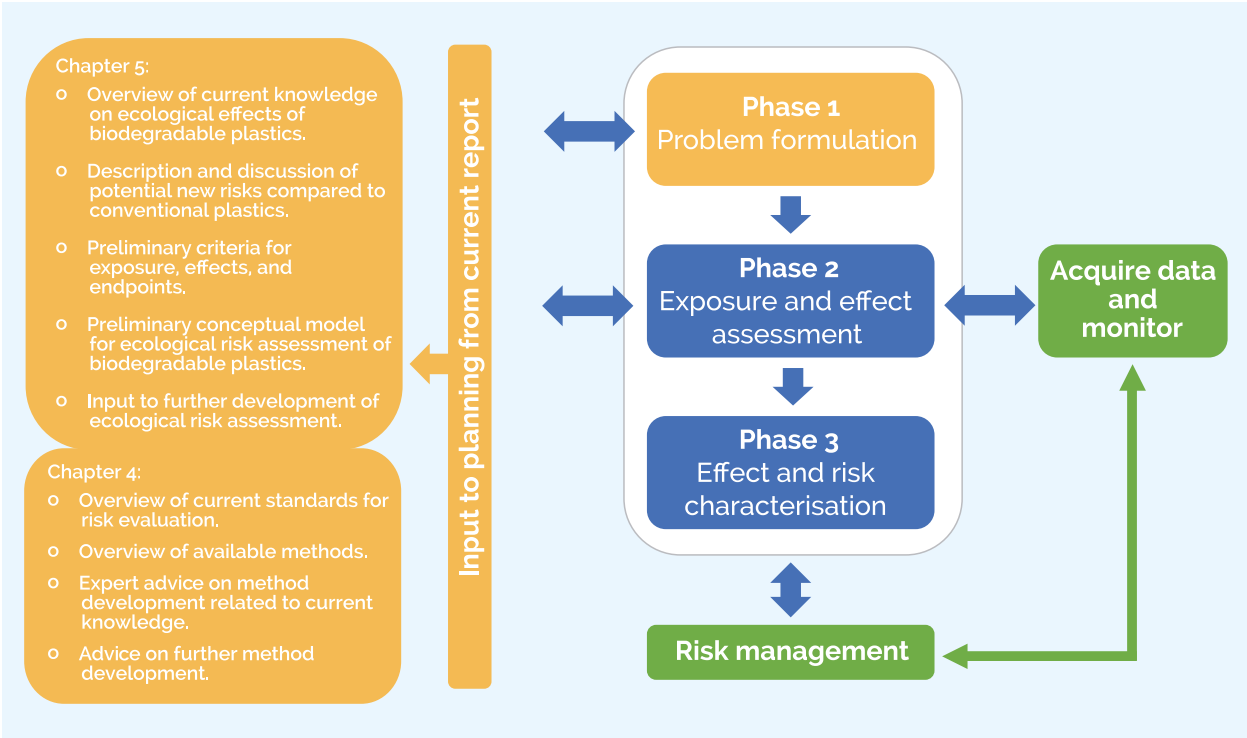

Figure 5.4: The main elements of ecological risk assessment with a summary of the input to problem formulation and method development for exposure and effect assessment provided in Chapters 5 and

Key messages

- The risk assessment of biodegradable plastics in the open environment is currently at the early phase of problem formulation, with much as yet unknown.

- The potential new hazards and effects of biodegradable plastics compared to conventional plastics are linked to their biodegradability. Additionally, their intended application and waste stream handling, considering current and future quantities produced, determine the dose exposed to the open environment. In this regard, it is important to stress the difference between biodegradable plastic products intended for environmental biodegradation and the ones intended for industrial composting, as their biodegradability in the open environment may differ significantly.

- For biodegradable plastics ending up in the open environment, a high biodegradation rate (what would be considered an "acceptable" environmental residence time remains to be determined) may reduce the ecological risks associated with physical harm as compared to conventional plastics. On the other hand, plastics that are readily biodegraded will increase the amount of bioavailable carbon in the receiving environment, which may influence biogeochemical cycles short or long term.

- Current literature shows that (bio)degradation rates of biodegradable plastics vary significantly between environments and with ecological and seasonal factors. This emphasises the importance and need to design and conduct specific risk assessments with a focus on environmental biodegradation rates and associated ecological effects in different types of receiving environments (e.g. marine, freshwater, sediments, soil). Furthermore, the methods applied to determine biodegradation need to include an assessment of mineralisation of plastic carbon to CO_2, verifying and differentiating biodegradation from exoenzymatic and abiotic degradation.

- Based on the current literature, the ecological risks of additives in biodegradable and compostable plastics are not clear and need to be further studied. Microplastics originating from biodegradable and compostable plastics may contribute to the negative effects known for microplastics in general. However, the level of contribution is dependent on their biodegradation rate in the receiving environment. Likewise, while persisting in the environment, large items of biodegradable plastics pose a risk of entanglement and ingestion by terrestrial and aquatic wildlife and smothering of habitats by acting as physical barriers, in the same manner as conventional plastics.

- The main identified knowledge gaps include biodegradation rates for different biodegradable plastic polymers and/or products in different environments and compartments of environments. Seasonal factors should be included as variables, the most important is probably temperature. We need to know more about the short and long-term consequences of irregular and regular exposure by organisms to biodegradable plastics related to current and predicted future exposure. Biodegradable plastics influence microbial communities by being an available surface and carbon source, thus their effects on biogeochemical

cycles and associated ecosystems needs to be studied. The ecological risks of additives of biodegradable and compostable plastics is not clear and needs to be further studied in environmental conditions, and their release rate related to the environmental biodegradation rate of the polymers.

- Biodegradable and compostable plastics may temporarily contribute to the negative effects known for conventional plastics. The exposure time (persistence) is dependent on their biodegradation rate in the receiving environment. Potential new hazards of biodegradable plastics compared to conventional plastics are linked to their biodegradability in terms of effects on microbial ecology, biogeochemical cycles, release rates and effects of additives, and effects of intermediate biodegradation products.

Chapter 6: Social, behavioural and policy aspects

What is this Chapter about?

- This Chapter draws upon the wider social and behavioural sciences, including psychology, economics, communication sciences, and environmental policy studies, to consolidate evidence on how a new technology such as biodegradable plastic is perceived, understood and used by consumers and other societal actors.

- It summarises the evidence to date on possible unintended consequences of the introduction and proliferation of biodegradable plastics; how communication and labelling can help support the appropriate use, management and disposal of biodegradable plastics; and evidence-based policy options to achieve awareness and behaviour change to prevent biodegradable plastics ending up in the open environment.

6.1 INTRODUCTION

6.1.1 Background

This Chapter consolidates evidence on how a new technology such as biodegradable plastic is perceived, understood, and used by consumers and other societal actors. It draws upon the wider social, behavioural and policy sciences (henceforth referred to as the 'social and behavioural sciences'), including psychology, economics, communication sciences, and environmental policy studies. This is based on the understanding that social and behavioural sciences play an important role the interplay between natural science insights and societal outcomes and responses (SAPEA, 2019).

The Chapter is based on a comprehensive review of the social and behavioural sciences literature published between 2000 and May 2020, in which 144 relevant publications were identified. While the review period spanned two decades, most of the evidence reviewed here was published in the last five to ten years. Examination of the reference lists further identified a small number of relevant publications from the late 1990s.

The primary focus of the Chapter is on consumers. To a large extent, this is a reflection of the published literature. While there are other relevant users and applications in a range of economic sectors, including agriculture and fisheries (see e.g. Chapter 3), the social and behavioural sciences literature on these users and sectors is scant. Similarly, while human decisions and actions of a wide range of stakeholders are relevant to the movement of plastics from the economy into the environment (SAPEA, 2019), there is an insufficiently large literature on other markets along the plastic supply chain (e.g. business-to-business; B2B) for a reliable evidence base. The focus on consumers can

further be justified by the potential growth in consumer applications of biodegradable plastics. While biodegradable and compostable plastics still have a very low market share, 59% of all plastic waste is produced by packaging; and sustainable packaging is expected to become one of the main applications of biodegradable plastics (also see Chapter 3).

Different social and behavioural sciences literatures use different terminologies relating to bioplastics in general, and biodegradable plastics in particular. These do not always align with technical definitions used in the biological and physical sciences (see Chapter 2). In particular, the term 'bioplastic' is differentially used to refer to either the bio-based origin or the biodegradable character of plastic. Throughout this Chapter, notwithstanding the definitions we laid out in Chapter 2, we use the term 'biodegradable' where it is explicitly used in the source, or where a different terminology is used to refer to the biodegradable character of the plastic material in question. This encompasses all plastic materials that can be considered biodegradable, compostable or home compostable, irrespective of whether conditions for biodegradation are specified. The term 'bio-based' is reserved for instances where the focus is on the renewable origin of the polymer's feedstock. The term 'bioplastic' is used as a generic term to collectively refer to bio-based and biodegradable polymers and in instances where it is not clear what type of bioplastic it refers to.

Figure 6.1, based on our review, illustrates (a) societal processes and key influencing factors that define the adoption, use and disposal of biodegradable plastics; (b) the stages where unintended consequences may occur, including intended and unintended leakage of biodegradable plastics into the open environment; and (c) potential policy measures that can be taken.

6.1.2 Biodegradable plastic and the transition to a circular economy

Both recyclable and biodegradable plastic can play a role in the transition to a circular economy (Carus & Dammer, 2018), but concerns regarding possible contamination of recycled plastic (Geueke et al., 2018), and large volumes of conventional plastic still ending up in the open environment, make the potential role of biodegradable plastic more prominent. So far, biodegradable plastics represent less than 1% of current global plastic production (see Chapter 3), but their market share is expected to grow given the increasing demand and the European Commission's recognition of the role of 'bioplastics' in a transition to a circular economy (Prata et al., 2019). It has to be noted that the use of biodegradable plastic materials can also be at odds with circular economy principles. Plastics that are designed to biodegrade may be more conducive to a linear use, in particular in short lifespan applications where there is a high likelihood of the materials ending up in the open environment (e.g. fireworks; see Chapter 3).

Adoption of biodegradable plastic

Circular economy → **Production of biodegradable plastic**

Consumer
Awareness → Attitudes → Preferences (WTP) → Behaviour

Farmer
Price difference + Yield difference − Costs (e.g. disposal) → Use of BDG plastic

Trade & retail (B2B)
Price difference + Consumer WTP − Costs (e.g. branding) → Use of BDG plastic

Use (volume and accumulation)

Disposal
Awareness
Labelling
Waste Infrastructure

OPEN ENVIRONMENT

Externalities, cross-sectoral economic impacts

Improper labelling
Uptake of less sustainable alternatives following bans
Inappropriate applications

Littering
Improper disposal/recycling
Industrial composting in open env.
Rebound effect

UNINTENDED CONSEQUENCES

Market-based (subsidies, tax)
Regulation (bans, standards, certification)

Information (labelling, education)
Market-based (subsidies, tax)
Regulation (bans)

Information (labelling, education)
Market-based (subsidies, EPR, deposit-return, pay-as-you-throw)
Regulation (standards, certification)
Assure waste infrastructure

POLICIES

Figure 6.1: Socioeconomic processes and behavioural factors affecting the pathways of biodegradable plastics in society. We indicate the possible unintended consequences for each stage and policies that have a potential to correct them (WTP = willingness to pay; B2B = business to business; BDG = biodegradable; EPR = extended producer responsibility).

As with any new technology, the adoption and proliferation of biodegradable plastics is a long-term process. On the production side, transition theory (F. De Haan & Rotmans, 2018; J. De Haan & Rotmans, 2011) suggests that when an innovative 'niche' technology gets a comparative advantage, it may replace the main 'regime' (the dominant existing technologies) when the latter comes under pressure. In the context of this report, it implies that experimentation with innovative biodegradable plastics is needed in the 'niche' environment by various stakeholders. A transition is a deep social process that also requires a policy window of opportunity to open (e.g. new regulations, standards or price instruments) to enable a shift from the dominant conventional plastics to innovative forms of plastics. Transition theory explicitly discusses the role of various stakeholders, legal and physical structures, culture and dominant practices, and is applied widely in other areas of sustainability studies, including energy transitions. On the consumer side, diffusion of innovation theory (Rogers, 2010) explains how new ideas and technologies are adopted, creating a pattern where a few consumers are innovators, a few lag behind, and the majority of consumers take intermediate stances. For a new technology to be adopted by consumers, it needs to have a relative economic or non-economic advantage over existing technologies; be compatible with their existing values, experiences and needs; understandable and easy to use; relatively risk free to experiment with; and have easily observable outcomes. To become part of a circular economy, biodegradable plastic should be accepted and used by consumers as intended, but also by businesses along the plastic supply chain, political parties, and societal stakeholders (Peuckert & Quitzow, 2017). These two theories provide a background for what is discussed further in this Chapter.

6.1.3 The production of biodegradable plastics

The adoption of biodegradable plastic is possible when behavioural factors on the consumer side align with the economic competitiveness of the products. A systematic review of private business models for sustainable plastic management identifies the development of bioplastics (comprising both bio-based and biodegradable) as a leading trend (Dijkstra et al., 2020). From the perspective of the business case archetypes (Bocken et al., 2014), the drive to 'substitute with natural or renewable processes' associated with bioplastics is the second most popular of all cases reviewed. Dijkstra et al. (2020) identify a range of drivers and barriers for industry to adopt more sustainable plastic production. The top drivers for producers to switch to bioplastics include:

- growing consumer demand for biodegradability
- a possibility for 'green branding'
- cost uncertainty for conventional plastics due to volatile oil prices and stringent government regulations
- competition and higher profit margins from green products
- pro-environmental consumer values

Top barriers include:

- risks associated with the development of new materials (e.g. property requirements, food safety, scaling up)
- the establishment of new supply chains with business-to-business interactions and technological learning
- difficulties with waste processing due to incompatibilities with traditional recycling systems

These barriers may lead to environmental trade-offs, rebound effects and unsustainable material sourcing, which can lead to 'greenwashing' (giving the false impression of environmental sustainability for marketing purposes) and add uncertainty (Dijkstra et al., 2020). Section 6.3 of this Chapter briefly reports on the macroeconomic effects of policies to promote the production of bioplastics, which may trigger economy-wide cross-sectoral feedbacks.

6.2 PUBLIC UNDERSTANDING, PERCEPTIONS AND BEHAVIOUR

6.2.1 Public understanding of biodegradable plastics

There is considerable consumer confusion surrounding the terminology used to describe bioplastics in general and biodegradable plastics in particular. As already discussed in Chapter 2, the term 'bioplastics' is a generic term that is used to refer to plastics that are partly or fully produced from biological feedstocks ('bio-based plastic') as well as to those that are considered biodegradable, including plastics that

are compostable or home-compostable ('biodegradable plastic'). Bio-based plastics can be chemically identical to their fossil-fuel/petrochemical-based counterparts ('fossil-based plastic') and will as a result have similar physical, perceptual and sensory properties (e.g. bio-polyethylene, bio-PE). Even biodegradable plastics that have a different chemical composition (e.g. PLA) often feel and look the same as conventional fossil-based plastics, making it difficult for consumers and other users to perceptually distinguish them. Biodegradable plastics are often derived in whole or in part from renewable feedstock, but do not need to be (see Chapter 2, Figure 2.1).

