Ministry of Environment and Food of Denmark
Environmental Protection Agency

Bio-based and Biodegradable Plastics in Denmark

Market, Applications, Waste Management and Implications in the Open Environment

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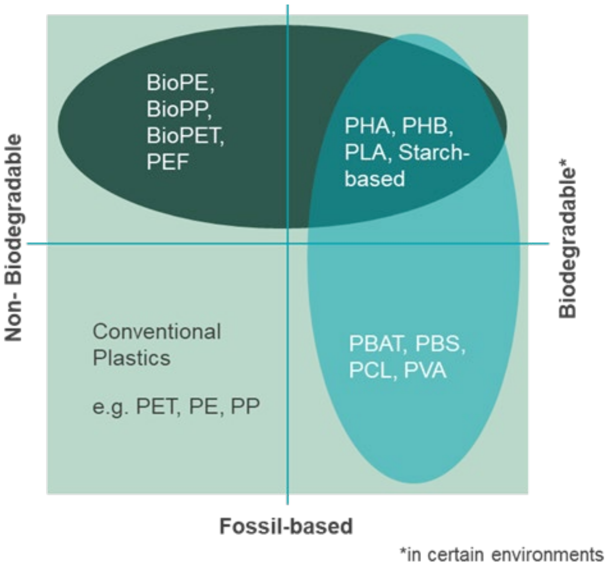
Executive Summary

There is currently considerable interest in bioplastics from consumers and industry and business, but there is still great uncertainty about the subject and several misconceptions exist. With the National Plastic Action Plan developed by the former Danish Government in December 2018 and the subsequent political agreement of 30th January 2019, Denmark has a consolidated plan of action for plastics. The plan focuses on less plastic in nature, smarter production and consumption, more cooperation in the value chain, better waste management, a stronger scientific evidence base and increased recycling—plan initiative no. 23 requires the building up of knowledge around the advantages and disadvantages of bio-based plastics. The Danish Environmental Protection Agency (Miljøstyrelsen) on the basis of the above need to build knowledge of biobased and biodegradable plastics as an alternative to conventional plastics based on fossil resources, including supply and market mapping and possible waste management scenarios. The following report is the result of research conducted to address this requirement.

Defining Bio-based and Biodegradable Plastics

A **bio-based plastic** can be defined as a polymer composed or derived in whole or in part of biological products issued from biomass—**it is a description of what it is made from**. No other functional or performance attributes can be assumed from polymers made from biomass. ‘Drop-in’ bio-based plastics are so called because of their ability to be exchanged directly with their fossil-based counterpart. Many of these have been available for a long time and are identical in chemical structure but use biomass feedstock. For example, bio-PET is simply PET made partially from biomass and can be recycled alongside fossil-based PET.



To claim a polymer as biodegradable is to describe a property— the inherent ability to degrade as a result of biological activity— **and not what it is made from**. As the diagram (left) shows, biodegradable plastics can be made from either bio-based or fossil-based feedstock. Some biodegradable plastics may biodegrade very quickly in one environment but over many years (or not at all) in a different environment. Therefore, it is very important to define timeframe and environment when describing and defining biodegradation.

Biodegradation in Practice

As biodegradation is the degradation caused by biological activity the material must therefore be capable of being assimilated by microorganisms. The way to gauge the progress of this process is to measure the consumption of oxygen or the production of CO2. The main aim of studying biodegradability of plastics directly in the open environment is to determine what the physical, chemical and biotic conditions exist in the places where these materials are likely to end up. By doing so, these can be applied in the development of standardised laboratory tests which are then used to certify products against.

A major limitation of current standardised tests is their lack of analysis in the field or in anaerobic conditions. Many plastics are likely to sink to the bottom of bodies of water and therefore are more likely to end up in surface sediments. Currently standard test methods exist for testing the biodegradation of plastics in or around beach sediments and the sea surface. Below this where light cannot penetrate and into the deep sea, less is known as the environment becomes more hazardous and logistically difficult to study.

In addition, standard tests are accelerated tests conducted under 'optimal conditions' not designed to precisely replicate the natural environment. **Standard soil tests are generally conducted at around 25°C and marine at 30°C**, both significantly higher than the average temperature found in the equivalent natural environments—**the average annual temperature for sea surface, soil and air in Denmark is around 10°C**. This does not mean biodegradation will not take place, but it will be significantly slowed. This means that the risk to wildlife is still present over that time.

There are no international Standard Specifications (which specify tests and requirements to validate that biodegradation takes place in a particular timeframe) **for biodegradation in marine environment**. These only exist for industrial composting and for the specific application of mulch films in soil. Some private certifications exist which could be used as minimum requirement whilst standards are being developed. However, it is recommended that these are only used for particular products that cannot be prevented from entering the open environment by other means. An example of this may be shot gun shell cups although there may be alternatives that remove the need for plastic in this application altogether. Where items can be easily recovered or prevented from littering, **the focus should be on incentivising appropriate behaviour especially in light of the lack of certainty around biodegradation performance in the environment**

The Market for Bio-based and Biodegradable Plastics

The size of the global market is hard to measure, and data is hard to find which is partly due to the small size of the market compared with conventional plastics and the dominance of just a few players. However, it been predicted that there are 1.18-1.28 million tonnes of bio-based or biodegradable products on the global market with this making up 0.4% of the total plastics market in 2016. Of this, 57% is bio-based non-biodegradable—essentially bio-based versions of common polymers such as Polyethylene.

Packaging is the most common market area for bio-based and biodegradable plastics with carrier bags and biowaste bags the most common applications in Europe. In Denmark there is an estimated 550 tonnes of compostable plastics placed on the market annually which is primarily comprised of biowaste and carrier bags.

Current there are no policy drivers within Denmark that are likely to promote significant growth in the biodegradable or bio-based plastic market as growth strategies do not contain any binding targets at present.

Waste Management of Compostable and Biodegradable Plastics

Organic waste treatment in Europe is varied, and each of the processes available (composting, anaerobic digestion (AD)) have different input requirements and acceptability of compostable plastics. Italy has good acceptance of compostable plastics and their composting and AD facilities can effectively deal with them; this is from a combination of the use of the dry AD process with a secondary maturation phase and that composting facilities are required to run for at least 90 days—both of these mean that enough time is provided to allow full biodegradation to take place.

Germany, however, have less acceptance of compostable plastics as their AD facilities are focussed on biogas production, and there are no regulations on compost maturity—the use of 'fresh compost' is widespread which is processed in as little as 6 weeks and is unlikely to provide the time for compostable plastics to fully biodegrade.

The majority of food waste in Demark is processed in a ‘wet’ AD that is generally incompatible with compostable plastics due to the short processing duration and reported issues with becoming stuck in machinery. AD plants in Denmark are also mostly focused on receiving agricultural waste and mainly receive household waste as a ‘pulp’ after pre-treatment and removal of all types of plastics—these rejects are usually sent for incineration. Any remaining plastic contamination is currently though to be minimal and not a particularly pressing problem according to the Danish AD plants that were interviewed as part of this study—this may be a result of low market penetration of compostable plastics in Denmark but plants are also confident that an increase would not be problematic in the future. With the EU requirement that organic waste is separately collected from 2024, more plants may operate purely by receive household organic waste (rather than predominately agricultural). This may result in some of the problems found in other countries where (all types of) plastic contamination is a significant issue in maintaining compost quality.

In terms of the plastics recycling industry, there is evidence to suggest that compostable plastics in conventional plastic recycling can reduce mechanical and aesthetic properties. The effects of this are more pronounced in high quality streams such as food grade PET and less so for mixed plastic films. Compostable plastics can be identified and removed from plastics recycling and even in Italy where these materials are widespread, the contamination levels are not generally high enough to cause specific concerns at this stage.

In Denmark plastics recyclers in Denmark remain unconcerned about compostable plastic contamination. As the primary use of the material is in bags, these are less likely to contaminate the high value rigid plastic streams and there is no driver to see this change in the future.

The European Standard for packaging recoverable through composting and biodegradation—EN 13432— does not reflect the practice that currently takes place in the majority of organic waste treatment plants in Denmark. The standard specifically states that a further aerobic composting process is required after any anaerobic process which is not currently or expected to be common practice in Denmark. It is also not a strict requirement that biodegradability under anaerobic conditions is determined and therefore products can and are certified without this test taking place.

This standard is therefore not a reliable way of ensuring that compostable plastics on the Danish market are performing effectively in organic waste treatment. Based on this, it is recommended that Denmark introduce a minimum requirement that all compostable plastic products on the market in Denmark must also be tested under the anaerobic conditions specified in EN 13432 (both biodegradation and disintegration tests).