The 'bio' prefix draws consumers' attention and is suggestive of sustainability and environmental protection (Yeh, Luecke, & Janssen, 2015). Accordingly, consumers associate the terms 'bioplastics' and 'bio-based plastics' with vague notions of renewability, natural origins and 'environmental friendliness'. They also confuse or conflate them with end-of-use characteristics, such as biodegradability, compostability and recyclability (Rumm, Klein, Zapilko, & Menrad, 2013). Consumers expect products or packaging that are labelled as bioplastic to have a renewable resource base and to degrade fully under home composting conditions, and that they can help with climate change mitigation and plastic waste reduction (Magnier & Crié, 2015; Kainz, 2016; Dilkes-Hoffman et al., 2019b; Neves et al., 2020).

The 'bio' prefix is also used to refer to organically-produced agricultural products and as a result creates images of ecological production methods (Kainz, 2016; Sijtsema et al., 2016). The term is therefore frequently used by companies to evoke positive associations with their products (Haider et al., 2019). Given that most of the currently available biodegradable polymers decompose in a timely manner only in industrial facilities under controlled conditions, and bio-based plastics degrade only over long periods just like their fossil-based counterparts, it is perhaps not surprising that there is considerable confusion and scepticism among consumers about products that combine the terms 'bio' and 'plastics' (Brockhaus, Petersen, & Kersten, 2016; Lynch, Klaassen, & Broerse, 2017). As a result, overenthusiastic marketing of bioplastics may lead to consumer backlash (Brockhaus et al., 2016).

Further confusion exists about the distinction between biodegradable and compostable plastics (WRAP, 2007). Many consumers understand the term 'biodegradable' as something that will break down 'naturally' in the open environment in the same way as something that is considered 'compostable'. While biodegradability and compostability have distinct technical definitions, they are often conflated and used as synonyms by consumers. It has to be noted that WRAP's (2007) research was conducted at a time when biodegradable and compostable packaging were still niche products and kerbside collection of recyclable plastics and compostable kitchen waste was still uncommon in the UK, where the research took place. It is possible that public understanding of the terminology has changed since. More recent studies, however, suggest that people are still unfamiliar with the different types of bioplastics and their technical definitions (e.g. Sijtsema et al., 2016). While consumers generally know something about the availability and production of bioplastics, they lack detailed understanding of different material types as well as their applications and

environmental impacts (Dilkes-Hoffman et al., 2019a; Kurka, 2012). This can in part be attributed to the limited relevance of bioplastics in consumers' day-to-day lives (Klein et al., 2019). Overall, the literature shows that current terminology and associated technical definitions of bio-based and biodegradable plastics are incongruent with how the public understands them.

A lack of detailed knowledge of different types of bioplastics does not mean that consumers cannot meaningfully discuss them. Consumers are able to make sense of the term being constructed from the two familiar words of 'bio' and 'plastic', especially when they are confronted with real or fictional illustrative products as a basis for discussion (Lynch et al., 2017). Primary-school aged children are already able to argue cogently about sustainability aspects of conventional and bioplastics (including biodegradable plastics), using arguments related to pollution prevention and the design of recyclable and biodegradable products (de Waard, Prins, & Van Joolingen, 2020). These discussions, however, predominantly focus on end-of-life attributes rather than on the sourcing and efficiency of materials used (Van Dam, 1996); and widespread confusion remains about the environmental benefits of bioplastics and how to dispose of them appropriately (Lynch et al., 2017). Consumers express a need for transparent and objective information on the environmental benefits of bio-based and biodegradable plastics as well as on how to deal with them at the end of their lives. This is discussed in more detail in Section 6.4.

6.2.2 CONSUMER PERCEPTIONS OF SUSTAINABLE AND BIODEGRADABLE PACKAGING

Sustainable packaging is one of the main applications of biodegradable plastics, with the aim of reducing their environmental impacts (Rujnic-Sokele & Pilipovic, 2017; Song et al., 2009). There is a burgeoning literature on consumer perceptions of bio-based and biodegradable plastic packaging based on wider research on consumer responses to sustainable packaging (Boz et al., 2020; Magnier & Crié, 2015; Martinho et al., 2015; Rokka & Uusitalo, 2008). Efforts to make packaging more sustainable are popular among consumers across the world, and consumer perceptions of such packaging are overwhelmingly positive (Boz et al., 2020).

Research shows that consumers judge the environmental friendliness of packaging based on material type and end-of-use disposal options rather than on the way they are sourced and produced (Heidbreder et al., 2019; Dilkes-Hoffman et al., 2019a; Boesen et al., 2016; Jerzyk, 2016; Scott & Vigar-Ellis, 2014; Young 2008). In particular, packaging that is recyclable and biodegradable is perceived as the most environmentally friendly (Herbes et al. 2018; Van Dam, 1996). This means that consumer perceptions and the actual environmental impacts of packaging do not always align. Steenis et al. (2017) conducted a formal life cycle assessment (LCA) alongside a consumer survey. They found that, while consumers rated bioplastics and glass as the most sustainable, these packaging materials had comparatively large environmental burdens as assessed by the LCA.

While material recyclability, reusability and biodegradability are rated highly by consumers across the world (Arboretti & Bordignon, 2016; Korhonen et al., 2015; Lewis and Stanley, 2012; Magnier & Crié, 2015; Scott & Vigar-Ellis, 2014), there are some cross-national differences in the way these end-of-life attributes are weighed (Herbes et al., 2018). There are suggestions that consumer perceptions and preferences for end-of-life attributes are at least partly dependent upon available waste infrastructures. Consumers from Western countries with well-developed recycling systems tend to rate recyclability of materials more highly, while consumers from countries with less developed recycling and waste separation systems have a relative preference for biodegradability (Korhonen et al., 2015). For example, Nguyen et al. (2020) show that consumers in Vietnam describe eco-friendly packaging as non-toxic and recyclable, but above all as biodegradable and easily decomposable. Research on consumer attitudes in lower- and middle-income countries is, however, scarce (Boz et al., 2020).

Consumer perceptions and responses to sustainable packaging can be extended to bio-based and biodegradable plastic packaging, which are similarly positive (Dilkes-Hoffman et al., 2019b) — although negative and ambivalent responses have also been reported (Blesin, Jaspersen, & Möhring, 2017; Kainz, 2016; Lynch et al., 2017; Magnier & Crié, 2015; also see Section 6.5). Consumers generally prefer bio-based materials over conventional fossil-based plastics (Kainz, 2016; Koutsimanis, Getter, Behe, Harte, & Almenar, 2012) and perceive them as more sustainable (Boesen et al., 2019; Steenis et al., 2017), even if the environmental impacts across their life cycle may be greater (Rujnic-Sokele & Pilipovic, 2017). Products that are only partly bio-based evoke far less positive emotions and are responded to in the same way as products made from conventional plastics (Reinders et al., 2017). Research further shows that biodegradable plastics are perceived as better for the environment than conventional fossil-based and 'easily recyclable' plastics (Dilkes-Hoffman et al., 2019b), but are seen as less convenient than durable plastic food packaging (Blesin et al., 2017; Dilkes-Hoffman et al., 2019b; Lynch et al., 2017).

In line with circular economy principles, biodegradable and non-biodegradable material should ideally be managed as part of a closed loop, captured, and transferred for reuse (Boz et al., 2020). Biodegradable plastics amount to new materials with different properties and need to be processed accordingly (Alaerts et al., 2018). Biodegradable plastics are unsuitable for landfill as they release methane under anaerobic conditions (Song et al., 2009), and some can cause problems if they enter existing recycling streams in significant quantities (Alaerts et al., 2018). Biodegradable plastic materials are better managed through organic waste streams for composting or digestion purposes instead; for example, to be turned into compost or used as a feedstock for other bio-based products (Russo et al., 2019). However, it is difficult to perceptually distinguish between biodegradable (e.g. PLA) and non-biodegradable but recyclable plastics (e.g. PET) due to their similar appearances. This means that the two cannot be separated by consumers or via manual sorting without appropriate labelling, and current optical sorting systems are also inadequate (Rujnic-Sokele & Pilipovic, 2017).

While consumer confusion is often mentioned as a factor in the contamination of recycling waste streams, consumers express frustration about a lack of intuitive recycling systems that allow them to discard their waste in an environmentally-friendly way (Neves et al., 2020). Consumer confusion about correct disposal of biodegradable plastics is caused by inconsistent terminology, a large amount of different plastic materials used for packaging, and a lack of clear standardised labelling that communicates how materials need to be used and discarded. In particular, there is confusion about the proper disposal of different types of bioplastics and their degradation pathways in the open environment (Boesen et al., 2019; de Waard et al., 2020; Haider et al., 2019; Lynch et al., 2017; Dilkes-Hofmann et al., 2019b; also see Section 6.4).

6.2.3 Farmer perceptions of biodegradable plastics in agriculture

As already mentioned at the beginning of this Chapter, most social and behavioural sciences research on the use of bio-based and biodegradable plastics has been on consumers. The findings of this literature cannot be generalised to other user groups and applications, such as in agriculture and fishing. There are, however, a small number of studies that have explored the use of biodegradable plastics by farmers.

Farmers are major consumers of plastics, mainly as mulch film for crop protection. Mulch film is difficult to recycle when it is contaminated with soil, vegetation and chemicals, and poses risks to the environment if landfilled or left on the field (Kasirajan & Ngouajio, 2012). Biodegradable plastic mulch film provides comparable benefits to those made from conventional fossil-based plastic, but then can be tilled into the soil after use, where it is expected to decompose under the right conditions. While agriculture generates a relatively small amount of plastic waste in Europe, especially as compared to consumer applications (Pazienza & De Lucia, 2020), there is a likelihood of biodegradable plastic mulch film ending up in the open environment, as the material is specifically designed to allow the materials to be left on the field. Chapter 5 discusses the ecological risks of biodegradable plastics in the open environment in more detail.

Farmers have positive views of biodegradable plastic mulch films, exhibit a great willingness to learn more about the material, and recognise the benefits of reduced pollution and the convenience of not having to remove or dispose of the materials (Goldberger, Jones, Miles, Wallace, & Inglis, 2015). The use of biodegradable plastic mulch film is, however, still far from widespread (Velandia et al., 2020a). Limited availability, costs and unpredictable degradation pathways (Goldberger et al., 2015) are mentioned as barriers to its adoption. Furthermore, many farmers consider the use of conventional plastics as benign or inconsequential relative to their production benefits (Schexnayder et al., 2017) and think that that biodegradable plastic is an unproven technology, with potential adverse impacts on soil health when left on the field (Goldberger et al., 2015).

There is particular uncertainty about the use of biodegradable plastic mulch film in organic farming (Dentzman & Goldberger, 2020). Organic farmers express more

concern about conventional fossil-based plastics than conventional farmers, and report that they are more likely to use biodegradable mulch film in the next five years. They remain, however, similarly hesitant to use biodegradable mulch film, and express concern about how it would break down in soil. Organic farmers also have to comply with organic standards, with some certifying organisations not allowing biodegradable mulch film products that are not made fully from bio-based feedstocks, even where they have been found to have minimal impacts on soil quality (Malinconico, 2017).

Based on a four-year-long field experiment, Mari et al. (2019) conclude that some biodegradable films provide economic benefits over conventional plastics, even without subsidies. However, the study notes that disadvantages for farmers may include an aesthetic displeasure when biodegradable mulch films break down, and a negative perception linked to inconvenience during installation.

Overall, the literature suggests that growers may switch to biodegradable plastic mulch film if it becomes more available and affordable, and can be proven to be harmless to soil health. There is potential for widespread use of biodegradable plastics in agriculture, given that a majority of farmers is interested in using the material at moderately higher prices (Velandia et al., 2020b) and consumers express a willingness to pay a premium for agricultural produce grown using biodegradable instead of conventional mulch film (Chen et al., 2019). Most research on farmer perceptions has, however, been conducted in the US and results may not apply to other countries and settings.

6.2.4 Consumer preferences and behaviour

A larger body of work has focused on consumer preferences and behaviour, including their willingness to pay (WTP) for sustainable and biodegradable packaging, as well as for biodegradable plastic products and packaging. WTP or economic valuation research aims to estimate the value a person places on goods by establishing how much money they are willing to forgo for a particular product. This is based on the assumption that the price consumers are willing to pay is an indication of the utility of that product.

Stated and revealed preference techniques can be used to elicit consumers' willingness to pay for products. The difference between the two is that stated preference techniques involve direct or indirect expressions of preferences, whereas revealed preference techniques rely on observations of actual choices that have been made by consumers. Stated preferences are usually derived from surveys in which consumers are confronted with real or hypothetical products with different combinations of attributes, or experiments in which respondents are asked to choose between products with different profiles. Stated preference techniques are subject to social desirability bias, whereby respondents may answer questions in a way to present themselves in a favourable manner. Social desirability bias can be avoided with revealed preference techniques (Klaiman, Ortega, & Garnache, 2016). There are, however, no revealed preference studies with biodegradable plastics,

due to a lack of available products and because they are mode difficult to conduct (Brockhaus et al., 2016).

There is good evidence that consumers are willing to pay a premium for green or sustainable packaging (Rokka & Uusitalo, 2008; Van Birgelen et al., 2008; Lindh et al., 2016; Prakash & Pathak, 2017; Heidbreder et al., 2019; Dilkes-Hoffman et al., 2019b; Ketelsen et al., 2020). Multiple studies across the world have shown that consumers are willing to pay more for biodegradable package options (Hao et al., 2019; Martinho et al., 2015; Muizniece-Brasava et al., 2011; Rokka & Uusitalo, 2008). The premium consumers are willing to pay is, however, small (Zhao et al., 2018), and dependent on the method of estimation (Yue et al., 2010). Research on consumer preferences for bio-based plastic products similarly show that consumers are willing to pay more for bio-based plastic products than for conventional ones made from fossil-based plastic (Kurka, 2012). While environmental considerations are key components of consumers' assessment of bio-based plastics, high price premiums are rejected in actual purchase decisions (Moser & Raffaelli, 2012). Here, it has to be noted that there is substantial heterogeneity among consumers, and that consumer preferences (including those expressed in WTP) for sustainable and biodegradable packaging are dependent on a number of individual and contextual factors, such as age (Korhonen et al., 2015; Koutsimanis et al., 2012), income (Gabriel & Menrad, 2015), attitudes towards health and the environment (Magnier & Crié, 2015; Martinho et al., 2015; Prakash & Pathak, 2017), and country of residence (Kurka, 2012).

There are only a few studies on consumer preferences for products with biodegradable plastic packaging. Boz et al. (2020) reports on a case study that examined consumer preferences for flower wrapping. While, on average, consumers express higher buying intentions and are willing to pay more for flowers with cellulose-based wrapping, a number of participants say they would only buy them if the price was the same as for flowers with conventional polypropylene wrapping. Koutsimanis et al. (Koutsimanis et al., 2012) used conjoint analysis to evaluate consumers preferences for packaging attributes for fresh food products, including material (petroleum versus bio-based plastic) and disposal method (compostable, recyclable, and non-recyclable). The research shows that USA-based consumers prefer bio-based over petroleum-based materials for packaging, but that there is no clear preference for any specific disposal method. As in other research, price was found to be the most important attribute affecting purchasing decisions. Chen et al. (2019) reported that consumers are willing to pay about 10% more for agricultural produce that is grown using biodegradable mulch film, and that the premium is higher after having received information about the benefits. These premiums are comparable to the ones found for other sustainable products and eco-labels. Orset et al. (2017) compared conventional PET plastic bottles (both recyclable and non-recyclable) with bio-based PLA (biodegradable, non-recyclable) and PEF (non-biodegradable, recyclable) water bottles alongside different communication messages, and found a significant premium associated with biodegradable plastic bottles. While communicating the biodegradable properties of PLA caused a drop in WTP for other types of plastic bottles, communicating the non-recyclable nature of PLA led to a lower WTP than for a recycled bottle made from

conventional PET (also see Section 6.4). This suggests that better knowledge of the implications of material properties can lead to different consumer preferences and that a plastic's recyclability may be of greater importance than its biodegradability.

While consumers have a clear preference for environmentally friendly packaging (Ketelsen et al., 2020), including those made from biodegradable plastic (Dilkes-Hofman et al., 2019b; Heidbreder et al., 2019), this preference does not necessarily translate into actual purchasing decisions. Also, direct expressions of WTP or willingness to buy are usually not sufficient. This divergence between what we say and what we do is a phenomenon that is known in different literatures as the value-action gap (e.g. Kollmuss & Agyeman, 2002), attitude-behaviour gap (Boulstridge & Carrigan, 2000) or intention-behaviour gap (Sniehotta, Scholz, & Schwarzer, 2005). As reported above, economists have long studied the difference between stated and revealed preferences (Koning, Filatova, & Bin, 2017). There are different explanations for the observed discrepancies, including a social desirability bias (i.e. the tendency to respond in a socially acceptable way), limited ecological validity of consumer studies (i.e. they provide data on formalised hypothetical and not 'real' purchase decisions), and behaviour being highly specific and context-dependent. Furthermore, consumption is not only determined by consumer preferences but also maintained by so-called 'systems of provision' through which products are produced and delivered to users (Fine, 2002). Products wanted by consumers often come pre-packaged, leaving them with little individual choice or agency regarding the sustainability of the packaging. Consumer behaviour relating to biodegradable plastics can therefore only be understood by situating it in the wider socio-economic and physical context in which consumption takes place.

Research reported in this Chapter shows that there may be demand for products that use fully bio-based and biodegradable materials, in line with consumer perceptions and preferences for these products. Introducing brands with bio-based attributes can result in enhanced purchase intentions, which can be attributed to more positive attitudes and emotions associated with those attributes (Reinders et al., 2017). As can be expected, green consumers express the strongest intentions to buy bioplastic products, followed by consumers with previous experience of bioplastics (Klein et al., 2020). However, given that these studies focused on intentions rather than actual purchase behaviour, they are subject to the same caveats as the reported WTP studies.

Behavioural aspects are important both in respect of the uptake and the disposal of biodegradable plastics. Gabriel and Menrad (2015) showed that most consumers will choose the standard plastic one, even when biodegradable and conventional plastic products are offered side-by-side with clear displays. In terms of the disposal of biodegradable plastic products, Taufik et al. (2020) found that, while compostable bio-based packaging is perceived the most positively in terms of its environmental benefits, consumers are more likely to dispose of it incorrectly. This suggests that there may be unintended behavioural consequences when more biodegradable plastic products are introduced (also see Section 6.3.2). It has to be noted that recycling behaviour is not purely an individual action reflecting a person's attitude towards the

environment (Van Birgelen et al., 2008), but that it is also determined by the available recycling infrastructure (also see Section 6.5.3). The wider environmental behaviour literature shows that attitudes are less predictive of behaviour with a supportive infrastructure that removes barriers to action (Guagnano et al., 1995). Introducing a recycling system that reduces the behavioural cost of recycling increased recycling rates the most among people with weaker pro-environmental attitudes (Best & Kneip, 2019). Whereas individuals with strong pro-environmental attitudes may put in a lot of effort irrespective of the available system, those with weaker pro-environmental attitudes may only perform a behaviour that has been made easy — showing the need to have appropriate recycling systems to support widespread behaviour change.

6.3 UNINTENDED CONSEQUENCES OF BIODEGRADABLE PLASTICS

Mismanagement and improper disposal of plastic has been a longstanding problem, leading to widespread plastic pollution (SAPEA, 2019). It has been estimated that only 9% of all plastics ever produced has been recycled and that around 80% has accumulated in landfill or the open environment (Geyer et al., 2017). Biodegradable plastics are frequently hailed as a partial solution to the plastic waste problem (Viera, Marques, Nazareth, Jimenez, & Castro, 2020; Voelker et al., 2019). However, the introduction of biodegradable plastics may produce unintended consequences. There could be three types of unintended consequences associated with biodegradable plastics: economic, behavioural and environmental.

6.3.1 Unintended economic consequences

Since prices for biodegradable plastics are generally higher than for conventional plastics (van den Oever et al., 2017), tax and subsidy instruments might be needed to promote their uptake. However, such interventions create economic side effects in other sectors that directly or indirectly use plastics. Escobar et al. (2018) estimate both direct and indirect economic effects of the diffusion of bio-based plastics supported by taxes on fossil-based plastics or subsidies for bio-based polymer production. In both scenarios, spillover effects may lead to the contraction of plastic-intensive sectors and an overall decrease in GDP as a result.

Rebound effects are a common unintended consequence of the introduction of more efficient technologies and have been widely observed for 'green' and sustainable innovations (Salvador et al., 2020; Zink & Geyer, 2017). The rebound effect, also known as Jevons' Paradox (Alcott, 2005), occurs when gains from efficiency savings are offset by a higher use of a resource. When consumers or other resource (e.g. energy) users become aware of the economic and environmental benefits of a new technology, market demand for the technology increases. This often causes cross-sectoral feedbacks in the economic system, with additional indirect changes in the use of the resource. Together, this may result in higher overall resource usage than before the introduction of the new technology. Material rebound effects can also be theorised if the introduction of new materials with a lower environmental impact leads

to increased consumption. The application of bioplastics in packaging could make consumers more careless about purchasing such products, due to reduced concerns about their impact on the environment (Font Vivanco et al., 2018; Girod & De Haan, 2009). For example, the use of biodegradable plastic materials may increase for short lifespan applications with a high likelihood of ending up in the open environment (e.g. wrappers or fireworks), making it more acceptable to use them and to discard them in the open environment (also see Section 6.3.2). There is no quantitative evidence showing material rebound effects following the introduction of biodegradable plastic products, most likely because of their early stage of adoption and relatively higher prices. Incomplete decomposition of commonly available biodegradable plastics and a risk of accumulation of residual plastics on agricultural land (Mari I et al., 2019), as well as possible reduced inhibition to litter biodegradable plastic materials (discussed in Section 6.3.2) and an understanding of how the economy may react (Dijkstra et al., 2020), suggest there is a risk of rebound effects where biodegradable plastics are introduced.

6.3.2 Unintended behavioural consequences

Possible unintended behavioural consequences of the introduction of biodegradable plastic materials include them ending up in the wrong waste or recycling stream and increased risk of their improper disposal through littering (Viera et al., 2020). There is evidence that unfamiliarity with biodegradable plastic materials and what to do with them post-consumption may lead to these unintended consequences (Sijtsema et al., 2016). As reported in the previous Chapter, Taufik et al. (2020) identified a paradox between the environmental appeal of bio-based plastic products and the way they are disposed of. Taufik et al. (2020) conducted a field experiment in which participants were shown a plastic bottle with labels on material provenance (i.e. whether the plastic is bio-based or not) and whether the bottle can be recycled or composted. While consumers were found to be highly positive about compostable bio-based plastic packaging because of their environmental benefits, they were less likely to dispose of them correctly. These findings are in line with Dilkes-Hoffman et al. (2019b), who showed that almost two-thirds of people would dispose of biodegradable plastic in the regular recycling bin rather than the green bin. Some biodegradable plastic may contaminate existing recycling streams, leading to low-quality recycled materials that may not be usable in the production of new products and thus interrupting the circular flow of materials and nutrients (Alaerts et al., 2018; see also Section 6.2.2 of this report).

There are other theoretical unintended behavioural consequences of consumers using biodegradable plastic applications in terms of negative behavioural spillover or moral licensing (Mazar & Zhong, 2010; Thomas et al., 2016; Truelove et al., 2014). Behavioural spillover refers to an observable causal effect that a change in one behaviour has on a different behaviour, which can both be positive or negative (Galizzi & Whitmarsh, 2019). Moral licensing is a specific form of behavioural spillover, whereby displaying a positive 'moral' behaviour can elicit more questionable behaviours, as people may feel they have established moral credentials that may license such behaviours. While there is evidence that moral licensing effects may occur under certain circumstances

(Blanken, Van de Ven, & Zeelenberg, 2015), there are currently no studies that have examined secondary behavioural effects in relation to biodegradable plastic. The evidence so far suggests that, where they exist, secondary behavioural effects are likely to be small (Thomas et al., 2016).

Another possible unintended behavioural consequence of the introduction of biodegradable plastic is an increased risk of littering. Standard LCA tends to focus on the use of energy and material resources, as well as the potential emissions that may occur over the lifetime of a product (e.g. Bisinella et al., 2018). This does not consider the risks of incorrect management and disposal of the products by end users, and the potential environmental damage that it may cause. Work by Civancik-Uslu et al. (2019) suggests that bags with a low environmental impact are more likely to be littered. This reflects that conventional single-use plastic bags tend to have a low environmental impact (Danish Environmental Protection Agency, 2018), but score high on the litter index of Civancik-Uslu et al. (2019) due to their low weight, value and functionality. In their assessment, Civancik-Uslu et al. assumed that the probability of biodegradable bags being abandoned in the environment is the same as conventional plastic bags at the same price level. It is not clear whether that assumption is justified. Other research shows that the general public find it more acceptable to drop biodegradable items than non-biodegradable items because it is thought they are less harmful for the environment (Zero Waste Scotland, 2012; Dilkes-Hofman et al., 2019b); and also report a greater likelihood of doing so themselves (Keep America Beautiful, 2009; Zero Waste Scotland, 2012). It is likely that this extends to biodegradable plastics in general. For example, Dilkes-Hoffman et al. (2019b) found that about one in ten of the Australian public would consider leaving biodegradable plastic food packaging at the beach. This indicates the potential of biodegradable plastic materials ending up in the open environment through littering (Haider et al., 2019). Confusion about and conflation of different types of innovative plastics suggests that there may be a risk of spillover effects to littering of other non-biodegradable plastics, in particular when they are labelled as 'bio-based' or as 'bioplastics' (also see Section 6.4).

6.3.3 Unintended environmental consequences

Using their new framework for assessing the socioeconomic, political and environmental impacts of bioeconomic transitions, Jander & Grundmann (2019) suggest that more ambitious obligations set by the German government are a key reason that the transition rate is higher for biofuels than for bioplastics. Similar obligations for bioplastics may advance the transition in that sector too. However, alongside others (e.g. Philp, et al., 2013), they emphasise that considered policy decisions should take into account overall environmental impacts, rather than promoting a blanket substitution of fossil fuel with bio-based sources. There may be further unintended environmental consequences as a result of the proliferation of biodegradable plastics in the economy and society. Section 6.3.1 already reported potential material rebound effects whereby innovative materials with lower environmental impacts may increase demand for such materials, due to reduced concerns about their environmental impacts (Font Vivanco et al., 2018). There may further be economy-wide unintended

environmental consequences. Escobar et al. (2018) link a computable general equilibrium (CGE) model with a biophysical land use model to project the impacts of increasing the share of bio-based plastics in the economy. By connecting different sectors of the global economy through production and consumption linkages with land use changes, the article traces direct and indirect impacts of bioplastics diffusion policies on greenhouse gas emissions and land use. The study identifies several immediate effects of the bioplastics expansion mediated through markets, including an increase of agricultural land rents impacting land for crops and livestock, and a decrease of forested land. Spillover effects mediated by secondary land use change occur globally, including expansion of forested land. The authors note the importance of performing similar assessments that couple economic and biophysical aspects of the diffusion of biodegradable plastics, but had to confine their study to bio-based plastics only because of data limitations. Several LCA studies report the environmental footprint of biodegradable and bio-based plastics as compared to other types of fossil-based plastic, but this is outside the scope of this Chapter.

Bio-based plastics that use first-generation feedstock (i.e. crops suitable for human or animal consumption) do not necessarily present a more sustainable alternative to fossil-based plastics (Mitchel, 2008; Philp et al., 2013; Von Lampe, 2008), particularly when the environmental impacts of land use changes are accounted for (Gironi & Piemonte, 2010). While the research is not specific to biodegradable plastics it is pertinent, given that the biodegradable market is dominated by producers using conventional feedstock. The literature calls for policy efforts to promote the use of 'carbon-poor lands' and second-generation feedstock such as non-food crops (wood, willow, straw) or, ideally, 'third-generation' waste products (e.g. vegetable oil, coffee grounds), which are proven to provide both environmental and economic benefits (e.g. Fahim, Chbib, & Mahmoud, 2019; Prata et al., 2019). Yeh et al. (2015) further draw attention to the potential risks associated with the use of first-generation feedstock for biodegradable plastics production, relating to the use of genetically modified crops and social acceptance.

Following the overview of environmental consequences of biodegradable mulch films on agricultural fields, Mari et al. (2019) note that not all materials that are labelled as biodegradable degrade immediately or completely in soil. Yet, farmers could be expected to till most or all of biodegradable mulch film into soil. The interaction of this habitual behaviour and environmental externalities could potentially lead to the unforeseen accumulation of undesired material in soils over time, leading to their degradation. If a proportion does not degrade at all, the non-degraded material may cause a decrease in agricultural yield in a similar way as conventional plastics (Brodhagen et al., 2017; Miles et al., 2017). A study conducted by Ghimire et al (2020), however, suggests that biodegradable mulch film may not accumulate to a significant level in the soil, even after repeated applications.

6.4 Labelling of biodegradable plastics

In most cases, there are no physical and/or sensory attributes that allow consumers to distinguish products made from bio-based or biodegradable plastic from those made from conventional fossil-based plastic (van den Oever et al., 2017). Labelling is therefore important to enable consumers to make informed decisions relating to the nature, provenance and impacts of materials, and how they should be disposed of (Horne, 2009; Shahrasbi, 2018). Consumers would like more information and clarity around bio-based and biodegradable plastics (Kainz, 2016). Bio-based plastics generally have a lower environmental impact in terms of carbon emissions as compared to conventional fossil-based plastics, and consumers may want this information to enable them to make more sustainable purchasing choices. However, information about the provenance of the bio-based origin of plastic holds little meaning in terms of a product's end-of-life functionality and thus how the material should be disposed of. In contrast, the terms 'biodegradable' and 'compostable' specifically refer to the post-consumption properties of plastic. This has implications for the labelling of products. Ultimately, consumers need to know about biodegradability so that they can make effective decisions about how to sort their waste. The following section outlines key challenges surrounding the efficacy of current labelling of biodegradable plastics, how these might be overcome, and what barriers may remain even with the most effective labelling.