Life Cycle assessment of Bio-based and Biodegradable Plastics

To utilise LCAs to their full potential they need to be viewed in the context of the entire system and reviewed in terms of their reliability considering what has been omitted as much as what has been included. This being said, the overriding trend in results for both bio-based and biodegradable plastics is that feedstock production impacts affect the resulting environmental impact categories more than any other lifecycle stage.

Biodegradable plastics add an extra layer of complexity to the bio-based picture and need to be considered on a case by case basis with an understanding of the detail behind the calculations. This is due to studies calculating impacts for very specific applications meaning those results are not easily generalised.

Finally, the predicted large improvements in the efficiency of bio-based feedstock production process over the coming years is a key conclusion—in the same way that fossil based plastics have had many decades to achieve this. When using LCA results as a basis decision making, the timeframe must be considered and if possible, a predicted future scenario developed. This will give a forward-thinking perspective and highlight the potential of bio-based and biodegradable plastics and facilitate fairer comparisons.

1. Glossary

The following are some of the key terms that are used throughout this report. Terminology in this subject can often be confusing and contradictory, therefore when taking this report in the wider context it is important to make sure that when discussing certain aspects that the nomenclature is aligned.

Anaerobic Digestion	The breakdown of organic material by micro-organisms in the absence of oxygen which produces biogas, which can be burned for energy onsite or upgraded for injection into the gas network, and digestate, which can be used as a fertiliser.
Bio-based plastics	Bio-based plastics are those with building blocks that are derived partly or wholly from plant-based feedstocks.
Biodegradable (Biodegradation)	The breakdown of an organic chemical compound by micro-organisms in the presence of oxygen to carbon dioxide, water and mineral salts of any other elements present (mineralization) and new biomass or in the absence of oxygen to carbon dioxide, methane, mineral salts and new biomass.
Certifications	Third party testing to an established test method or standard. Often including a labelling scheme. Also includes certifications that do not have international standards associated with them such as the marine and fresh water environments.
Compostable Plastic	Plastic that biodegrades in industrial composting and is compliant with EN 13432
Conventional Plastic	Plastic derived from fossil-based feedstocks that is not considered to be biodegradable or compostable in any reasonable timeframe
EN 13432	The European standard “Requirements for packaging recoverable through composting and biodegradation.” This is the standard used to test that a packaging material is compostable in industrial composting.
Home Compostable Plastic	Plastic that biodegrades in home compost in under 12 months. In absence of a UK of European standard this refers to the specification from OK Compost: Home.
Industrial Composting	A blanket term which includes all forms of centralised organic waste treatment that is characterised by high levels of control and results in various forms of soil improver.
Materials recycling Facility (MRF)	A plant that receives, separates and prepares recyclable materials for sale to material manufacturers
Polymer/Plastic	A polymer is a chemical compound that contains a chain of repeating molecular units. A plastic material is a polymer, typically modified with additives, which can be moulded or shaped by pressure and temperature.
Waste to Energy (WtE)	Incineration of residual waste where energy is recovered as electricity and/or heat

1.1 Material Abbreviations

The following is a list of the material acronyms and abbreviations that are used in this report

Bio-PA	Bio-based Polyamides
Bio-PE	Bio-based Polyethylene
Bio-PET	Bio-based Polyethylene Terephthalate
Bio-PP	Bio-based polypropylene
HDPE	High density Polyethylene
LDPE	Low Density Polyethylene
MEG	Monoethylene Glycol
PA	Polyamides
PCL	Polycaprolactone
PEF	Polyethylenefuranoate
PET	Polyethylene Terephthalate
PHA	Polyhydroxyalkanoate
PHB	Polyhydroxybutyrate
PLA	Polylactic acid
PP	Polypropylene

2. Introduction and Objectives

2.1 Background

There is currently considerable interest in bioplastics from consumers and industry and business, but there is still great uncertainty about the subject and several misconceptions exist. With the National Plastic Action Plan developed by the former Danish Governmen in December 2018 and the subsequent political agreement of 30th January 2019, Denmark has a consolidated plan of action for plastics.

The plan focuses on less plastic in nature, smarter production and consumption, more cooperation in the value chain, better waste management, a stronger scientific evidence base and increased recycling. The action plan contains 27 initiatives to help ensure a Denmark with a more circular plastic economy. In addition, there are a number of other initiatives described in the political agreement of 30 January 2019. According to the plan initiative no. 23 requires the building up of knowledge around the advantages and disadvantages of bio-based plastics.

2.2 Objectives

The Danish Environmental Protection Agency (Miljøstyrelsen) on the basis of the above need to build knowledge of biobased and biodegradable plastics as an alternative to conventional plastics based on fossil resources, including supply and market mapping and possible waste management scenarios. To this end the following requirements were investigated during the course of this report:

- Literature review of biodegradable plastics and how they behave under different conditions and outline of ongoing studies
- Description of current standards and regulations, and recommendations for possible future standards and regulations for Denmark
- Description and analysis of the national and global levels of feedstock and material along with current and future applications of biobased and biodegradable plastics
- Description and analysis of scenarios for waste products of bio-based and biodegradable plastics, including options for recycling, composting and other biological treatment in relation to Danish conditions
- Analysis of other countries waste management of bio-based and biodegradable plastics

3. Defining Bio-based and Biodegradable Plastics

3.1 Bio-based Plastics

There are several definitions for the term ‘bio-based plastic’ although most are similar to the one used by the International Union of Pure and Applied Chemistry[1]:

> **” …a polymer composed or derived in whole or in part of biological products issued from bio-mass (including plant, animal, and marine or forestry materials).”**

It should be noted that, while fossil fuels had their origins in animal life and biomass, hydrocarbon fossil fuels are not considered bio-based. Importantly, however, under most definitions a product can be referred to as bio-based even if it has mostly fossil-based content, thus it is important to look at ‘bio-based content’. The bio-based content is the amount of biomass used by percentage of weight to create the final product; for example, in bio-PET 32% of the final product is made of a completely bio-derived monomer whereas the other monomer is fossil-based, giving the product a 32% bio-based content. It is measured either through the material’s bio-based carbon content or the mass of bio-derived substances within the material. Some certifications require a minimum bio-based content under one or either of these tests. Test and certification methods for this are further described in Section 5.1.1.

For the purposes of this report there is no lower limit of bio-based content specified, but all materials discussed fall under the above definition.

3.1.1 ‘Drop-in’ and Novel Bio-based Plastics

Bio-based plastics can be further categorised as drop-in or novel plastics. ‘Drop-in’ bio-based plastics are so called because of their ability to be exchanged directly with their fossil-based counterpart. Many of these have been available for a long time and are identical in chemical structure but using a biomass feedstock. For example, bio-PET (as used in Coca Cola’s PlantBottle) is simply PET made partially from biomass. There are similar bio-based alternatives to PE and PP.

On the other hand, there are completely novel bio-based plastics with a chemical structure like no other, for example PLA (the most common biodegradable bio-based material) and PEF (a newer non-biodegradable bio-based PET replacement). These novel materials are used because of their specific performance capabilities or properties e.g. PEF has better barrier properties than PET.

Compared to novel bio-based plastics, drop-in bio-based plastics are easier to process in existing manufacturing and recycling systems as they are identical to their fossil-based counterparts. Existing sorting plants for plastic products are set to accept fossil-based plastics and do not have separate streams for the newer bio-based plastics.

3.2 Biodegradable Plastics

It is important to note that almost all materials may ultimately biodegrade, even in the open environment, though some conventional plastic items are predicted to take many hundreds of

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[1] Vert, M., Doi, Y., Hellwich, K.-H., et al. (2012) Terminology for biorelated polymers and applications (IUPAC Recommendations 2012), Pure and Applied Chemistry, Vol.84, No.2, pp.377–410

years to do so[2]. Some biodegradable plastics may biodegrade very quickly in one environment but degrade over many years (or not at all) in a different environment. Therefore, it is very important to define timeframe and environment when describing and defining biodegradation. There are many definitions from national and international organisations which vary significantly but generally do not specify a particular environment or timeframe. Two definitions from CEN[3] are shown below:

Biodegradation

> **" A degradation caused by biological activity, especially by enzymatic action, leading to a significant change in the chemical structure of a material".**

Biodegradable Plastic

> **" A degradable material in which the degradation results from the action of microorganisms and ultimately the material is converted to water, carbon dioxide and/or methane and a new cell biomass".**

Some definitions (notably from ISO) only refer to a chemical change in the material by microorganisms, however, the CEN (and German DIN) standards refer to the conversion of material into microbial metabolic products i.e. they can be consumed by microbes.
These definitions are further qualified with corresponding test methods, standards and certifications for specific environments, such as industrial composting. It should be emphasised that the term biodegradable has little or no meaning without a clear specification of the exact environmental conditions that this process is expected to occur in. For example, the term compostable plastic refers to a material that can biodegrade in an industrial composting facility but not necessarily in a home composting situation and even less so in the open environment.
The generally accepted mechanism for the acceptance of products that claim to be biodegradable in specific environments is to develop a lab scale test which can be repeatable and representative. This allows standards to be developed that can be certified to, which in theory, gives producers and retailers the framework to appropriately specify materials with the performance requirements for a given application. This is discussed further in section 5.1.2

3.3 The Difference Between Bio-based and Biodegradable Plastics

There is often confusion around the nature of bio-based plastics in comparison to biodegradable plastics. Consumers may—quite understandably—believe that bio-based plastics will biodegrade. Whilst this may be true of some, it is not true of all, as the plant-based feedstock can also be used to make conventional (non-biodegradable) plastic. Figure 1 shows some of the common types of plastic and whether their feedstock is fossil or bio-based.
Only a few are both derived from natural materials and known to biodegrade under certain conditions. Equally, there are also bio-based versions of conventional plastics which are chemical and functionally identical but are synthesized from organic rather than a fossil-based feedstock. There are also plastic materials that are made from fossil-based material but are known to biodegrade.

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[2] The Ocean Conservancy (2003) *Pocket Guide to Marine Debris*, 2003

[3] European Committee for Standardization *EN 13193:2000 Packaging. Packaging and the environment. Terminology*

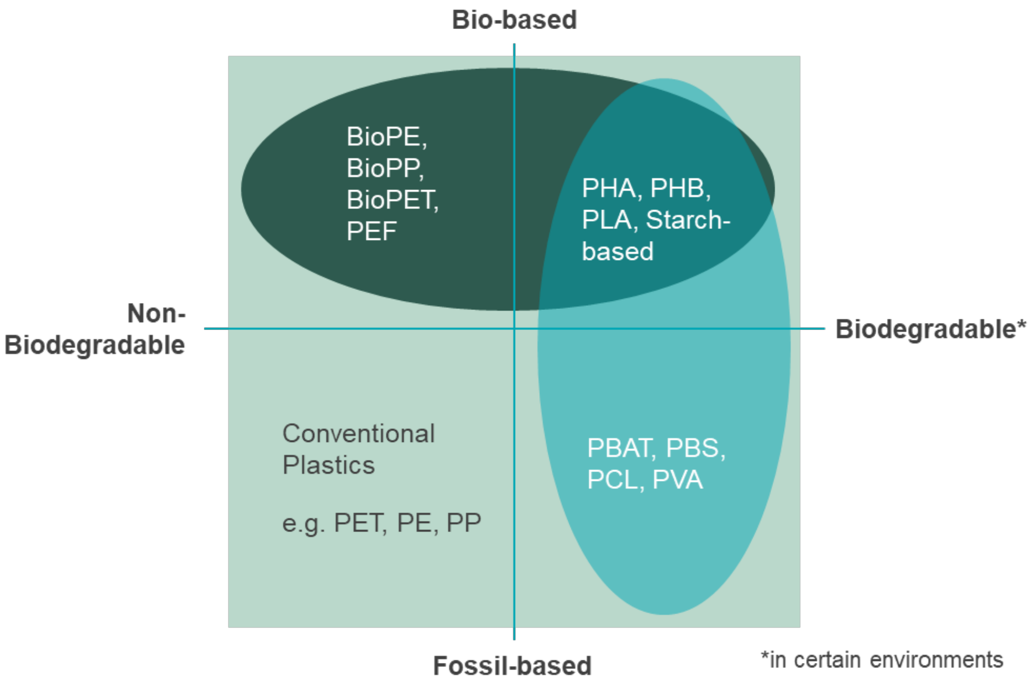


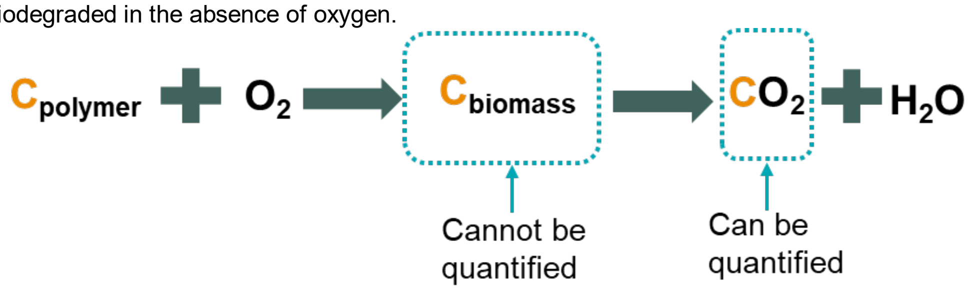
FIGURE 1. Bio-based and Biodegradable Plastics[4]

[4] Based on the figure shown at: https://www.european-bioplastics.org/bioplastics/materials/

4. Biodegradation in Practice

4.1 The Science of Plastic Biodegradation

As biodegradation is the degradation caused by biological activity the material must therefore be capable of being assimilated by microorganisms. The aerobic process shown in the simplified equation below shows how the microorganisms use oxygen to metabolise (biodegrade) the carbon in the polymer which in then mineralised into CO2 and water. The microorganisms secrete enzymes which break down (cleave) the polymer chains to a size which makes them bioavailable. This biodegradation process takes place on the surface as the enzymes cannot penetrate the polymer which means that the carbon in the core of the plastic is unavailable until the outer is metabolised. This is the primary reason why thicker material biodegrades slower. Anaerobic biodegradation is similar, but requires specific strains of microorganism which can sustain growth in the absence of oxygen. Without oxygen, the organism metabolises the carbon and hydrogen in the polymer to produce CH4 – methane—rather than CO2 and water. This is the same process that takes place deep in landfills when organic matter is biodegraded in the absence of oxygen.



Source: Adapted from Chinaglia et al[5]

The way to gauge the progress of this process is to measure the consumption of oxygen or the production of CO2. Biodegradation percentage is most often calculated as the ratio between the CO2 produced and the theoretical CO2 if all of the carbon in the material were oxidised. A proportion of the carbon will always be converted to biomass and therefore 100% biodegradation will not result in 100% mineralisation (i.e. 100% of the available carbon converted to CO2)[6]. In this way it is only mineralisation that is directly measured rather than biodegradation itself.

There is yet to be a developed a reliable method to measure the transfer of carbon into biomass although this has recently been achieved on a small scale by labelling the carbon in the polymer and tracking it through the process.[7]

Different environments will also lead to fast or slower biodegradation based on, amongst other factors, prevalence of microorganisms and the temperature (which directly affects microorganism activity – discussed further in Section 5.3.1). Figure 2 shows examples of the environments plastics may end up in and the conditions that are commonly found there. The environments can also be sub-divided into 'managed' and 'un-manged' with the former allowing specific control of the environment in order to provide optimum conditions for biodegradation to take place.

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[5] Chinaglia, S., Tosin, M., and Degli-Innocenti, F. (2018) Biodegradation rate of biodegradable plastics at molecular level, *Polymer Degradation and Stability*, Vol.147, pp.237–244

[6] Bettas Ardisson, G., Tosin, M., Barbale, M., and Degli-Innocenti, F. (2014) Biodegradation of plastics in soil and effects on nitrification activity. A laboratory approach, *Frontiers in Microbiology*, Vol.5

[7] Zumstein et al. (2018) Biodegradation of synthetic polymers in soils: Tracking carbon into CO2 and microbial biomass, Sci. Adv. 2018;4: eaas9024