6.4.1 Current labelling

As shown in Chapter 4, a wide array of labelling surrounds bio-based materials, some relating to third-party certification based on regulated standards. The DIN Certco certification for bio-based materials pertains to the EU standard EN 16640 (2015), and the USDA and Vinçotte certifications relate to the ASTM standard D6866 (two different methods for calculating a plastic's bio-based carbon content). However, many other labels and first- or second-party certifications have been developed that can be confusing and even deceptive (van den Oever et al., 2017). Labelling a product as 'bio-based' can function as a marketing tool, driving sustainable purchasing or at least a higher willingness to pay (Kainz, 2016). Petersen and Brockhaus (Petersen & Brockhaus, 2017) found that it is possible to influence consumers' perception of a product's sustainability and quality by clearly communicating the use of sustainable materials, such as recycled and bio-based plastics, through labelling. Labels informing consumers about the origin of a product can serve the wider purpose of driving consumer awareness and understanding of sustainability issues (Gutierrez & Thornton, 2014). However, as highlighted above, labelling relating to material provenance does not convey information on how products should be managed and discarded at the end of their functional lives. There is a dearth of literature on consumer understanding and responses to the labelling of biodegradable plastic materials, making it difficult to assess how effective they are in directing appropriate post-consumption behaviour.

There is significant ambiguity in relation to the labelling of biodegradable plastics specifically, with a range of unregulated voluntary certification and labelling schemes

(Nazareth et al., 2019). International standards and corresponding accredited third-party certification schemes do exist but tend to be specific to biodegradability in controlled composting conditions. Industrial compostability is indicated in Europe by the DIN Certco 'Seedling' logo, and the Vinçotte 'OK compost' logos, which demonstrate that a product meets the standard EN 13432 (DIN EN 13432) for green bin disposal. While Vinçotte have developed more specific certification labels (OK compost HOME, OK biodegradable SOIL, OK biodegradable WATER and OK biodegradable MARINE), these are not widely used or recognised, and are based on a range of fragmented standards. Notably, the 'OK biodegradable WATER certification' claiming to "guarantee biodegradation in a natural freshwater environment" is based on two international standards specific to biodegradation in sludge and waste-water, which contribute to EN 14987 — the European standard for plastic disposability in waste-water treatment plants (Defra, 2015). There is, however, limited evidence regarding public understanding of labelling of biodegradable plastic.

Many consumers are aware of the terms 'biodegradable', 'compostable' and 'recyclable', but they rarely have detailed knowledge of their technical definitions, and what that means in terms of disposal (D'Souza et al., 2006). Consumers use the terms biodegradability and compostability interchangeably (Kainz, Zapilko, Decker, & Menrad, 2013; WRAP, 2007). Compostability itself is an ambiguous term, which people may understand as being suitable for home composting. This may contribute to difficulties in differentiating between materials that biodegrade in open and controlled environments, and conflation of the end-of-life characteristics of biodegradability, compostability and recyclability more generally (Rumm et al., 2013). Confusion around what constitutes biodegradability and a lack of regulated standards and certification relating to open environment biodegradability free up space for unregulated first- and second-party certification, 'greenwashing' and false biodegradability claims. For example, Nazareth et al. (Nazareth et al., 2019) found that four out of six product samples from US, Brazilian and Canadian markets that claimed 100% biodegradability showed no evidence of degradation after 180 days' immersion in seawater. False biodegradability claims were even found for polyethylene plastic bags, highlighting the potential scope of consumer deception as well as the considerable environmental risks associated with it.

6.4.2 What labelling is needed

Shahrasbi (2018) highlights the tension between the need to prevent deceptive advertising and the need to show scientific achievement in creating eco-friendly products. While every material degrades over long enough periods, biodegradability is usually understood as a product or material completely decomposing into elements found in nature within a reasonably short period of time after disposal (Federal Trade Commission, 2012). The term 'biodegradable' refers to a specific end-of-life property of a relatively small proportion of bio-based plastics on the market (Philp et al., 2013), with an even smaller proportion degrading in the open environment (Yeh et al., 2015). While acknowledging difficulties relating to defining plastic biodegradability outside controlled conditions, Shahrasbi (2018) calls for degradability claims to be qualified and

communicated 'clearly and prominently' to the extent necessary to avoid deception. This would require scientific testing conducted in an environment that simulates where waste products are customarily disposed and/or likely to end up. Across the research, regulated standards and associated certification are highlighted as crucial (Horne, 2009; Karan et al., 2019; Nazareth et al., 2019; Peuckert & Quitzow, 2017; Shahrasbi, 2018; Yeh et al., 2015). To be trustworthy and consistent, certification should be carried out by accredited third-party bodies in relation to international standards (Philp et al., 2013). It is also emphasised that, given the ambiguity surrounding terminology, any labelling relating specifically to plastics that biodegrade in the open environment should seek to improve clarity by clearly communicating what environments are included and excluded. Materials designed for industrial composting should be explicitly labelled as such (e.g. Nazareth et al., 2019; Shahrasbi, 2018).

The broader literature on labelling suggests that consumers have a preference for simple, standardised and colourful labels and logos, as they attract attention and enable clear decision-making (Horne, 2009; Rumm et al., 2013; WRAP, 2007). Regulated or government-sponsored labelling is favoured (Horne, 2009), and label recognition has been found to be high in countries that have a long tradition of uniformly labelled food (Lindh et al., 2016). Gutierrez & Thornton (2014) highlight the need to strike a balance between labels providing enough detail for consumers to understand them, but not too much, to avoid overwhelming consumers. Notably, abstract or ambiguous terms such as 'bio-based' or 'biodegradable' should be avoided (D'Souza et al., 2006; Rumm, 2016; Rumm et al., 2013). While disposability is a key consideration in this context, studies by Scherer et al. (2017, 2018a, 2018b) found that products displaying information about the national and regional origins of raw materials are preferred by consumers, indicating the potential value of such information in promoting the purchase of biodegradable plastics.

6.4.3 Limitations of labelling

It is assumed that if consumers are provided with relevant and easily accessible information about the nature of a product and its disposability criteria, they will adapt their pre-consumption and post-consumption behaviours accordingly, at least those who consider sustainability important (Horne, 2009). However, labels may not always work as intended for a multitude of reasons. As outlined in Section 6.2, awareness and intent do not always translate into action. Effective waste separation and processing is a prerequisite for the environmental benefits of biodegradable plastics to be realised, to ensure that they do not mistakenly end up in the open environment, landfill or inappropriate recycling streams. There are a range of factors shaping disposal behaviour that even the clearest labelling cannot fully address. For example, a key barrier to effective waste separation among consumers is the sheer quantity of materials and labels that exist. The proliferation of labels around biodegradable, bio-based and 'eco' products more generally has been found to cause confusion, information overload and a consequent lack of understanding or corresponding behavioural change (Gadema & Oglethorpe, 2011; Horne 2009; Janßen & Langen, 2017; Youssef & Abderrazak, 2009; Zhao et al., 2018). In Germany, there are already 400 existing labels for food and fast-

moving consumer goods (FMCG; Verbraucherkommission Baden-Württemberg, 2011). Adding new labels and certifications can result in further confusion and poses a risk that consumers will start ignoring labelling altogether.

In their research on packaging labels more broadly, Buelow et al. (2010) found that significant confusion around complex labelling leads to poor consumer understanding, care, and decision making. The notion of 'care' and its relation to feelings of overwhelm and confusion has been highlighted in several other studies. At a time when kerbside collection of plastics was still in its infancy in Britain, WRAP (WRAP, 2007) found that a majority of British consumers never looked at packaging labels for disposal information. Similarly, in a study using eye-tracking technology, an overwhelming majority of participants did not notice a sustainability ratings logo at all (Boz et al., 2020). Even when consumers pay attention to labels, it is not guaranteed that they will be able to effectively interpret what they mean in terms of sustainability or disposal criteria. Heightened uncertainties and confusion surrounding new materials such as biodegradable plastics are likely to compound issues relating to a lack of background understanding. Expanding the number of different materials may lead to complications around waste separation and collection.

The impact of consumer confusion on waste separation behaviour is modified by factors relating to the broader waste infrastructure. Literature on existing recycling behaviour suggests that the material landscape is central in shaping and enabling behaviours. A randomised trial examining the effectiveness of a range of messages relating to depot and community recycling found that, while specific instructions were the most impactful form of messaging, the degree to which this influenced recycling behaviour was moderated by a range of additional factors such as proximity of facilities and car access (Rhodes et al., 2014). This is in line with other research showing that infrastructural factors, such as collection frequency and depot proximity (McDonald & Ball, 1998; Struk, 2017), as well as clearly designed bins in public settings (Duffy & Verges, 2009), enable effective waste separation behaviour. In addition, material influences such as packaging characteristics have been shown to determine disposal behaviour alongside information (Williams, Wikström, Wetter-Edman, & Kristensson, 2018). Finally, an enabling material infrastructure has been found not only to potentially moderate the behavioural consequences of consumer attitudes, but also to shape attitudes themselves. As highlighted by Van Birgelen et al. (Van Birgelen et al., 2008), consumer inaction can stem from a lack of belief that individual environmental actions will have an impact. Alongside regulated labelling and certification, an effective waste infrastructure can indicate to consumers that government and industry are taking action, thus increasing confidence that individual efforts will be worthwhile (Barnosky, Delmas, & Huysentruyt, 2019). This suggests that, without an enabling material infrastructure and associated government and industry action that support the recycling and separation of materials by consumers, even the most effective labelling is unlikely to be sufficient to ensure effective waste disposal.

In sum, while there is strong public support and even demand for clear environmental labelling, it is not known to what extent labels are effective in changing consumers'

purchase or disposal behaviour. Labels that refer to product materials or characteristics (e.g. whether they are recyclable or biodegradable) are only relevant if they influence post-consumption actions, and this influence is moderated by a range of broader value and infrastructural systems. The use of labels must be positioned within a wider enabling landscape, involving educational, economic, regulatory and infrastructural strategies at a policy level (Horne, 2009).

The main applications of biodegradable plastics are currently in packaging and other consumer products (e.g. food waste caddy liners, wet wipes), but they are also used along the product supply chains and in other economic sectors such as agriculture and fishing (Kaeb, Aeschelmann, Dammer, & Carus, 2016). While appropriate labelling for disposal is equally important for other commercial and non-commercial users, there is no dedicated literature on the use and effectiveness of labelling beyond those intended for consumers. For example, there is great interest in biodegradable plastic materials from the agricultural sector (see Section 6.2.3), yet it is not clear whether farmers are aware that some products labelled as biodegradable may only degrade fully under conditions of industrial composting (Brodhagen et al., 2017) and that their usage may lead to unintended environmental consequences (see Section 6.3). Given that biodegradable mulch films are specifically designed to be tilled into soils, there is an additional need for the labelling to clearly communicate the speed and conditions under which the materials degrade so that farmers are able to make informed decisions about how to manage the materials. Farmers have a direct economic interest in maintaining the health of their soil and can be expected to pay attention to labelling and instructions communicating appropriate usage (see Section 6.5.1)., however, no empirical evidence is available in this area.

6.5 EVIDENCE-BASED POLICY OPTIONS AND REGULATION

Biodegradable plastics provide opportunities to move economies from a linear to a circular model with higher resource efficiency, if waste products re-enter the economy through a biological cycle (Confente, Scarpi, & Russo, 2020; Ellen MacArthur Foundation, 2015) but also pose risks if they are used inappropriately as an alternative to poor waste management disposal practices (see e.g. Section 6.3). Different policy options are available to promote the appropriate use and management of materials, in line with circular economy principles (SAPEA, 2019). The following section will outline research examining the potential of different policy options to achieve awareness and behavioural change, relating to both increasing the appropriate uptake and the appropriate management of biodegradable plastics, and to diminishing other unintended consequences. This is crucial, as the positive impacts of adopting biodegradable plastics are heavily dependent on the specifics of how they are produced, used and disposed of (Song et al., 2009). Policies to promote sustainability are traditionally classified into information, market-based, and regulatory policies and can be applied at the production, consumption or disposal stage of the circular economy (Alpizar et al., 2020). The literature further suggests that, despite increasing emphasis on information policies in achieving sustainability goals (Bavel et al., 2013, Hartley et al., 2018b; Leggett, 2014; Ogunola et al., 2017), more integrated approaches

are required to ensure the appropriate uptake and management of plastics that biodegrade in the open environment (e.g. Ren, 2003; Jander & Grundmann, 2019).

6.5.1 Information policies

As highlighted in the previous Chapters, while public attitudes are generally positive (e.g. Boz et al., 2020; Dilkes-Hoffman et al., 2019b), there is little understanding around either how biodegradable plastics are produced or how to dispose of them appropriately (e.g. Lynch et al., 2017). The research outlined in Section 6.4 explored the use of labelling in communicating this information, revealing key barriers relating to consumers' ability to interpret and trust the information itself (e.g. Buelow et al., 2010; WRAP, 2007; Horne, 2009), and broader influencing factors such as existing waste infrastructure (Williams et al., 2018). While research suggests that information policies beyond labelling, such as education, can be effective in raising awareness of sustainability issues, they do not necessarily lead to behavioural change (cf. SAPEA, 2019).

The gap between awareness and action can be reduced by paying specific attention to both the content and method of communication. Rather than simply raising awareness, education campaigns increasingly seek to promote an understanding of how to take effective action. In their assessment of how two European educational initiatives relating to marine litter impacted on student behaviour, (Hartley et al., 2018a) found participatory pedagogies can be used to promote ownership and empower action. The research highlights the potential of online training and 'new media' approaches in delivering education campaigns. Schiffer et al. (2020) outline the applicability of a similar 'systems thinking approach' in a higher education context. A growing body of literature emphasises the potential of such pedagogies as a long-term strategy to address sustainability goals, by promoting active citizenship and holistic understanding (e.g. Capra & Luisi, 2014; Goleman et al., 2012).

Other information policy approaches to promote proper use and disposal of plastics in general include nudging (setting default to 'no plastic' altogether), social comparison, appeal to social norms, and targeted individual communication campaigns (Alpizar et al., 2020). Yet, as Sections 6.2 and 6.4 have highlighted, structural factors such as higher prices and access to disposal facilities limit behavioural change relating to biodegradable plastics. These structural barriers cannot be addressed by information policies alone, and potentially could produce counterproductive outcomes (e.g. Lewis & Potter, 2010). In light of the barriers posed by the price of biodegradable plastics, lack of clear standards surrounding biodegradability calls for market-based and regulatory policy measures, as well as policies relating to waste infrastructure in general (e.g. Jander & Grundmann, 2019; Karan et al., 2019; Prata et al., 2019). As indicated throughout the following sections, however, education can be effective in combination with structural policy approaches.

6.5.2 Market-based policies

Research shows that higher costs associated with biodegradable plastics at least partly contribute to the gap between consumer attitudes and behaviour. Even among those who can and are willing to pay a premium, price may inhibit behavioural change (e.g. Van Birgelen et al., 2008). This highlights the role of market-based policies, such as subsidies or taxes, to promote the market penetration and uptake of biodegradable plastics (e.g. Dijkstra et al., 2020; Friedrich, 2020; Jander & Grundmann, 2019; Mari I et al., 2019; Velandia et al., 2020b). Economic incentives are also suggested to promote effective disposal behaviour, e.g. through deposit return and 'pay-as-you-throw' schemes. The following Chapters assess the effectiveness of a range of different financial instruments in the areas of agriculture, trade and retail, consumption, and production.