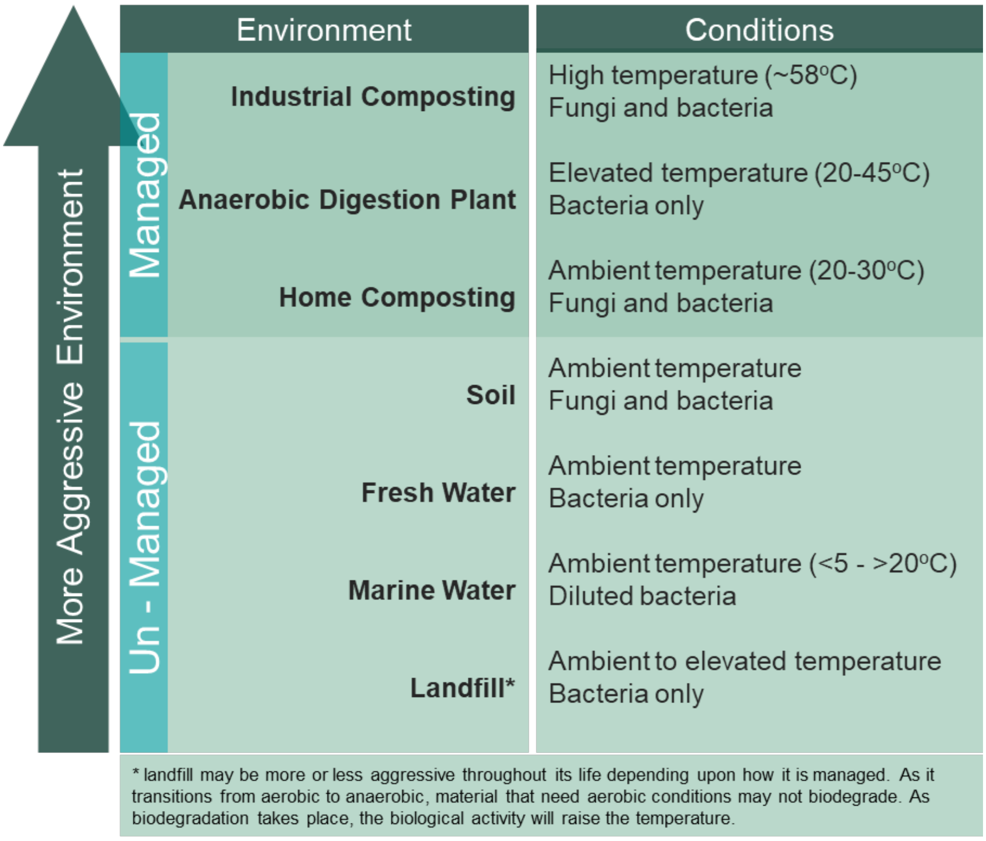

FIGURE 2. Environments for Biodegradation
Source: Adapted from- Degradable Polymers and Materials – Principles & Practice,33-43, 2012. Editors: Khemani, K. and Scholz, C

4.2 Studying Biodegradation in the Open Environment

The main aim of studying biodegradability of plastics directly in the open environment is to determine what the physical, chemical and biotic conditions exist in the places where these materials are likely to end up. By doing so, these can be applied in the development of standardised laboratory tests which are then used to certify products against.

A major limitation of current standardised tests is their lack of analysis in the field or in anaerobic conditions. Many plastics are likely to sink to the bottom of bodies of water and therefore are more likely to end up in surface sediments. Surface sediments vary greatly in the level of available oxygen; factors such as available dissolved oxygen in the water, amount of organic carbon in the sediments and the degree of turbulence from the movement of sediment-dwelling organisms all influence whether aerobic conditions likely to be achieved.[8]

Open-Bio, a six-year EU funded project ended in 2016 with one work package aimed at testing in-situ biodegradation and developing draft test methods and specifications on the marine degradation of bio-based materials.[9,10] This was considered *pre-normative research* paving the way for standard specifications to be developed.

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[8] National Oceanic and Atmospheric Administration *DeepCCZ: Why Does the Oxygen Penetration Depth Vary in Different Sediments?*, accessed 8 November 2019, https://oceanexplorer.noaa.gov/explorations/18ccz/logs/june13/june13.html

[9] Weber, M., Makarow, D., Unger, B., et al. (2018) Assessing Marine Biodegradability of Plastic—Towards an Environmentally Relevant International Standard Test Scheme, *Proceedings of the International Conference on Microplastic Pollution in the Mediterranean Sea*, pp.189–193

[10] *Open-Bio: Opening bio-based markets via standards, labelling and procurement*, accessed 17 October 2019, https://www.biobasedeconomy.eu/projects/open-bio/

A number of tests were conducted for this project off the coast of Greece and Italy which measured the disintegration of various bio-based plastics in the eulittoral zone (intertidal beach), sublittoral zone (seafloor) and the pelagic zone (water column). The test samples were held in metal frames in the different scenarios. Sensors attached to the frames recorded the surrounding conditions, such as temperature, and regular samples were taken from the test materials for analysis.[11] The disintegration of the materials was measured and combined with the results from laboratory tests, which measured CO_2 production and O_2 consumption. This is important, as in-situ experiments for degradation in the marine environment cannot directly measure biodegradation (i.e. the CO_2 produced by microorganisms), but must rely on inferences such as disintegration, mass loss or molecular weight reduction—this can be problematic as mass loss may occur without biodegradation. Linking these two aspects together allows conclusions to begin to be drawn around the methodological criteria and procedures that are required to measure the rate of biodegradation.[12] This development is still ongoing and is likely to do so for some time.
Published scientific experiments testing for biodegradability in the marine environment are uncommon, but mostly involve techniques such as mesh cages placed in different zones of the marine environment. Although marine habitats can be split into many different areas (for which definitions vary), there are three basic types which are the focus of test development currently (also shown in Figure 3: Ocean Zones);

- **Littoral zone** – the area in and around the shore line which is sometimes divided into;
  - **Supralittoral –** where spring high tides splash but not submerge
  - **Eulittoral** – shoreline that is regularly exposed and submerged throughout a day
  - **Sublittoral** - Permanently submerged extending out to the continental shelf where light still reaches
- **Benthic Zone** – Extending from the continental shelf to the deep-sea floor
- **Pelagic Zone** – The water column away from coastal areas

Currently standard test methods exist for eulittoral/sublittoral zones and the pelagic zone — although the pelagic zone encompasses the water column from sea surface to sea floor, testing has largely focused on the photic zone down to 200 m. This is where sunlight can penetrate to and thus is where the majority of marine life resides. Below this and into the deep sea, less is known as the environment becomes more hazardous and logistically difficult to study.

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[11] HYDRA Institut für Meereswissenschaften (2015) *Plastic in the Sea - Research Project OPEN-BIO*

[12] Lott, C., Weber, M., Makarow, D., and Unger *Open-Bio: Opening bio-based markets via standards, labelling and procurement. Deliverable N° 5.8: Marine degradation test field assessment*

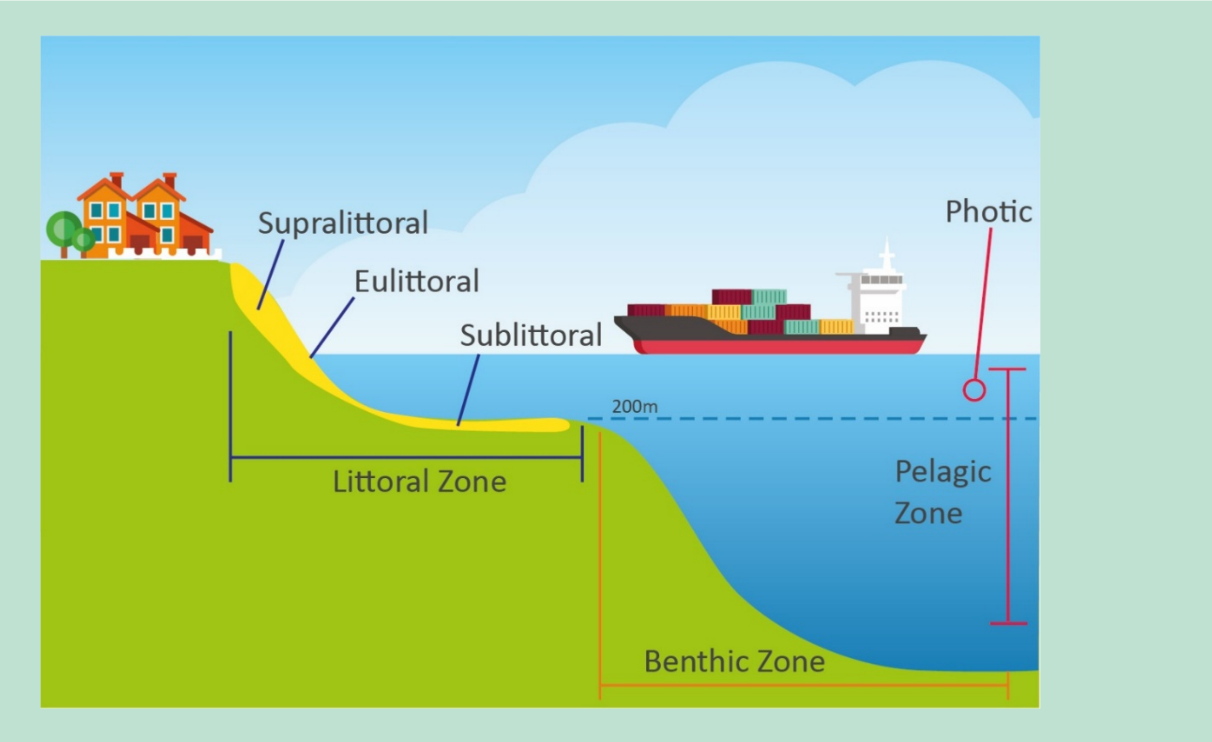

FIGURE 3. Ocean Zones

Furthermore, many plastics including a lot of the more common bio-based biodegradable plastics are negatively buoyant in water would tend to sink and therefore are more likely to end up on riverbeds, the sea floor, and buried in sediments.[13] The exact pathways that plastics will take once in the marine environment is not fully understood, but far more is thought to enter the oceans than has been found floating on the surface even amongst those plastics that would usually be expected to float— The process of 'biofouling' where organisms colonise the material and increase its weight is known to contribute to this.[14,15]

Upper layers of sediments also vary greatly in the level of available oxygen; factors such as available dissolved oxygen in the water, amount of organic carbon in the sediments and the degree of turbulence within sediment from movement of benthic and sediment-dwelling organisms may impact this. Therefore, aerobic conditions are not guaranteed for biodegrading sunken plastics. The lack of test methods that reflect anaerobic conditions is problematic in this regard.