Agriculture. Addressing economic barriers to the uptake of biodegradable plastics is particularly pertinent in the agricultural sector. Research in this area concludes that the government has a role in making biodegradable plastics a financially viable alternative to fossil-based plastics, in light of both price sensitivity and poorly understood broader economic risks. For example, in their evaluation of the impact on profits associated with a transition from polyethene to biodegradable plastic films in Tennessee pumpkin production, Velandia et al. (2020a) found key influencing factors to be the cost of biodegradable mulch films, cost of labour, and reductions in pumpkin sale price. Price movements are central in determining whether the impact on profits is positive or negative. Based on market prices at the time of study, transitioning to biodegradable mulch films was found to have a positive impact, but negative if a price discount was accounted for. The research concludes that lower price points are needed for a transition to biodegradable plastic mulch films. Similarly, Mari et al. (2019) found that, in the context of open-air pepper production in Spain, farmers were reluctant to pay more for biodegradable film as an alternative to the commonly-used black polyethene. Their economic evaluation based on the data from a field experiment found that, for three out of four biodegradable plastics, subsidy rates of 38%-50% would be required to make them economically-viable alternatives to polyethene, which is higher than current subsidy levels.

De Lucia and Pazienza (2019) elicited Italian farmers' preferences for particular policy instruments for incentivising effective plastic waste management in agriculture through a quantitative survey. The interviewed farmers identified tax credits as the most effective incentive, followed by an extended producer responsibility (EPR) scheme and subsidies. These preferences were primarily due to tax credits having lower transaction costs and administrative processing times than the other measures. Yet, as the authors note, a tax credit instrument may produce unintended consequences such as a rebound effect (see Section 6.3). Preference for different policy tools was found to vary for different kinds of plastic waste, with tax-credit mechanisms favoured for plastic bags and fertiliser/chemical bottles associated with cereal crops, but subsidies for plastic films and packaging. Finally, proximity to disposal site and horticulture production were found to increase the likelihood of adopting the

EPR policy. The analysis did, however, not differentiate between conventional and biodegradable plastic waste management.

Trade and retail. Within the trade and retail sectors, using biodegradable or bio-based plastics as part of Corporate Social Responsibility schemes, or a shift towards circular business models, can be a way of gaining competitive advantage through 'eco-credentials' (Finlayson, 2015; Lim & Arumugam, 2019; Salvador et al., 2020). However, Dijkstra et al. (2020) and Friedrich (2020) emphasise that these benefits do not always outweigh the costs. Both studies found higher comparative costs of bio-based plastics to be restrictive, even within economies and industries with more scope for price flexibility. They highlight a need for government financial and regulatory mechanisms to encourage the use of more sustainable plastic alternatives, rather than self-regulation by industry, where costs are absorbed or passed on to consumers. Friedrich (Friedrich, 2020) found support for taxing fossil-based plastic packaging as a means to increase the uptake of bio-based plastic packaging. Participants favoured a Pigovian approach, where the plastic's social and environmental costs determine the rate of the tax. This approach was also found to be effective in the energy industry, making additional costs difficult to pass on and making more sustainable alternatives economically favourable (Friedrich, 2020).

While tax interventions are more likely to meet political or industry resistance (Ren, 2003), EPR is discussed as a potentially more problematic mechanism for internalising a product's environmental costs, given potential issues arising from the transfer of costs from inefficient waste management operations to industry (Orset et al., 2017). In a study on the implementation of EPR in Belgium and Portugal, Marques et al. (2014) found that the transfer of costs depends on whether diverting packaging waste from other operations is accounted for as a cost or benefit for local authorities. Challenges around the implementation of EPR are also highlighted by Ren (2003), particularly where market and legal structures are 'less developed' and information on the externalities of different products is limited. Ren suggests tax reductions to be applied alongside biodegradability standards and certification, and the development of public procurement policies favouring biodegradable plastics. Peuckert & Quitzow (2017) further identify public procurement as an important mechanism for promoting the market penetration of bio-based plastics more generally and a lack of regulatory standards as a key barrier to their inclusion in purchasing schemes.

Consumption. While industry and producer responsibility are critical in ensuring effective disposal of plastics, consumer behaviour is also important (see Section 6.3.3). Research shows that financial incentives can help to address some of the consumer barriers. Among measures found to be effective in increasing waste separation are deposit-refund schemes, 'pay-as-you-throw' schemes, and subsidies for home composting equipment (Kurisu & Bortoleto, 2011; Prata et al., 2019; Struk, 2017). In relation to purchasing behaviours, Orset et al. (2017) explored French consumers' responses to different policies relating to plastic water bottles. Subsidies and taxation promoting the use of recyclable and biodegradable plastics were found to be more effective in establishing behaviour change than information policies.

Relating to bio-based plastics more generally, Escobar et. al (2018) analysed the environmental and economic impacts of two market-based policies stimulating consumer uptake: tax on fossil-based plastic and subsidies on bioplastics. They assessed the global and regional consequences of reaching 5% substitution of conventional plastics with bioplastics and found that, in terms of environmental impacts, both tax and subsidy policies reduce demand for fossil fuels but create spillover effects in terms of food prices and land use changes. In contrast to other studies omitting land use spillovers (Escobar et al., 2018; Spierling et al., 2018), Escobar et. al (2018) conclude that biopolymers do not necessarily promote sustainability and stress the need to focus on enhancing the biodegradability of plastics and on promoting new technologies that do not compete for agricultural land. This has important implications for any market-based related to the development and production of plastics that biodegrade in the open environment.

Production. Alongside the literature calling for market-based policies to promote the production of biodegradable plastics, there is a body of literature highlighting a need for careful attention to what kind of production is incentivised (Jander & Grundmann, 2019; Philp et al., 2013). The OECD (2013) highlights a global lack of specific policy in the bioplastics sector, to which most biodegradable plastic production belongs. The OECD report calls for policy instruments across sectors, from production to consumption, including subsidies, taxes and quotas that could provide sector-specific indicative or binding targets. Using their new framework for assessing the socioeconomic, political and environmental impacts of bioeconomic transitions, Jander and Grundmann (2019) suggest that more ambitious obligations set by the government relating to biofuels are a key reason behind a lower transition rate in the bioplastics sector in Germany. However, alongside others (e.g. Philp et al., 2013), they argue that considered policy decisions should take into account overall environmental impacts, rather than promoting a blanket substitution of fossil fuel with bio-based sources. Bioeconomy transition indicators such as the Substitution Share Indicator (SSI) are highlighted as important in supporting such policy decisions, by making implications for sustainability clearer (Jander & Grundmann, 2019).

6.5.3 Regulatory policies

Single-use plastic bans and charges. The previous section has highlighted a need for consideration of the specific nature of bio-based or biodegradable plastics incentivised by market-based policies. Research suggests a need for similar consideration around regulatory policies involving bans and charges on single-use plastics, implemented by various governments in support of a transition towards more sustainable alternatives (Clap & Swanston, 2009; Heidbreder et al., 2019; Nielsen, Holmberg, & Stripple, 2019). Many countries have reported positive impacts resulting from bans and charges on single-use plastics (Convery et al., 2007; Poortinga et al., 2013; Thomas et al., 2016). Such initiatives have not only shown to be highly effective in changing behaviour, but also in raising awareness (Pacatang, 2020; Thomas et al., 2016). However, bans and charges on single-use, fossil-based plastics can lead to negative unintended consequences (Nielsen et al., 2019), not

least because of consumer misunderstanding. For example, Synthia and Kabir (2015) reported that Bangladesh's plastic bag ban led to the emergence of new bag varieties in Dhaka. They found that 98% of respondents considered (mistakenly) that new bag varieties were biodegradable or more 'eco-friendly' than those that were banned. Viera et al. (2020) highlight how such outcomes may be exacerbated by a lack of standards and regulation relating to the biodegradability of plastics. Many of the biodegradability claims of several 'sustainable' straw options that were offered as alternatives in response to single-use plastic bans appeared to be false. Viera et al (2020) suggest that such greenwashing misleads consumers, which may lead to inappropriate purchase and disposal decisions (also see Section 6.4). So while there is an important role for both market-based and regulatory policies in promoting the production, consumption and disposal of biodegradable plastics, it is important to remain mindful of potential unintended consequences relating to a lack of specificity and clear standards surrounding the alternatives that are incentivised. To reduce the potential for unintended outcomes, economic and regulatory strategies need to be developed in concert with clear, regulated standards and certification frameworks (e.g. Karan et al., 2019; Nazareth et al., 2019).

Regulatory standards. Section 6.4 highlighted confusion around the current labelling and certification of biodegradable plastics as a key barrier to behavioural change. Section 6.5 has so far discussed the potential limitations of information, market-based and regulatory policies in the absence of clear standards around both what plastics can be considered biodegradable (e.g. Nazareth et al., 2019), and how they should be used and disposed of accordingly (e.g. Voelker et al., 2019). There is widespread agreement in the literature that there is a need for both regulated standards and the authorisation of specific third-party certification bodies to provide assurance that products meet specific standards (e.g. Horne, 2009; Karan et al., 2019; Nazareth et al., 2019; Peuckert & Quitzow, 2017; Shahrasbi, 2018; Song et al., 2009; Voelker et al., 2019; Yeh et al., 2015). Given the global scope of the biodegradable plastics market, it is suggested that these standards should be international, with certification bodies authorised by parastatal institutions (Philp et al., 2013). As outlined in Section 6.4 and discussed at length in Chapter 4, at present there is a legislated EU standard for anaerobic compostability (EN 13432), providing criteria for the DIN Certco 'Seedling' and the Vincotte 'OK compostable' certifications. However, there are no current European standards specific to plastic biodegradability in open environments, or to home-compostable plastics, other than those relating to the biodegradability of agricultural mulch films (EN 17033, 2018), and of plastics in wastewater treatment plants (EN 14987).

While the scientific complexity of defining biodegradability in open environments may pose difficulties in the creation of legislated standards and certification schemes, the risks of current ambiguity and lack of regulation is apparent. As emphasised in Section 6.4.2, any standards developed in relation to biodegradable plastics suitable for home composting or open environments will require terminology (and accredited certification and labelling schemes) that clearly differentiate them from existing standards for anaerobic compostability to ensure that materials do not result in the

wrong waste streams (Song et al., 2009, Ogunola et al., 2017, Prata et al., 2019, Philp et al., 2013). Effective waste separation is not only a product of clear standards and messaging, but a central aspect of an enabling waste infrastructure more broadly.

6.5.4 Aligning policies and waste infrastructure

Plastics that biodegrade in the open environment or are home-compostable aim, by design, to circumvent existing waste infrastructures. This necessitates their separation from recycling or landfill waste streams, and differentiation from biodegradable plastics that require industrial composting (Voelker et al., 2019). Meeting these specific disposal criteria is fundamental to biodegradable plastics' successful contribution to a circular economy. As such, it is crucial to develop policies and standards specific to biodegradable plastics that work alongside an effective waste management infrastructure (Changwichan & Gheewala, 2020; Jander & Grundmann, 2019; Miranda, Silva, & Pereira, 2020; Prata et al., 2019; Ren, 2003; Rujnic-Sokele & Pilipovic, 2017; Shen et al., 2020; Ogunola et al., 2017). An integrated, systemic approach is needed to avoid increasing the complexity and confusion surrounding existing waste management systems (Changwichan & Gheewala, 2020; Jander & Grundmann, 2019; Prata et al., 2019; Ren, 2003; Shen et al., 2020).

Promoting the use of biodegradable plastics in appropriate applications, alongside information and incentives for correct disposal and the development of specific waste collection and treatment infrastructure, are recommended only as long-term measures, following material improvements and incentive schemes relating to the existing waste infrastructure (Prata et al., 2019). This resonates with wider research emphasising that plastics that biodegrade in the open environment are not 'the' solution to plastic pollution but may present one strand within broader efforts to tackle it (e.g. Shen et al., 2020). Their potential rests in only a limited number of single-use or 'short lifespan' applications, such as food packaging and agricultural products where there is already a high risk of them ending up in the open environment (Prata et al., 2019; Rujnic-Sokele & Pilipovic, 2017; Song et al., 2009). The research covered above suggests that integrated policy approaches that use the principles of a circular economy can contribute to their successful introduction and management, and minimise economic and environmental risks. It is emphasised that, in such an evolving, high-tech field, policy should remain flexible to enable effective response to emerging unknowns, and to avoid posing barriers to development and innovation (Yeh et al., 2015, Changwichan & Gheewala, 2020, Philp et al., 2013).

6.6 WHAT IS NOT KNOWN

The evidence presented in this Chapter shows that there is widespread confusion, and not only among consumers, about what plastic materials can be considered biodegradable, what their degradation pathways are, and how they should be handled post-consumption. There are a range of unknowns in the social and behavioural sciences literature on the biodegradability of plastics in the open environment.

While the potential for unintended economic, environmental and behavioural consequences has been established, no quantitative studies on economic and material rebound effects (and other unintended consequences) exist due to low market penetration rates. That means that it is currently not known whether such unintended consequences will be realised as biodegradable plastics become economically efficient.

It is also not known to what extent unintended consequences can be avoided by information campaigns and labelling. While labelling and certification are essential to support consumer decision making, it is not clear to what extent it will help consumers to adapt their pre-consumption and post-consumption behaviour. In particular, it is not known to what extent further labelling will confuse rather than inform consumers. More research is needed to explore whether or not the proliferation of different materials and labels may cause confusion and information overload in consumers, and could undermine the understanding and behavioural changes it is supposed to support.

One of the key challenges is to ensure that plastics that only biodegrade in industrial facilities do not end up in the open environment. This requires evidence of appropriate disposal and composting facilities that are needed alongside policies for consumer awareness and behaviour, to facilitate a circular economy in which resources are retained and reused.

There is a dearth of academic literature on the use of biodegradable plastics by users other than consumers and farmers. As a consequence, there is no robust evidence on the potential of biodegradable plastics applications in other economic sectors that end up in the open environment. Similarly, little is known about the use and movement of biodegradable plastics along product supply chains and business-to-business markets. It is likely that there are similar issues relating to user confusion, lack of standardised labelling, and suboptimal waste management infrastructures that may lead to the mismanagement of biodegradable plastic materials. However, dedicated research is needed as findings from consumer studies cannot be generalised to these different sectors and markets.

Furthermore, most research to date has been from Europe and North America, with only a few studies conducted in other parts of the world, in particular lower- and middle-income countries. Results from the social and behavioural sciences on consumer perceptions and behaviour are highly context-dependent. The use of bioplastics is unlikely to be restricted to Western parts of the world, and it is currently not known what benefits and risks are associated with their use in countries with less developed recycling and waste separation systems, and the role of public perceptions and behaviour therein.

Finally, little is known about appropriate and inappropriate applications of biodegradable plastics, how consumers (and other users) respond to these different applications, and the likelihood of intentional and unintentional release in the open environment. In particular, more social and behavioural research is needed on non-

consumer applications in other economic sectors, such as agriculture and fisheries, and markets along the plastic supply chain (e.g. business-to-business).

Key messages

- Consumer perceptions of bio-based and biodegradable plastics are positive, as informed by positive environmental associations with the terminology and expected end-of-use disposal options.

- Current technical terminology relating to 'bio-based' and 'biodegradable' plastics is incongruent with public understanding of the different terms. There is widespread consumer confusion about what plastic materials can be considered biodegradable, their degradation pathways in different environments, and how they should be handled post-consumption. In particular, the difference between biodegradable and (home) compostable plastic materials is not clear to many consumers. To avoid consumer confusion and deception, the use of the term 'biodegradable' should not be used for materials that do not degrade in the environment in which they are likely to end up.