A common criticism of laboratory testing is its lack of representativeness to field conditions. For instance, the inoculum introduced to substances as the biodegradation agent, varies between tests, potentially causing differing results.[16] There is also the issue of whether these microorganisms are commonly found in open environments. They are often selected from

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[13] Piero Franz (2015) *Aerobic Biodegradation of Third generation Mater Bi under marine condition*, 2015
Piero Franz (2015) *Aerobic Biodegradation of Third generation Mater Bi under marine condition*, 2015

[14] Lebreton, L., Slat, B., Ferrari, F., et al. (2018) Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic, *Scientific Reports*, Vol.8, No.1, p.4666

[15] Jambeck, J.R., Geyer, R., Wilcox, C., et al. (2015) Plastic waste inputs from land into the ocean, *Science*, Vol.347, No.6223, pp.768–771

[16] Pagga, U. (1997) Testing biodegradability with standardized methods, *Chemosphere*, Vol.35, No.12, pp.2953–2972

wastewater sludge, animal faeces or soil samples and undergo a filtration and culturing process, which could limit the biodiversity of the inoculum.[17]

In addition, standard tests are *accelerated tests* conducted under 'optimal conditions' not designed to precisely replicate the natural environment. Standard soil tests are generally conducted at around 25°C and marine at 30°C, both significantly higher than the average temperature found in the equivalent natural environments. This is due to the commercial requirement that the tests be completed in a reasonable timeframe. For environments where the average temperate is lower than specified in the tests—which would be the case for the majority of the marine environment outside of the very surface of the ocean or the beach sediment in summer—the implication is not that biodegradation would not take place, but it would be considerably slowed. Time is a particularly important aspect as the longer the material remains in the environment, the greater the chances of it causing negative impacts—the scale of such impacts is the subject of a large amount of scientific study in recent years, but quantifying this is still not something that can be done with certainty at this stge.

It is also important to note that the rate of biodegradation of materials in a marine environment, while limited to a degree by oxygen, is also heavily limited by nutrient availability e.g. nitrogen, phosphorus and iron. Nutrient quantities vary depending on location and depth, as well as temperatures. The further down the stratifications of marine sediment, the less dense the populations of micro-organisms become, changing to micro-organism communities able to survive in anoxic environments. This demonstrates the challenging nature of studying this field and that it may not be possible that all circumstances can be represented by laboratory tests.

Given these limitations, considering results from a wide range of test scenarios will be paramount to building a picture of how biodegradable a material is.

4.2.1 On-going Plastic Biodegradability Studies

Research into biodegradable plastics and how they react in different environments is on-going in both the public and private sectors across the world. To provide an understanding of the active research areas, a desk-based review, collating a cross section of on-going plastic biodegradable plastics studies has been undertaken. The emphasis of the review has been on studies researching the biodegradability of biodegradable plastics in different situations. A full list of studies found can be found in Appendix 7**Error! Reference source not found.**.

The main actor in the field of plastic biodegradability research was found to be universities with private companies mostly limiting their research to biodegradability standards.

Universities across the world are now researching biodegradable plastics. There are a variety of different research angles being taken with some research groups focusing wholly on testing the biodegradability of current plastics, others who are quantifying the properties of biodegradable plastics, and some who are developing new biodegradable polymers.

There is also a variety in the scope of research and how much focus there is on biodegradable plastics. For some projects biodegradable polymers are the main research area but in others the scope is wider, either encompassing all biobased products or as a part of a general sustainability objective.

Active research, found as part of the desktop review, could broadly be grouped into four broad research areas. Table 1 lists these and references specific projects to provide an understanding of the variety of work currently active.

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[17] Harrison, J.P., Boardman, C., O'Callaghan, K., Delort, A.-M., and Song, J. (2018) Biodegradability standards for carrier bags and plastic films in aquatic environments: a critical review, *Royal Society Open Science*, Vol.5, No.5, p.171792

TABLE 1. University Research areas

Studying the biodegradation of biodegradable plastics	**Danmarks Teknicke Universitet**: Researching bio-based plastics in general, including biodegradability. **University of Stuttgart**: Researching plastic degradation in different marine environments and how degraded products affect the marine environment.
Quantifying the properties of biodegradable plastics	**University of Houston**: Comparing the structural properties of biodegradable plastics with traditional plastic polymers. **Cornell university**: Looking into the technical properties of biodegradable plastics.
Developing new biodegradable polymers	**Aston University:** Working to improving the physical properties of biodegradable polyesters. **University of Lund:** Creating new biodegradable polyesters from sawdust.
Applications of biodegradable plastics	**Wageningen University**: Looking into the biodegradability of plant pot alternatives. **University of Bath**: Researching biodegradable replacements to microbeads in cosmetics.

A larger group of universities have sustainability or biomass focused research groups looking into a variety of issues and only touch on biodegradable plastics. For example, University College London has a research group on the circularity of biopolymers, their research touches on biodegradability but the main focus is on reviewing recycling options of bio-based plastics such as catalysed reactions.
Private companies are also playing a role in active primary research. This is sometimes through collaboration with universities and private companies, such as the bio-plastics cluster group at Hannover University which is currently working with industry to develop new biodegradable plastics.
One of the main contributions from private companies comes from the development of standards and the associate certified testing laboratories. The tests include tests on compostability or biodegradability but also more niche tests such as disintegration. These laboratories often also carry out their own primary research. An example is the Belgium Organic Waste Systems which has an association with the University of Ghent and has research labs looking into biodegradability and compostability of plastics as well as anaerobic digestion.

4.3 Biodegradation Testing in Laboratory Conditions

4.3.1 Testing in Composting or Soil

There is a suite of ISO tests that are the building blocks of the country level and EU level standards. The tests define in detail the testing procedures for biodegradation, disintegration and toxicity effects. Tests differ in the choice of inoculum (microbially active medium e.g. soil, compost etc.) and the measurement methods for recording the biodegradation and disintegration levels. (e.g. ISO 14851 – oxygen demand and ISO 14852 – evolved carbon dioxide) – the current tests are summarised in Appendix A.1.0.
The purpose of lab testing is to show the inherent nature of the material to biodegrade under a given set of conditions which is defined in ISO 14855 as a:

> **"breakdown of an organic compound by microorganisms in the presence of oxygen into carbon dioxide, water and mineral salts of any other elements present (mineralization) plus new biomass.".**

The most commonly used test for biodegradation is ISO 14855 (Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions). The test simulates intensive aerobic composting conditions as found in industrial composting facilities. The test material is mixed with a stabilised, mature compost derived from the organic fraction

of municipal solid waste (the inoculum). The mixture is incubated at a constant temperature of 58°C ± 2°C until a plateau phase of biodegradation is recorded, which should be reached in no more than 6 months.
The test measures the carbon dioxide evolved and compares this with the theoretical maximum amount of carbon dioxide that the material could produce. Cellulose reference material is also tested in parallel under the same conditions and the test is deemed invalid if the refence material does not shown to biodegrade—indicating that some part of the test procedure is not operating correctly.
The type of inoculum used in a test will impact on the biodegradation process. ISO 14855 states that:

> **"Well aerated compost from a properly operating aerobic composting plant shall be used as the inoculum…It is recommended that compost from a plant composting the organic fraction of solid municipal waste be used in order to ensure sufficient diversity of microorganisms. The age of the compost should preferably be between 2 and 4 months."**

The age of the compost is important as the maturity of the compost dictates the level of biological activity present. In this case, compost of 2-4 months in age is still very biologically active and would be considered 'fresh compost' under the German Rottegrad system.[18]
Certain substances will not be suitable for testing with ISO 14855, particularly colouring inks, additives or colourants. In these cases, the alternative tests ISO 14851 and 14852 have been designed which test within an aqueous medium. The inoculum is derived from activated sludge, compost or soil. Biodegradation is measured either through the analysis of evolved carbon dioxide (ISO 14852) or through the consumption of oxygen (ISO 14851).
ISO 17556 is another biodegradation test that can be used for some plastic materials but it uses a soil inoculum and measures biodegradation by the amount of oxygen consumed rather than by the amount of evolved carbon. Using soil means that the inoculum is likely to be less biologically active than a mature compost, but as the soil can be taken from anywhere, this is difficult to verify.
Disintegration of plastics are tested using ISO 16929 and ISO 20200. ISO 16929 takes pieces of the sample material that are 5cm x 5cm (or 10cm x 10cm for films) and places them in a compost bin of minimum volume 140L. The compost bin is filled with a homogenous biowaste of the same age and origin with the addition of 10-60% bulking agent. The compost is turned weekly during the first 4 weeks of the test, then fortnightly until the end of the test. (12 weeks in total) The mixture is then passed through a 10mm sieve followed by a 2mm sieve to pick out remaining particles of the test material. These are visually inspected. ISO 20200 differs in that it uses a laboratory scale test with a synthetic solid waste inoculated with mature compost. The degree of disintegration is calculated quantitatively by comparing the initial dry mass of the material with the dry mass of residual material that didn't pass through the sieve—this particular task requires a high level of training and skill to accurately identity fragments within the compost.

[18] https://www.kompost.de/uploads/media/Compost_Course_gesamt_01.pdf

4.3.2 Testing in Marine Conditions

Significantly fewer standard tests for marine biodegradability exist. A 2015 EU report stated that there were only five marine-specific standard tests; all of them test using aerobic conditions and ASTM D7473 only testing for disintegration rather than biodegradation.[19] Since 2015, two other marine standardised tests have become available from the International Organisation for Standardisation (ISO) and ASTM D6692 has been withdrawn; there are still none that assess biodegradation in an anaerobic environment—See Table 2.**Error! Reference source not found.**

No European Committee for Standardisation (CEN) test standards exist at present although this is not a particular problem in itself as ISO test methods are commonly used in European Specifications. For the open environment and specifically the marine environment the development of test methods is still ongoing.

The test procedures are very similar to those for compost and soil, but the inoculum being some form of marine derived material—usually sea water and/or sediment from the sea bed.

TABLE 2. Current Marine Test Standards

Standard or Test Method	Inoculum	Temperature (°C)	Measurement Type	Test Duration
OECD 306 (1992)	Natural Seawater with added nutrients	15—20°C	Oxygen demand CO2 evolution	60 Days 28 Days
ISO 16221:2001	Natural Seawater with added nutrients	15—25°C	Oxygen demand CO2 evolution	60 Days
ISO 18830:2016	Sediment or sediment and seawater	15–28 (± 2)	Oxygen demand	<24 months
ISO 19679:2016	Sediment or sediment and seawater	15–28 (± 2)	CO2 evolution	<24 months
ASTM D6691-09	Seawater	30 (± 1)	CO2 evolution	< 3 months
ASTM D7473-12	Seawater or a combination of seawater and sediment	varies	Visual check for degradation (disintegration)	< 6 months
ASTM D7991-15	Sediment and seawater	15–28 (± 2)	CO2 evolution	<24 months

[19] Weber, M., Lott, C., and HYDRA Institute (2015) Open-Bio: Opening bio-based markets via standards, labelling and procurement. Deliverable N° 5.5: Review of current methods and standards relevant to marine degradation

Summary of Biodegradation in Practice

As biodegradation is the degradation caused by biological activity the material must therefore be capable of being assimilated by microorganisms. The way to gauge the progress of this process is to measure the consumption of oxygen or the production of CO2.

The main aim of studying biodegradability of plastics directly in the open environment is to determine what the physical, chemical and biotic conditions exist in the places where these materials are likely to end up. By doing so, these can be applied in the development of standardised laboratory tests which are then used to certify products against.

A major limitation of current standardised tests is their lack of analysis in the field or in anaerobic conditions. Many plastics are likely to sink to the bottom of bodies of water and therefore are more likely to end up in surface sediments. Currently standard test methods exist for testing the biodegradation of plastics in or around beach sediments and the sea surface. Below this where light cannot penetrate and into the deep sea, less is known as the environment becomes more hazardous and logistically difficult to study.

In addition, standard tests are accelerated tests conducted under ‘optimal conditions’ not designed to precisely replicate the natural environment. Standard soil tests are generally conducted at around 25°C and marine at 30°C, both significantly higher than the average temperature found in the equivalent natural environments.

5. Standards and Certifications

For this section of the report the focus is on how the products are tested and certified in practice and the issues around doing this.

Standard Test Methods – These are often standardised and detail the conditions the material should be tested under to obtain specific and repeatable results. In a laboratory setting (previously described in Section 4.3). These also often stipulate specific timescales and temperatures that the tests can be performed under.

Standard Specifications – These are national or international standards that provide specific thresholds to achieve under related standard test methods—usually a percentage biodegradation or fragmentation. The standards stipulate which tests are required and may require a deviation from temperatures or timescales. Meeting the standard is often considered a requirement for certifications.

Certifications – These are distinct from standards in that certifications can be provided by an organisation (public or private) and therefore do not necessarily provide legitimacy unless they refer to established and accepted test methods and standard specification. Often these incorporate a labelling scheme.

5.1 Bio-based Plastics

5.1.1 Certifying Bio-based Content

In Europe there are no agreed minimum requirements in the amount of bio-based content for a product or material to be called a bio-based plastic. However, there are standardised test methods and associated independent certifications that allow manufacturers to indicate the content using a labelling scheme.

EN 17228 was published in 2019 and covers the terminology, characteristics and communication for bio-based polymers. This refences EN 16785 which determines two methods for measuring bio-based content; radio carbon analysis and material balance.

The most common method for determining bio-based carbon content is tracked Carbon-14. C-14 is radioactive and occurs in living organisms but degrades as soon as the organism is no longer living. This can be detected, and given that the C-14 in fossil fuel derived material is old enough to have decayed, it will not register. The 'younger' C-14 will be active and can be recorded. The difference between the two is the bio-based concentration.

This is used in two European certification and labelling schemes—TUV Austria's OK bio-based and DIN Certco's DIN Geprüft— to determine the bio-based content with the appropriate label awarded as a result (See Figure 4 and Figure 5). Both certifications do not certify any materials or products under 20% bio-based carbon content and do show the specific level of bio-based content in the labelling scheme.

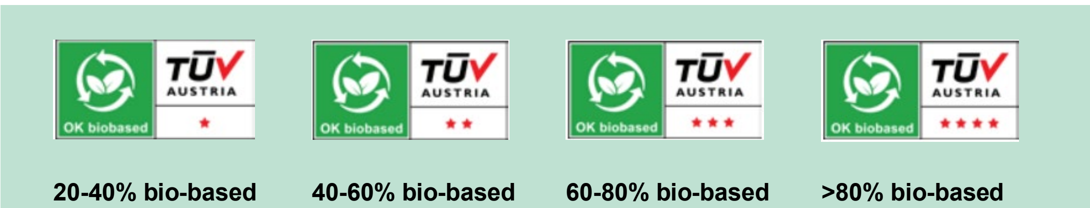

FIGURE 4. TUV Austria Bio-Based Labelling

FIGURE 5. DIN Certco DIN Geprüft Labelling[20]

Further afield, the United States under the U.S. Department of Agriculture (USDA) have been running a national scheme—the BioPreferred Program— since 2002 in order to promote bio-based materials. It is also required that all federal agencies purchase biobased products in categories identified by the USDA—the current list includes 139 product categories, all with minimum bio-based requirements depending upon the product type.[21]

FIGURE 6. USDA Biobased Certification label

It is important when assessing bio-based content, to realise that the method and associated standard used the calculate this can produce different results. This means that different labelling scheme are not always compatible or can be compared. For example, the USDA scheme uses ASTM D6866, whereas Europe uses EN 16785. These methods will produce a different result. Given that there is no agreed way of specifying bio-based content, the existence of these different methods is not inherently problematic; however, they may be problematic if they are all used side-by-side in the same country (where products are bought from countries using different certifications) or for the same product types.
Currently, 183 products are certified by TUV Austria under their labelling scheme, with two of these products registered to Danish companies: Ellepot plant pot[22] and the BabyDan[23] child safety gate which are both certified to four stars. The Netherlands and Italy have the highest number of certifications in Europe with 28 and 14 respectively.
The greatest proportion of certified products are packaging products (see Figure 7) with 65 products certified. Bags and catering products have similar numbers of products certified with proportions of 17% and 15% respectively and garden, horticultural & agricultural products make up the lowest proportion of certified products at 15%. A quarter of all the certifications are products categorised as ‘other’. An analysis of these products found that they represent a wide range of products including: tape, light switches, paint, nappies, trainers, and potties. The

[20] *Din Certco website homepage*, accessed 9 November 2018, *http://www.dincertco.de/*

[21] https://www.biopreferred.gov/BioPreferred/faces/pages/ProductCategories.xhtml

[22] https://www.ellepot.com/

[23] https://www.babydan.com/

products categorised in this 'other' category tended not to be single use products, but bio-based versions of more durable products.
Of the products certified there is a relatively wide spread as to star rating, as shown in Figure 8. Products certified to the 4-star rating (over 80% biobased content) have the largest share, with the rest of the products spread fairly evenly over the 1, 2- and 3-star ratings.