- Due to positive farmer perceptions and the potential benefits of biodegradable plastics in crop protection, there is potential for widespread use of biodegradable plastics in agriculture, with a risk of the materials ending up in the open environment. There is, however, inconclusive evidence regarding the risks of accumulation of biodegradable plastic materials in the field.

- While consumers express a willingness to pay a small premium for biodegradable plastics, widespread uptake is likely only with competitive prices and the proliferation of consumer applications.

- Consumer confusion about proper disposal routes and the degradation properties of biodegradable plastics may cause unintended consequences, including biodegradable materials ending up in the wrong recycling stream, improper composting and an increased risk of materials ending up in the open environment through littering.

- A lack of clear standardised labelling not only has the potential to confuse but also to mislead. Given consumer confusion about the nature and provenance, degradation pathways and correct disposal of biodegradable plastics, information policies, such as educational campaigns and labelling, are essential to transition successfully to a circular bioeconomy. Labelling and certification are unlikely to be sufficient to fully change consumer behaviour in support of a circular bioeconomy.

- Market-based policies (including taxes, subsidies and Extended Producer Responsibility) and regulations (bans, standards, and certification) are also needed to change the behaviour of actors across different economic sectors and contexts. However, the use of market-based instruments to promote the production of bio-based and biodegradable plastics may have negative economy-wide environmental and economic consequences as a result of changes in land-use and cross-sectoral economic side effects.

Policies and standards specific to biodegradable plastics need to be considered to work alongside an effective waste management infrastructure, in order to avoid

biodegradable plastic materials being mismanaged and them ending up and accumulating in the open environment.

Chapter 7: Conclusions and Policy Options

7.1. CONCLUSIONS

Plastics have transformed our everyday lives and yet, at the same time, discarded plastic is causing enormous negative impacts on the environment, human and animal health, as well as incurring high economic costs for society. All forecasts indicate that the production of plastic will continue to increase, with 'hotspots' of plastic pollution in regions of the world that are least able to deal with it because of underdeveloped waste infrastructures.

Within the European Union, a Plastics Strategy has been introduced that relies on reducing, reusing and recycling plastic materials, based on the principles of a Circular Economy. The Strategy identifies the need for a clear regulatory framework for biodegradable plastics, with clear, harmonised rules for defining and labelling biodegradable and compostable plastics. It seeks to develop life cycle assessment by which to identify beneficial uses of biodegradable or compostable plastics, and the criteria for potential applications. Once identified, the European Commission will consider measures to stimulate innovation and drive market developments in biodegradable plastics. The Group of Chief Scientific Advisors has been asked to support the preparation of a framework by specifically examining biodegradable plastics in the open environment, and, to this end, SAPEA has reviewed the scientific evidence to inform the Advisors.

In this report, we identify and critically evaluate criteria under which the use of biodegradable plastics in *specific applications* may help to alleviate plastics pollution of the open environment. We conclude that biodegradable plastics do have a role within a circular economy that is based on the principles of resource efficiency. In particular, biodegradable plastics may have benefits over conventional plastics in applications where it is challenging or prohibitively expensive to avoid fragments ending up in the open environment or to remove them after use. They may also be beneficial where it is difficult to separate plastic from organic material that is destined for composting or wastewater treatment. At the same time, we do not consider replacing conventional plastics by biodegradable plastics as a viable strategy by which to solve the ever-increasing plastic pollution problem. Biodegradable plastics should not be used as an alternative to poor waste management or as an answer to inappropriate disposal, in particular littering. Good waste management practices are key.

The extent to which biodegradable plastics can be successfully incorporated into a circular economy is dependent on how they are produced, used and disposed of. Integrated approaches should be considered to ensure the appropriate uptake

and management of plastics that biodegrade in the open environment or can be composted at home.

Broadly speaking, the Working Group identifies five disposal scenarios for end-of-life items made of biodegradable plastics. These outcomes are determined by (1) the application of the plastic, (2) the available waste management system, (3) policies and regulations in place, (4) information or labelling to guide the user on appropriate disposal, and (5) behaviours of the end user in relation to that information. Biodegradable plastics will only deliver benefits over conventional plastics where applications reach an appropriate end-of-life scenario. As such, it is crucial to develop policies and standards that work alongside an effective waste management infrastructure. An integrated, systemic approach is essential to avoid increasing the complexity of existing waste management systems. Promoting the use of biodegradable plastics in appropriate applications, alongside information and incentives for correct disposal, and the development of specific waste collection and treatment infrastructure, are recommended only after making material improvements and increasing incentive schemes relating to the existing waste infrastructure.

We emphasise that plastics that biodegrade in the open environment are not a panacea for tackling plastic pollution, but they may present one strand within broader efforts to address it. Their potential rests on a limited number of defined applications. It is important to emphasise that, while the report illustrates examples of where biodegradable plastics may bring benefit as well as those where the benefits are less certain, there is no one-size-fits-all solution. To achieve net benefit from the use of biodegradable plastics as part of the circular economy, whilst also keeping in mind the perspective of environmental risk, the potential advantages of biodegradable plastics over conventional plastics must be considered on a case-by-case, application-by-application basis.

At the same time, we highlight that, in this rapidly evolving and high-tech field, policy should remain sufficiently flexible to be able to respond to emerging new knowledge and avoid placing barriers to future development and innovation.

7.2. EVIDENCE-BASED POLICY OPTIONS

We complete our report by putting forward a range of options that may serve policymakers in choosing paths that lead to the appropriate use and management of biodegradable plastics in line with circular economy principles. Our evidence-based policy options cover the following areas:

- Definitions of biodegradable plastics and biodegradation
- Regulation
- Standards and certification
- Risk assessment
- Information, labelling and education
- Incentives, subsidies, new business models
- Research, development, and innovation

Definitions of biodegradable plastics and biodegradation

1. Precise definitions for terms such as 'biodegradable plastics', 'bioplastics' and 'biopolymers' are essential for a future European strategy and framework. They should consider and account for the interpretational ambiguities and strictly reserve the term 'biodegradable' for plastic(s) that have passed the required testing standards for biodegradation within a defined timespan. The use of certain terminology that implies the *potential* for biodegradability of a material should be approached with caution to avoid false claims; all false labelling should be deterred. We define plastic biodegradation as follows:

   Plastic biodegradation is the microbial conversion of all its organic constituents to carbon dioxide, new microbial biomass and mineral salts under oxic conditions, or to carbon dioxide, methane, new microbial biomass and mineral salts under anoxic conditions.

2. Inorganic components and polymers will require a separate scientific assessment and regulatory considerations related to these inorganic components. We advise that these inorganic constituents are separately assessed on a case-by-case basis. A clear recommendation is that plastics purely composed of inorganic polymers ought not the be labelled 'biodegradable' as this would be in violation of the definition above.

3. Determining whether a plastic item undergoes biodegradation in the open environment is dependent not only on the plastic material properties, but also on the specific conditions that prevail in the receiving environment. Plastic biodegradability should therefore be considered as a *system property* rather than solely as a material property. Biodegradability focuses on the interplay that takes place between the material properties that provide the potential for biodegradation to occur and the environmental conditions that match this potential and thereby allow for biodegradation to occur.

4. For product certification purposes, it is critical to define the maximum timeframe over which a certain extent of biodegradation needs to be achieved in a given receiving environment. The required biodegradation times and extents should be application- and product-specific and, when defined, need consideration of the potential ecological impact. as well as of concentrations of biodegradable plastics in a specific environment that are considered environmentally and societally acceptable.

5. The term 'open environment' is too broad and generic when it comes to product regulation, because both abiotic and biotic factors governing the rates and extents of plastic biodegradation vary vastly between different natural systems. It therefore is important to explicitly define for which specific natural environment biodegradation is considered and assessed.

6. Claims of plastic biodegradability should be supported by laboratory tests that show the two-step process of the successful conversion of all organic components of the plastic to CO_2 (or CO_2 and CH_4) and microbial biomass. Providing data only on completion of the first step (i.e., data demonstrating a decrease in the molecular weight of the polymeric building blocks of the plastic) is not an acceptable measurement endpoint for biodegradation because it falls

short of demonstrating this process. Regulatory concepts developed for low molecular weight compounds require adjustment to account for the additional complexity resulting from the need for abiotic and/or biotic breakdown of polymers in the open environment.

Regulation

7   Regulation should ensure that biodegradable plastics are integrated into the waste hierarchy, and that their use is not advocated as an alternative to appropriate waste management practices and infrastructures. A dedicated infrastructure for the disposal of different plastic wastes should be made widely available. Regulations on the use of biodegradable plastics should be based on a holistic evaluation in terms of the overall waste hierarchy and the potential environmental benefits or risks associated with the use of existing or novel biodegradable plastics, compared to conventional plastics.

8   The biodegradation pathways required for regulation and certification should be application- and product-specific, and should consider the potential ecological impact, as well as the concentrations of biodegradable plastics in a specific environment that are considered societally and environmentally acceptable.

9   Bans and charges, such as those on single-use conventional plastics, have been shown to change behaviour and raise awareness. However, there may be unintended consequences of biodegradable plastics, not least as a result of interpretational ambiguities associated with the term. This can be exacerbated by the lack of standards and regulation relating to the biodegradability of plastics. False claims and the use of the term 'biodegradability' for marketing purposes has the potential to mislead consumers.

Standards and certification

10   There is a need for both regulated standards and the authorisation of specific third-party certification bodies to provide assurance that products meet specific standards. Given the global reach of the biodegradable plastics market, it is suggested that these standards should be international, with certification bodies authorised by parastatal institutions.

11   Biodegradability testing should be done on the final product, to ensure that it captures any potential changes in biodegradability resulting from the mixing of materials, the use of additives, and the manufacturing process. Biodegradation assessments should follow a three-tier approach, where biodegradability (i.e. the final product of biodegradation) is verified in lab tests and, in field and tank tests, the biodegradation rates are assessed under environmentally relevant conditions.

12   A multi-tier test scheme is also needed to address the impacts and effects of biodegradable plastics in the open environment, with the systematic assessment of biodegradation rates under selected relevant environmental conditions. The selection should be based on defined criteria, be product-specific, and should provide a good overview of the environments of interest. Selection criteria should include identifying the relevant environment, its habitats, and their conditions.

13   Testing and certification of a plastic item should consider four main elements: (1) the determination of biodegradability, (2) the assessment of biodegradation

rate under environmentally relevant conditions, (3) the modelling of the lifetime/persistence in the environments of interest, and (4) the assessment of the effects on the environment on an organism and ecosystem level.

14 Any claims of plastic biodegradability should demonstrate, in laboratory tests, the successful conversion of all organic components of the plastic to CO_2 (or CO_2 and CH_4) and microbial biomass. Test conditions for biodegradation, both in laboratory and field studies, should be relevant and realistic for the environments in which the plastics are intended to be used, or can be expected to be transported to. In laboratory screening tests for biodegradability, the conditions of the environment of interest should be optimised and its matrices used (e.g. soil, water, aquatic sediment). Transferability into the environment is best validated by field and tank tests, to achieve environmental relevance and to assess the biodegradation rates under *in-situ* conditions. Tests to determine the impacts of biodegradable plastics should take into account the impacts on both organisms and the entire ecosystems. Existing standards should be adapted according to the relevant criteria and, if missing, be set up for the relevant environmental habitats and conditions for all three tiers – lab, field and mesocosm.

15 Pass levels should be determined by considering items that biodegrade quickly (in a timeframe of a few weeks) and more slowly (in the timeframe of several months to years).

Risk assessment

16 The potential ecological benefits of biodegradable plastics compared to conventional plastics relates directly to their biodegradability in the environment, as well as potential new ecological risks. The need for standardised methods for the determination of environmental biodegradation rates of biodegradable and compostable plastics is critical for current and future ecological risk assessment. It also calls for the development of a risk assessment framework.

17 Risk assessment should consider the potential adverse effects of large quantities or high concentrations of biodegradable plastics and their conversion products, arising from localised usage and accumulation ('hotspots').

Information, labelling and education

18 Labelling of plastic products, including biodegradable plastics, should clearly indicate appropriate and inappropriate disposal pathways. Labelling of plastic items needs to inform the end user not just about the potential for biodegradation but also the receiving environment required to achieve it. Whilst information policies beyond labelling, such as education, can be effective in raising awareness of sustainability issues, they do not necessarily lead to behavioural change. The gap between awareness and action can be reduced by paying specific attention to both the content and method of communication, providing clear behavioural options, and reducing barriers to effective action.

19 In light of the barriers posed by the price of biodegradable plastics, the lack of clear standards surrounding biodegradability calls for both market-based and regulatory policy measures, as well as policies relating to waste infrastructure in general, to promote appropriate use and disposal of biodegradable plastic.

Education can be effective when provided in combination with structural policy approaches.

Incentives, subsidies, new business models

20 Any standards developed in relation to biodegradable plastics suitable for home composting or open environments will require clearly defined terminology (and accredited certification and labelling schemes) to ensure that they do not end up in the wrong waste streams. Effective waste separation is not only an outcome of clear standards and messaging but is a central part of a reliable waste infrastructure more broadly.

21. The external costs associated with waste management or environmental impact should be used to guide manufacturer decisions on material usage for consumer applications. Economic incentives are important in promoting effective disposal behaviour by both consumers and industry. Addressing economic barriers to the appropriate uptake of biodegradable plastics is particularly pertinent in certain sectors, such as agriculture. Within the trade and retail sectors, biodegradable plastics can be part of Corporate Social Responsibility (CSR) schemes, or a shift towards circular business models, and as a way of gaining competitive advantage through 'eco-credentials', although these benefits may not always outweigh the costs. Government financial and regulatory mechanisms, as well as public procurement, can encourage the use of more sustainable plastic alternatives, rather than self-regulation by industry, where costs are absorbed or passed on to consumers.

22. Higher costs associated with biodegradable plastics at least partly contribute to the gap between consumer attitudes and behaviour. Even among those who can and are willing to pay a premium, price may inhibit their uptake. This highlights the role of market-based policies such as subsidies or taxation schemes to promote market penetration and uptake of biodegradable plastics. Financial incentives can help to address some of the consumer barriers.

23. Care should be taken in terms of what kinds of production and consumption of biodegradable plastics are incentivised. It suggests the need for more policy instruments, including subsidies, taxes and targets/quotas, that are sector-specific. Bio-economy transition indicators could guide and support policy decisions.

Research, development, and innovation

24 There is a considerable need for more research and reliable data to inform key areas of policymaking on biodegradable plastics in the open environment. Examples include but are not limited to:

a Data generated from a consistent set of biodegradable plastics across different environments, as a way of benchmarking differences in the biodegradation rates between these environments

b Data on the extent to which the transfer of biodegradable plastics between receiving environments occurs

c The effects of the main conditions (e.g. nutrients, oxygen, sediment grain sizes, etc.)

d The shape of the plastic objects and the definition of biodegradation classes to account for different biodegradation rates, based on surface-to-volume ratios.

e The development of standard test methods for the biodegradation of plastic materials on land and in freshwater, and of overarching standard specifications for materials that biodegrade in soil, freshwater and the marine environment. Ecotoxicity tests that examine the effects of biodegradable plastics on the *ecosystem level* are not currently available as standards and need to be developed to inform testing schemes

f Data on sources, transportation pathways and sinks of different applications of biodegradable plastic materials, and the role of consumers and other societal actors therein, to identify relevant environmental conditions for testing and certification

25 To address the data gaps, a concerted research initiative from academia, industry, businesses and public authorities is urgently needed to provide a data catalogue of biodegradable plastic materials, with their performance in a variety of ecological settings, expressed as range of biodegradation rates.