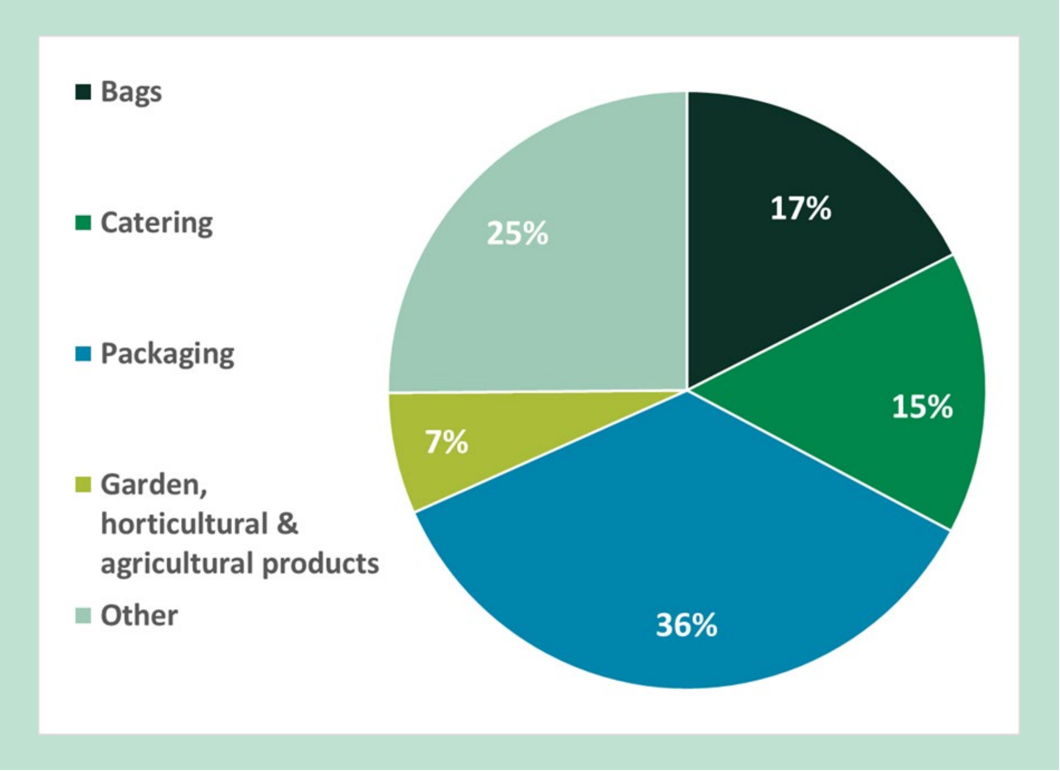

FIGURE 7. Percentage of Products Certified to TUV OK Biobased Standard by Product Type

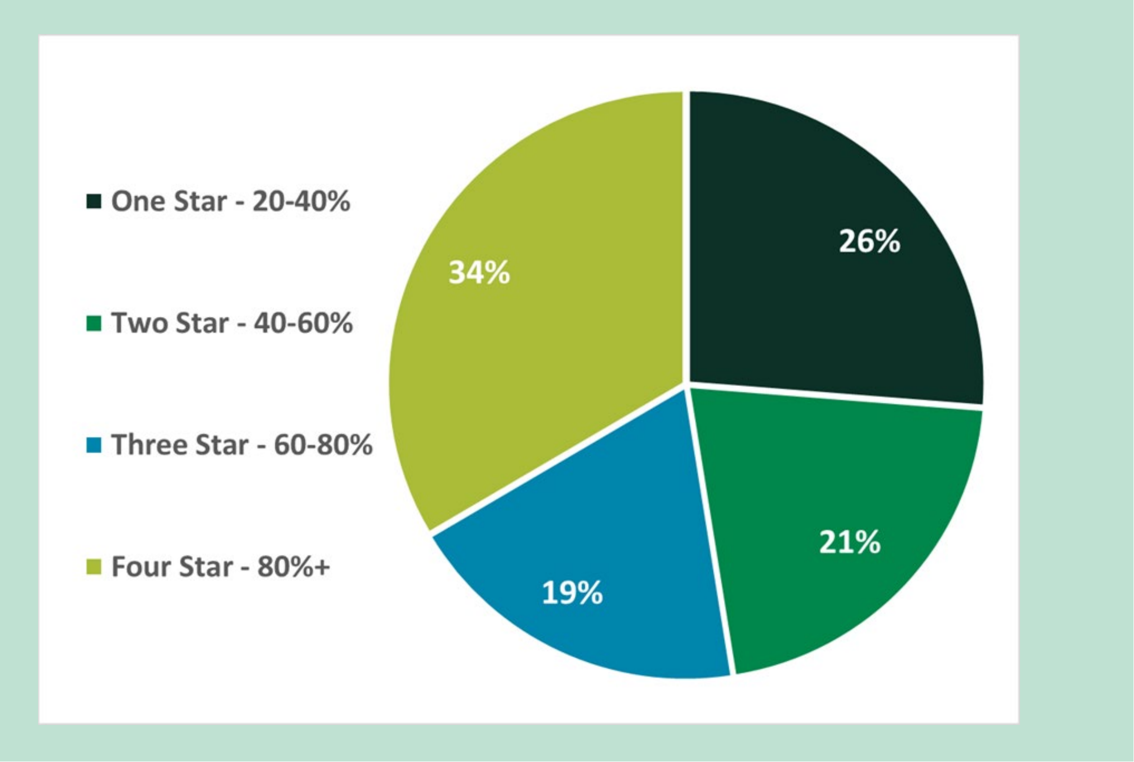

FIGURE 8. Proportion of Products Certified by Star Rating

5.1.2 Bio-based Feedstock Verification

There are a variety of certification schemes on the market. In the previous section of this report certifications relating to the bio-based content of the product were discussed; this section collates certificated ethical standards relating to the production of the bio-based feedstocks. Most of the sustainability standards are compliant with the European Union's Renewable Energy Directive (RED)[24] with only a few schemes operating independently. The independently running schemes are mostly very specific to a sector, e.g. cosmetics, and only consider bio-based plastics as a minor part of the criteria.

The Renewable Energy Directive contains legislation relating to the production of biomass for biofuel use within the EU. The legislation is a mixture of public and private regulation with the RED prescribing a list of minimum criteria and then approving voluntary public schemes which comply with the minimum requirements. Although these schemes are compliant with the RED directive for biofuel production many of them are also applicable for any use of biomass, including bio-based plastics. All schemes relevant to bio-based plastic production have been collated in Appendix 8.

The large number of schemes comes from the variation in the scope of crops or feedstocks they are relevant to. For example, some only apply to a particular crop such as the not for-profit, Bonsurcro[25], which has developed a certification scheme specifically for sugarcane and Round Table Responsible Soy (RTRS)[26] which certifies soy production. Both of these are example of industry led organisations with the primary aim of advocating for these particular crops.

As most schemes comply with the RED minimum criteria, there is a base standard and robustness. The minimum criteria include:

- feedstock producers comply with the sustainability criteria;
- information on the sustainability characteristics can be traced to the origin of the feedstock;
- all information is well documented;
- companies are audited before they start to participate in the scheme and retroactive audits take place regularly;
- the auditors have both the generic and specific auditing skills needed with regards to the scheme's criteria; and
- recognition for a voluntary scheme can last for a period of five years.

There is however, scope for variation between schemes, both within the RED minimum criteria, and with schemes requiring standards above and beyond the minimum. Variations within the RED minimum criteria include the scope of chain of custody and how GHG emissions are calculated. For the chain of custody criteria, most schemes consider the entire supply chain, others however, stop tracing feedstock at the first gathering point or the first delivery point. For GHG emissions the RED permits either default values for GHG emissions or for the actual values to be calculated. Those schemes which use the actual values for GHG emissions and trace feedstock the whole way up the supply chain are arguably more robust.

Some schemes also specify standards beyond the minimum requirements of the RED. The RED has been criticized by several government oversight bodies on the low bar set for sustainability and social standards and that those schemes which satisfy only the minimum requirements of a scheme are diluting the impact of those schemes which are more stretching. The World Wildlife Fund (WWF) in a 2013 report reported that multi-stakeholder schemes

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[24] EU (2018) Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (Text with EEA relevance.)