26 Future research and development in biodegradable plastics should consider that polymers that rely on enzymatic hydrolysis to degrade in step 1 of biodegradation are more likely to undergo the desired hydrolytic degradation across different open receiving environment than polymers that rely on enzymatic oxidations.

27 The development of biodegradable materials for certain applications (an example we give is dolly rope that biodegrades in marine seabed conditions) could make a valuable contribution to reducing pollution.

28 Product labelling needs to be evaluated in terms of its efficacy in guiding consumer behaviour and in determining plastic end-of-life fate.

29 Research on the long-term ecological effects of biodegradable plastics and their additives needs to be prioritised. This is especially important regarding the application of biodegradable mulch films in agriculture, for example, as the potential ecological effects also concern food production and safety, as well as soil health.

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Annex 1: List of Working Group members

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Dr Miriam Weber, HYDRA Marine Sciences (Germany)

The above experts were identified with the support of:

- The Royal Swedish Academy of Engineering Sciences
- The Norwegian Academy of Technical Sciences
- The Royal Netherlands Academy of Arts and Sciences
- Swiss Academies of Arts and Sciences
- The Council of Finnish Academies
- The Royal Society
- The European Academy Networks forming the SAPEA consortium

Annex 2: Acknowledgements

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SAM Coordination Group
Professor Nicole Grobert (chair), Group of Chief Scientific Advisors
Professor Rolf-Dieter Heuer, Group of Chief Scientific Advisors
Professor Ann-Christine Albertsson, SAPEA Working Group chair
Dr Michael Sander, SAPEA Working Group
Professor Richard Thompson, SAPEA Working Group
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Annex 3: Background to the report

In September 2019, Commissioner Karmenu Vella (Environment, Maritime Affairs and Fisheries) wrote to Commissioner Carlos Moedas (Research, Innovation and Science) with a request for the support of the Group for Chief Scientific Advisors in establishing a clear regulatory framework for biodegradable plastics, within the context of the implementation of the EU Plastics Strategy. Specifically, the Advisors were asked to address the following question:

> *From a scientific point of view and an end-of-life perspective, and applying to plastics that biodegrade either in the terrestrial, riverine, or marine environments, and considering the waste hierarchy and circular-economy approach: What are the criteria and corresponding applications of biodegradable plastics that are beneficial to the environment, compared with non-biodegradable plastics?*

A workshop took place on 27 November 2019 in Brussels, to assist in establishing the scope of the work, including the sub-questions that SAPEA was asked to address as part of the evidence review requested by the Advisors (see Chapter 1 for details). The final version of the scoping paper was approved and published by the Advisors in December 2019.

Working Group

SAPEA set up an international and interdisciplinary working group with eleven members from eight European countries, with Professor Ann-Christine Albertsson (Sweden) as Chair. Members represented a broad range of disciplines required for the review, including material sciences, environmental chemistry, microbiology, economics and psychology. All Working Group members were required to fill out the Standard Declaration of Interest Form of the European Commission, in accordance with SAPEA's Quality Guidelines.

Due to the COVID-19 pandemic, all ten meetings of the Working Group took place online, over the period from February to November 2020. The first draft of the Working Group's report was delivered in June 2020, with subsequent drafts in September, October and November.

Coordination of the review

Professor Nicole Grobert led on the topic for the Group of Chief Scientific Advisors. Academia Europaea acted as the Lead Academy on behalf of SAPEA, represented by Professor Ole Petersen. Regular meetings of the SAM Coordination Group took place over the duration of the review.

Literature review

A proposal to undertake a mapping review of the literature was accepted by the Working Group. Specialists in systematic review at Cardiff University carried out a search of recently published research evidence within the field. An advisory group was formed to support the review team; members included the Chair (Ann-Christine Albertsson) and a Member of the Working Group (Wouter Poortinga), plus a subject expert from Cardiff University (Isabelle Durance, Professor and Director of the Water Research Institute). A final draft of the report was informally peer-reviewed by two external experts, one a subject expert (Dr Costas Velis, University of Leeds) and the other an expert in systematic review (Dr Gabor Lovei, Aarhus University). The mapping review is published separately, as a supporting document to the Evidence Review Report, and is available on the SAPEA website.

Information specialists at Cardiff University also undertook specific literature searches, when requested by members of the Working Group.

SAPEA expert workshop

An online expert workshop was run on 10 September. Its purpose was to receive feedback on the draft Evidence Review Report from the wider expert community. Invited experts from seven European countries spoke at the workshop, with three contributors from the USA and Canada. In all, there were 36 participants. Following a keynote presentation, each Chapter of the report was presented by the Chapter lead, with feedback given by two discussants. A final session was dedicated to a discussion of evidence-based policy options. The report of the workshop is published separately, as a companion document to the Evidence Review Report, and is available on the SAPEA website. The invited experts are listed in Annex 1.

Peer review

In October, SAPEA organised a double-blind peer review of the draft report, in accordance with the SAPEA Quality Guidelines. Five reviewers, representing a diverse and complementary range of disciplines, provided feedback, which was systematically addressed by the Working Group. The reviewers are listed in Annex 2.

Communications and outreach

This Evidence Review Report and the Scientific Opinion were published on 14 December 2020. Both reports will be promoted through a comprehensive outreach programme, commencing early in 2021.

Annex 4: Policy landscape and other initiatives relating to biodegradable plastics

Introduction

The pressure on the environment posed by plastic pollution has long been identified by policymakers. When it comes to EU policy, the biodegradability of plastics has increasingly been identified in frameworks aimed at addressing the existing challenges. This is the context in which the Group of Scientific Advisors has been asked to support forthcoming specific policymaking. Alongside the request for expert advice and evidence on the use of biodegradable plastics, the need to map out the main policy initiatives and strategies put forward by the European Union in this field has also been identified.

This map focuses on frameworks that mention or highlight the importance of biodegradable plastics. In developing the policy landscape, we have conducted the search mostly via EUR-Lex, the European Union's own legislative database. We have used a series of expressions always comprising *biodegradability* and *plastics* and variations. We have also scanned the relevant texts for other potentially relevant initiatives. While we believe this map to be fairly comprehensive, it may not include every single initiative containing the above-mentioned expressions.

With a few exceptions, the external links provided direct access to EUR-Lex where the full text, related documents and other details concerning the EU initiatives and frameworks can be found. We hope that, by bringing together these primary sources, we are supporting the understanding of the political and policy context surrounding the academic debate on the biodegradability of plastics.

Policy Landscape

Green Paper on a *European Strategy on Plastic Waste in the Environment*

- Communication adopted by EC on 7 March 2013
    - › Includes section on *Promotion of biodegradable plastics and bio-based plastics*
    - › Wider review of waste legislation announced as follow-up to this Communication

G7 Alliance on Resource Efficiency

- Established by G7 Elmau Summit Declaration and Annex in June 2015

2030 Agenda for Sustainable Development

- 17 SDGs adopted at UN Sustainable Development Summit in September 2015

Communication *Closing the loop - An EU action plan for the Circular Economy*

- G7 Alliance on Resource Efficiency [June 2015]
- 2030 Agenda for Sustainable Development (SDG 12) [September 2015]
- Communication adopted by EC on 2 December 2015
  - It identifies plastics as key priority and committed to preparing a strategy to address challenges relating to plastics
  - Strategy to address biodegradability, among other questions
- EESC Opinion adopted on 27 April 2016
- Council conclusions adopted on 20 June 2016
- CoR Opinion adopted on 12 October 2016

Communication *Investing in a smart, innovative and sustainable Industry - A renewed EU Industrial Policy Strategy*

- Communication adopted by EC on 13 September 2017

Commission Work Programme 2018 - An agenda for a more united, stronger and more democratic Europe

- Communication adopted by EC on 24 October 2017
  - Confirmation of focus on plastic production and use, ensure that all plastic packaging is recyclable by 2030

EC Communication on *A European Strategy for Plastics in a Circular Economy*

- EC Communication *Closing the loop – An EU action plan for the Circular Economy* [December 2015]
- EC Work Programme 2018 [October 2017]
- Communication adopted by EC on 16 January 2018
  - SWD/2018/16 – Staff Working Document
  - Highlights importance of plastics industry, investment and innovation in line with EU Industrial Policy Strategy
  - Announces legislative initiative on marine litter from plastics
  - Contains section on *Establishing a clear regulatory framework for plastics with biodegradable properties*
- Report *on the impact of the use of oxo-degradable plastic on the environment* published by the EC on the same day
- EESC Opinion adopted on 23 May 2018
- EP Resolution on the Communication adopted on 13 September 2018
  - Contains section on *Bio-based plastics, biodegradability and compostability*
  - European Parliament: Legislative Observatory
  - European Parliament: Legislative Train

- CoR Opinion adopted on 10 October 2018
  - › Contains section on *Biodegradable Plastics*

Circular Economy Stakeholder Conference, 20-21 February 2018

- Taking stock of *EU Action Plan for the Circular Economy*
- Discussion on upcoming deliverables
- Update on first achievements of the *European Circular Economy Stakeholder Platform*

Circular Plastics Alliance

- Established in December 2018, under Annex III of European Strategy for Plastics

Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment

- Flash Eurobarometer 388: Attitudes of Europeans towards Waste Management and Resource Efficiency [June 2014]
  - › Open Data Portal
- 2030 Agenda for Sustainable Development (SDG 14) [September 2015]
- Reinventing Plastics Stakeholder Conference [26 September 2017]
- Special Eurobarometer 468: Attitudes of European citizens towards the environment [November 2017]
  - › Open Data Portal
- Public Consultation
  - › Reducing marine litter: action on single-use plastics and fishing gear [15 December 2017 to 9 February 2018]
- EC Communication on *A European Strategy for Plastics in a Circular Economy* [January 2018]
- Circular Economy Stakeholder Conference [February 2018]
- Legislative initiative adopted by EC on 28 May 2018
  - › SWD/2018/254 – Staff Working Document: Impact Assessment
  - › SWD/2018/255 – Staff Working Document: Summary of Impact Assessment
  - › SEC/2018/0253 – EC Regulatory Scrutiny Board: Opinion on Impact Assessment
  - › SWD/2018/256 – Staff Working Document: Implementation Plan
  - › SWD/2018/257 – Staff Working Document: Synopsis Report Stakeholder Consultation
- CoR Opinion adopted on 10 October 2018
  - › Amendments relating to biodegradability are suggested
- EESC Opinion adopted in plenary on 17 October 2018

- Highlights as limitation the absence of regulation backing up concept of *biodegradability* (4.9)

- [EP Position on initiative](#) adopted on 24 October 2018

- Proposes amendment to initiative to include definition on *Biodegradable Plastic*

- [European Parliament: Legislative Observatory](#)

- [European Parliament: Legislative Train Schedule](#)

- [EP Research Service: Briefing, June 2019](#)

- [Council Position](#) adopted on 31 October 2018

- Provision agreement between co-legislators reached on 19 December 2018

- Act signed by co-legislators on 5 June 2019, published in OJ on 12 June 2019

- Contains definition of *Biodegradable Plastics*

European Green Deal

- Flagship strategy published by EC on 11 December 2019
  - › Commits to development of regulatory framework for biodegradable and bio-based plastics

Communication on *A new Circular Economy Action Plan For a cleaner and more competitive Europe*

- [2030 Agenda for Sustainable Development](#) [September 2015]

- [EC Communication *Closing the loop – An EU action plan for the Circular Economy*](#) [December 2015]

- [EC Communication on *A European Strategy for Plastics in a Circular Economy*](#) [January 2018]

- [European Green Deal](#) [December 2019]

- Communication adopted by EC on 11 March 2020
  - › [SWD/2020/100](#) – Staff Working Document: *Leading the way to a global circular economy: state of play and outlook*
  - › Commits to policy framework on the use of biodegradable or compostable plastics

Other relevant legislative initiatives relating to Plastics, Food, Packaging, Waste and the Circular Economy

- [Directive 94/62/EC on packaging and packaging waste](#) [December 1994]
  - › [Decision relating to the publication of references for standards EN 13428:2000, EN 13429:2000, EN 13430:2000, EN 13431:2000 and EN 13432:2000](#) [June 2001]
  - › Amended by [Directive (EU) 2018/852](#) to address packaging waste and transition to circular economy

- [Directive 2000/60/EC establishing a framework for Community action in the field of water policy](#) [October 2000]

- Regulation (EC) No 648/2004 on detergents [March 2004]

- Regulation (EC) No 1935/2004 on materials and articles intended to come into contact with food [October 2004]

  > It repeals Directive 80/590/EEC and Directive 89/109/EEC

  > Commission Regulation (EC) No 2023/2006 on good manufacturing practice for materials and articles intended to come into contact with food [December 2006]

  > Commission Directive 2007/42/EC relating to materials and articles made of regenerated cellulose film intended to come into contact with foodstuffs [June 2007]

  > Commission Regulation (EC) No 282/2008 on recycled plastic materials and articles intended to come into contact with foods [March 2008]

  > Commission Regulation (EU) No 10/2011 on plastic materials and articles intended to come into contact with food [January 2011]

- Regulation (EC) No 1013/2006 on shipments of waste [June 2006]

- Regulation (EC) No 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) [December 2006]

- Directive 2008/56/EC establishing a framework for community action in the field of marine environmental policy [June 2008]

- Directive 2008/98/EC on waste [November 2008]

- Regulation (EU) No 1169/2011 on the provision of food information to consumers [October 2011]

- Directive 2011/83/EU on consumer rights [October 2011]

- Regulation (EU) No 528/2012 concerning the making available on the market and use of biocidal products [May 2012]

- Regulation (EU) No 1025/2012 on European standardisation [October 2012]

- Directive (EU) 2019/883 on port reception facilities for the delivery of waste from ships [April 2019]

  > It amends Directive 2010/65/EU

  > It repeals Directive 2000/59/EC

Regulation (EU) 2019/1009 laying down rules on the making available on the market of EU fertilising products [June 2019]

- It amends Regulation (EC) No 1069/2009 and Regulation (EC) No 1107/2009

- It repeals Regulation (EC) No 2003/2003

Annex 5: Glossary

Term	Explanation
Additives	Organic and inorganic compounds and substances mixed into or applied to the surface of plastics to bestow desired material properties on the plastic. These additives are diverse and include, but are not limited to, antioxidants, binders, colourants, flame retardants, inhibitors, plasticisers, reinforcements, and stabilisers.
Amide	Derivatives of oxoacids $RkE(=O)l(OH)m$ ($l \neq 0$) in which the acidic hydroxy group has been replaced by an amino or substituted amino group [1].
Anabolism	The synthesis of complex molecules in living organisms from simpler ones together with the storage of energy; constructive metabolism.
Anoxic	In the absence of oxygen.
Antioxidant(s)	Agents added to plastic to deter or retard degradation of polymers arising from peroxy free radical-induced autooxidations. The free radicals can be generated by heat, radiation, mechanical shear or reactive metallic catalytic residual impurities [2].
Arrhenius rate law	The Arrenhius rate law describes the dependance of reaction rates on temperature.
Benthic	Associated with or occurring on the bottom of a body of water
Binder	Material or matrix holding fibres together. In reinforced plastic, the binder matrix holds together the reinforcement fibres [ASTM D883-20a].
Bioaccumulation	Gradual accumulation of an organic compound, such as pesticides, in an organism. Bioaccumulation occurs when an organism absorbs a compound at a rate higher than that at which the compound is lost from the organism.
Biobased plastic	Plastic containing organic carbon of renewable origin from, plant, animal or microbial sources
Biodegradable plastic	A plastic that undergoes biodegradation involving the metabolic utilisation of the plastic carbon by microorganisms such as bacteria, fungi, and algae resulting in the conversion of plastic carbon to CO_2 (and CH_4) and microbial biomass. See Chapter 2 for detailed discussion.
Biodegradation potential	The theoretical potential for a material to biodegrade. See Chapter 2 for detailed discussion.
Biodeterioration	Refers to the impact of microorganisms on the properties of a plastic. In contrast to biodegradation, biodeterioration does not stipulate the metabolic utilisation of smaller plastic-rderived organic compounds by the microorganism.
Bioplastic(s)	A generic term that subsumes both plastic materials composed of biodegradable polymers as well as plastic materials composed of bio-based polymers.
Biopolymer	A polymer produced by a living organism [1-4].
Blend (of polymers)	A mix of two or more polymers to get a single phase as opposed to a composite which is a multiphase, multicomponent system.

Carapace	The upper section of the exoskeleton of a crustacean (e.g. crabs, lobsters, prawns, krill), spiders, or tortoise
Colourant(s)	Dye or pigment used to impart specific colour to plastic for aesthetic or technical requirements. Colourants can be present in the bulk plastic or be applied to their surface. Dyes are soluble in polymers whereas pigments are largely insoluble [3].
Composite	A material consisting of two or more distinct components (fillers or reinforcing materials) in a compatible binding matrix. When at least one of the distinct immiscible components is a polymer, the material is called as polymer composite [3, ASTM D883-20a].
Copolymer	A polymer that is derived from more than one monomer.
Covalent bond	A chemical bond that involves the sharing of electron pairs between atoms.
Degradable plastic	A plastic or matrix which can degrade under certain environmental conditions in specific time period, resulting in loss of properties as measured by standard test methods. Degradation of plastic can result either from hydrolysis (hydrolytic degradation), oxidation (oxidative degradation) and due to light (photo degradation) or a combination of these effects [ASTM D883-20a].
Degradation	Chemical changes in a polymeric material that usually result in undesirable changes in the in-use properties of the material [1].
Dioxygen	The oxygen molecule O_2.
Disintegration	The physical breakdown of a plastic material into very small fragments [ISO/DIS 17088]. These changes can be either undesirable, such as cracking and chemical disintegration of plastics in use, or desirable, as in the case of plastic biodegradation.
Ecosystem resilience	The ability of an ecosystem to absorb various disturbances and reorganise while undergoing state changes to maintain critical functions.
Ecotoxicology	A branch of toxicology that concerns the study of the harmful effects caused by natural and synthetic pollutants to biota in aquatic and terrestrial ecosystems.
Endpoint	In chemistry: the completion of a reaction. (Toxicological) measurement endpoint: Measurable (ecological) response to a stressor to the valued characteristic chosen as an assessment endpoint.
Environmental compartment	A realm in the environment, e.g. water, air, land, soil, biota, aquatic sediments, etc.
Enzyme(s)	Macromolecules, mostly of protein nature, that function as (bio)catalysts, thereby increasing reaction rates [1].
Ester	Chemical compound derived from an acid (organic or inorganic) in which at least one –OH (hydroxyl) group is replaced by an –O–alkyl (alkoxy) group.
Eulittoral	The intertidal zone that extends from the spring high tide line, which is rarely inundated, to the spring low tide line, which is rarely not inundated. It is alternately exposed and submerged,once or twice daily.
Eutrophic	A lake or other water body that is rich in nutrients, thereby supporting a dense plant population. The decomposition of the plants can affect animal life by depriving the water body of oxygen.

Fibre (also Filament)	A homogeneous strand of a material with finite length which is an order of magnitude larger than the diameter of the fibre. Fibres can be of natural origin or synthetically generated by drawing from a bulk material [1,2].
Fillers	Particles added to resin or binders (plastics, composites, concrete) to change specific product properties, lower the product costs, or a combination of both.
Flame retardants	Additives provide varying degrees of flammability protection. Flame retardants are some of the largest volume additive used in polymeric materials.
Free radical(s)	A species containing an unpaired electron that is formed through a chemical reaction. It is typically highly unstable and reacts further.
Glass transition	A reversible change in an amorphous polymer or in amorphous regions of a partially crystalline polymer, occurring while transitioning either from or to a viscous or rubbery state from or to a hard and relatively brittle state. The temperature at which this transition takes place is referred to as glass transition temperature (Tg) [3, ASTM D883-20a].
Glycosidic bond	A molecular bond that joins a carbohydrate (sugar) molecule to another group, which may or may not be another carbohydrate.
Half life	In a bio-chemical process for a substance, the time required for the amount of that substance in a system to be reduced to one half of its initial value by the processes [1,3]. Half lives also apply to chemical reactions.
Hazard	The ability of a chemical or component to harm organisms or cause harm to an ecosystem.
Homopolymer	A polymer constituted of long chains comprising of repetitive units of same monomers linked together as a result of polymerisation process [1].
Hydrocarbon plastics	Plastics which are composed largely of hydrocarbon chains in their structures, made by polymerisation of monomers composed of hydrogen and carbon only. An organic compound having hydrogen and carbon atoms in its chemical structure is referred to as a hydrocarbon [3, ASTM D883-20a].
Hydrolases	Enzymes that catalyse the cleavage of C–O, C–N, and other bonds by reactions involving the addition or removal of water [1].
Hydrolysis (Hydrolitic; Hydrolysable)	Any chemical reaction involving water molecules resulting in the breaking of a 'hydrolysable' chemical bonds.
Hydrophilic	A molecule or substance attracted to water.
Hydrophobic	A molecule or substance that repels water.
In vitro	Latin for 'in the glass'. Studies performed outside the biological context of the organisms, cells, or molecules of interest, e.g. laboratory experiments
In vivo	Latin for 'in the living'. Studies in which effects of a substance/procedure are tested on whole, living organisms or cells.
Infaunal	Aquatic animals that live in the substrate of a body of water and which are especially common in soft sediments.
Inhibitor	A substance that decreases the rate of a chemical reaction. An inhibitor may also get consumed during the course of chemical reaction [2].

Inoculum	Substance containing microorganisms from pure culture(s) or defined environment, which is used to start a new culture or experiment.
Intertidal	The area that is above water level at low tide and underwater at high tide.
Isotope	Nuclides having the same atomic number but different mass numbers [1].
Lacustrine	Relating to, or associated with, lakes.
Life cycle assessment (LCA)	A methodology for assessing environmental impacts associated with all stages of a product's life, from raw material extraction through materials processing, manufacture, distribution, and use.
Life cycle impact assessment (LCIA)	Steps that assess the type and extent of environmental impacts that may arise quantitatively based on data collected in a life cycle inventory, i.e. an inventory of input and output flows for a product system. Such flows include inputs of water, energy, and raw materials, and releases to air, land, and water.
Lignin	Macromolecular constituents of wood related to lignans , composed of phenolic propylbenzene skeletal units, linked at various sites and apparently randomly [1, 4].
Macromolecule(s)	A molecule of high relative molecular mass, the structure of which essentially comprises the multiple repetition of units derived, actually or conceptually, from molecules of low relative molecular mass.
Mesocosm	An experimental tank or enclosure system (indor or outdoor) to examine natural settings under controlled conditions.
Mesophilic	Descriptive of microorganisms that thrive at moderate temperatures between 20 and 45°C.
Mesotrophic	Ecosystems with intermediate nutrient supply levels that can show elevated productivity
Methanogenesis	The process of generation of methane by methanogens, which are strictly anaerobic microorganisms.
Microcosm	Microcosms are artificial, simplified ecosystems that are used to simulate and predict the behaviour of natural ecosystems under controlled conditions.
Mineralisation	The conversion of and organic substrate (including biodegradable plastics) into the gases CO_2 (and CH_4), water, inorganic salts. mineralisation involves metabolic activity of microorganisms.
Mol	The unit of measurement for 'amount of substance' in the International System (SI) of Units. A mol of a substance contains exactly 6.02214076×10^{23} elementary entities, which may be atoms, molecules, ions, or electrons [1].
Monomer	A small molecule which is capable of reacting with either like or unlike molecules via chemical linkages to form long chain macromolecules [2, 3].
Mulch film	Sheets of thin plastics added on top of agricultural soils to increase crop yield by various means.
Olefins	Acyclic and cyclic hydrocarbons having one or more carbon–carbon double bonds, apart from the formal ones in aromatic compounds. The class olefins subsumes alkenes and cycloalkenes and the corresponding polyenes [1].

Oligomer (Oligomerisation)	A substance originating from repetitive linkage of a monomer to like molecules. Based on number of repetitive monomeric units linked oligomers are often referred to as dimers (two monomer units), trimers (three), and tetramers (four). This conversion process is called oligomerisation [1, ASTM D883-20a].
Oligotrophic	Ecosystems with low nutrient supply levels and usually low productivity.
Open environment	All natural (eco)systems including terrestrial environments (e.g., soils), riverine and lacustrine freshwater environments, as well as marine environments (e.g., estuaries and oceans). The term includes human-impacted ecosystems, such as agro-environments, but does not include manmade managed systems such as industrial and domestic composts. For full discussion, see Chapter 2.
Oxic condition	Environmental condition in which gaseous or dissolved oxygen is present.
Oxo-degradable	Conventional plastics which include additives to accelerate the fragmentation of the material into very small pieces, triggered by UV radiation or heat exposure. Due to these additives, the plastic fragments over time into plastic particles, and finally microplastics, with similar properties to microplastics originating from the fragmentation of conventional plastics.
Pedology	A discipline within soil science which focuses on understanding and characterising soil formation, evolution, and the theoretical frameworks through which we understand a soil body, often in the context of the natural environment
Pelagic	The water column of the open ocean. The pelagic zone can be thought of in terms of an imaginary cylinder or water column that goes from the surface of the sea almost to the bottom.
Peroxide	A class of chemical compounds in which two oxygen atoms are linked together by a covalent bond (R-O-O-R). Several organic and inorganic peroxides are useful as initiators of polymerisation reactions.
Photo-oxidation	Light-induced degradation of a plastic in the presence of oxygen or ozone.
Pigovian tax	A tax placed on any good which creates negative externalities. The aim of a Pigovian tax is to make the price of the good equal to the social marginal cost and create a more socially efficient allocation of resources.
Plastic biodegradation	The microbial conversion of all organic constituents in plastic to carbon dioxide, new microbial biomass and mineral salts under oxic conditions, or to carbon dioxide, methane, new microbial biomass and mineral salts under anoxic conditions. See Chapter 2 for full discussion.
Plastic(s)	A material that contains as an essential ingredient one or more organic polymeric substances of large molecular weight. It is solid in its finished form but can be shaped by flow during manufacturing or finishing into finished articles [ASTM D883-20a].
Plasticiser	A diverse group of chemicals added to polymers to enhance their flexibility, resilience and melt flow properties by lowering the glass transition temperature (Tg) of the amorphous part of the material. Plasticisers also improve the impact resistance of plastic, especially during cold conditions [3].
Polyester	A category of polymers that contain the ester functional group in their main chain.

Polymer(s), Polymeric materials	Defined by IUPAC as "a substrate composed of macromolecules" and furthermore macromolecules as "a molecule of high relative molecular mass, the structure of which essentially comprises the multiple repetition units derived, actually or conceptually, from molecules of low relative molecular mass" [1].
Polyolefins	Polyolefin is a type of polymer produced from simple olefin as a monomer [3].
Polysaccarides	Compounds consisting of a large number of monosaccharides linked glycosidically [1].
Psychrophilic	Cold-loving bacteria that have an optimal temperature for growth at about 15°C or lower, a maximal temperature for growth at about 20°C and a minimal temperature for growth at 0°C or lower.
Psychrotrophs	Cold-tolerant bacteria that have the ability to grow at low temperatures but have optimal and maximal growth temperatures above 15°C and 20°C, respectively.
Radical chain scission	A chemical chain reaction involving the production of free radicals.
Rate-determining step	The intermediary step that determines the speed of the entire reaction or process.
Reinforcement	A strong inert material (filler/fibre) incorporated into the plastic to improve its strength, stiffness, and impact resistance. The reinforcing material must form a strong adhesive bond with the base resin [1].
Risk	The probability that harm will occur under a set of circumstances.
Saprobiation	An increased level of organic matter and the potential subsequent oxygen depletion in water bodies.
Spherulite	A polycrystalline, roughly spherical morphology consisting of lath, fibrous or lamellar crystals emanating from a common centre, these are observed in most crystalline plastics [1, 4].
Stabiliser(s)	Chemical substances added to plastic materials to assist in stabilising the physical and chemical properties of the polymer compound throughout the processing and service life of the material and articles made therefrom. stabilisers are used to provide protection from thermal alterations, oxidative and UV light induced damage to material. Most widely used stabilisers trap or quench free radicals, thereby slowing down oxidative and UV-based degradation reactions. stabilisers may affect the biodegradation of the plastic [3].
Sublittoral	Living, growing, or accumulating near to or just below the shore.
Substitution Share Indicator	This indicator relates bio-based substitute products to their fossil-based counterparts and accounts for indirect fossil resource flows, which are estimated using a bottom-up approach, based on life cycle inventory data, and a top-down approach, based on input–output data.
Synthetic plastic	A material containing one or more high molecular weight organic polymer originating from biological, biochemical or petrochemical source, which has been chemically processed or modified to improve its desired properties [3].
Thermophilic	Organisms that thrive at relatively high temperatures, between 41 and 122°C.
Toxicity	A measure of adverse effects exerted by a chemical agent on a living organism or a biochemical process under specific environmental conditions and concentrations [3].

Trophic level	A group of organisms within an ecosystem which occupy the same level in a food chain.
Waste Hierarchy	The EU's approach to waste management is to adopt a waste hierarchy, which sets the following priority order when shaping waste policy and managing waste at the operational level: prevention, (preparing for) reuse, recycling, recovery and, as the least preferred option, disposal (which includes landfilling and incineration without energy recovery).

[1] IUPAC (1997). *Compendium of Chemical Terminology, 2nd ed. (the "Gold Book").* Compiled by McNaught, A. D., & Wilkinson, A. Oxford: Blackwell Scientific Publications. Online version (2019-) created by S. J. Chalk. doi:10.1351/goldbook

[2] Harper, C. A. & Petrie, E. M. (2003). *Plastics Materials and Processes: A Concise Encyclopedia.*

[3] Encyclopedic Dictionary of Polymers (2007). doi:10.1007/978-0-387-30160-0

[4] Merriam-Webster.com Dictionary. Retrieved from: https://www.merriam-webster.com/dictionary

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