[25] https://www.bonsucro.com/

[26] http://www.responsiblesoy.org/

such as International Sustainability and Carbon Certification (ISCC), Roundtable on Sustainable Palm Oil (RSPO)[27] and (Roundtable on Sustainable Biomaterials (RSB)[28] had the highest ecological and social requirements. The ISCC was developed via an open multi-stakeholder process which included over 250 organisations. A report by the University of Twente[29] highlighted that the scheme exceeds the requirements of the RED directive in several areas including protection of surface water and groundwater and preservation of soil.
The ISEAL (International Social and Environmental Accreditation and Labeling) Alliance[30], a membership association for sustainability standards, also found that the certification schemes in existence before the RED also tend to have stricter requirements. They reasoned that this is because schemes created after RED are driven by the RED minimum criteria and don't tend to extend the scope of requirements.
In conclusion, there are multiple ethical standard schemes on the market which are relevant to bio-plastic production. These schemes are mostly defined by the EU Renewable Energy Directive minimum criteria although some, namely the older and multi-stakeholder schemes go further than the minimum criteria. The RED minimum criteria have recently been updated and strengthened with the changes needing to be implemented by 30 June 2021 for national schemes and the first half of 2020 for voluntary schemes. This will raise the bar for all RED approved schemes.

5.2 Biodegradable Plastics

Biodegradable plastics are more difficult to set standards and certifications for as the requirement is not around the specification of the material, but how it performs in many varied environments.

5.2.1 Standards

Until recently, the only environments that were subject to current international standards for biodegradation were industrial composting and AD, in the form of the European Standard EN 13432[31] for packaging (of any material) and EN 14995 for plastic products (the test criteria are identical between the two standards with only the scope differing). This is primarily because industrial composting and AD facilities can be simulated effectively and the conditions are strictly controlled.

5.2.1.1 Industrial Composting

The EN 13432 composting standard essentially requires:

- Disintegration – the sample is mixed with organic waste and maintained under test scale composting conditions for 12 weeks after which time no more than 10% of material fragments are allowed to be larger than 2 mm.
- Biodegradability – a measure of the actual metabolic, microbial conversion, under composting conditions, of the sample into the water, carbon dioxide and new cell biomass. Within a maximum of 6 months, biodegradation of the test sample must generate an amount of carbon dioxide that is at least 90% as much as the carbon dioxide given off from a control/reference material—usually cellulose.
- The absence of any negative effect on the composting process.

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[27] RSPO https://www.rspo.org/

[28] *RSB*, https://rsb.org/

[29] Jannic Hamelmann, and University of Twente (2016) *A comparative analysis of certification schemes*, June 2016, https://essay.utwente.nl/70726/1/Hamelmann_BA_BMS.pdf

[30] *ISEAL Alliance*, https://www.isealalliance.org/

[31] European Committee for Standardization (2000) *EN 13432 - Packaging - Requirements for Packaging Recoverable Through Composting and Biodegradation - Test Scheme and Evaluation Criteria for the Final Acceptance of Packaging*, 2000

It is important to emphasise that the six months biodegradation requirement is usually far longer than the actual processing time in an industrial composting plant, with a plant's active phase normally lasting 3-6 weeks and post-composting stabilization lasting 2-3 months.
There is some scepticism towards these standards and the methods used to determine the requirements. Some have argued that it is not possible to recreate these environments, as the industrial composting and AD processes themselves are not standardised and vary from place to place. However, as already discussed, the purpose of lab testing for biodegradation is to show the inherent nature of the material to biodegrade. These tests necessarily can't fully replicate what takes place in an industrial composter, but aim to simplify the process to produce reliable and reproducible results. The disintegration test should be used as the appropriate indicator for real-life conditions as the tests try to replicate these.

5.2.1.2 Anaerobic Biodegradation

The anaerobic biodegradation test in EN 13432 (for simulation of AD) requires only 50% degradation after two months in anaerobic fermentation, but the assumption is that this will be followed by aerobic composting, during which biodegradation can continue further. With regard to disintegration, the standard requires that after five weeks of combined anaerobic and aerobic treatment less than 10% of the original sample remains after sieving over a 2 mm mesh.
In practice, second-stage composting is not always undertaken and many AD plants will in any case aim to screen out the majority of polymers (of all kinds) as they can cause problems in the processing equipment, particularly for 'wet' AD processes.

5.2.1.3 Other Environments

Further difficulty arises in more uncontrolled, open environments. No current international standard exists for biodegradation in the marine environment. The American ASTM standard specification for biodegradable plastic in the marine environment — ASTM D7081[32] — was withdrawn in 2014 and has yet to be replaced.
This standard specification required testing aerobic biodegradation in sea water using test method ASTM D6691[33] at a temperature of 30 +/- 2 °C for up to six months. The specification required a minimum of 30% biodegradation to pass (measured as a conversion of carbon to CO2). This low threshold is one the main reasons that the specification was withdrawn as it is a particularly low threshold when compared with those used in other environments (often 90%). The test method, ASTM D6691, still remains current, however it is now recognised that testing purely in sea water is insufficient as many biodegradable plastics as negatively buoyant and will ultimately sink to the sea bed or remain in costal sediments.[34]
Although work has been ongoing for a number of years to develop a new standard specification and associated threshold(s), there are significant challenges in doing so. For example, the marine environment is actually a whole host of environments with varying temperatures and organic life. To categorically state that a particular plastic will biodegrade in all these environments is, perhaps, an impossible task. The certification 'OK Marine' (shown in 5.2.2) is closely aligned to the withdrawn specification but in recognition of the low threshold this has been increased to 90%. It still only requires testing in seawater, however. The certification still widely used by organisations to certify and promote their products as marine biodegradable, despite the issues described.
The challenge of deciding what is an acceptable period of time for a plastic to reside in the ocean has yet to be overcome. Most of this research is focused on the time to biodegrade in

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[32] *ASTM D7081-05: Standard Specification for Non-Floating Biodegradable Plastics in the Marine Environment,* accessed 9 November 2018, https://www.astm.org/DATABASE.CART/WITHDRAWN/D7081.htm

[33] *ASTM D6691 - 17 Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in the Marine Environment by a Defined Microbial Consortium or Natural Sea Water Inoculum*, accessed 21 October 2019, https://www.astm.org/Standards/D6691.htm

[34] Piero Franz (2015) *Aerobic Biodegradation of Third generation Mater Bi under marine condition*, 2015

different marine environments, but much less is known about whether the risk posed to wildlife from entanglement or ingestion is directly linked to this timescale i.e. does the risk reduce as biodegradation time reduces? This is unlikely to be resolved soon.

5.2.1.4 Mulch Film Standard

In mid-2018 a new standard for biodegradable mulch films for use in agriculture and horticulture has been introduced— EN 17033[35]. This standard aligns with the TUV Austria and DIN Certco certifications on soil biodegradation (see Figure 9) with a minimum specification of 90% biodegradation required within two years, as well as various eco-toxicity tests and restrictions on the use of hazardous substances. The standard is product and application specific, therefore claims of adherence to the standard for anything other than mulch films would be incorrect. As this standard is so new, the impact of its adoption and acceptance has yet to be realised.

This is expected to override all existing country level standards in the EU and may be the catalyst for an increase in the use of biodegradable mulch films in Europe. This also comes at a time when the standard for recoverable mulch films— EN 13655—was updated to include a minimum material thickness of 25µm to help prevent the material breaking up as it is removed from the field. Conventional mulch films can be as low as 5 - 10µm, so if there is a move towards conventional mulch films being compliant with EN 13655 (possibly as more EPR or mandatory recycling schemes are developed), the increase in thickness may also subsequently increase the average cost. Consequently, thinner biodegradable alternatives may become more competitive—by way of an example in Spanish pepper farming, prices for 15µm biodegradable mulch films can range from €500 to over €1,000 per hectare compared with PE films which cost around €400 for the same thickness[36]. A 70% increase in PE thickness and an associated price increase starts to see cost parity between the two materials especially when the additional cost of around €200 per hectare is factored for removal of the PE.

There are also potential increases in costs on the horizon if proposals in the EU Plastics Strategy[37] for mandatory extended producer responsibility schemes (EPR) are taken forward—this is the subject of a European Commission study due to take place throughout 2020. EPR may also drive the market towards thicker films (and may even require compliance with EN 13655) to reduce recovery costs. The true cost of mulch film waste management is often disguised, but this may no longer be the case. These changes may increase the biodegradable mulch film market in Europe as the costs begin to compare favourably.

5.2.2 Certifications

Despite the lack of agreed standards, there are third-party certifications for many environments. Figure 9 shows the certifications available from TUV Austria[38]. Only the OK Compost Industrial is based entirely on a recognised standard. The other certifications use standardised test methods or other related standards, but the test threshold has been independently set by this organisation. For example, the home composting certification uses EN 13432, but specifies a lower temperature and a longer test period. It is these test thresholds that are potentially contentious, as they allow materials to be certified as biodegradable in these environments

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[35] BS EN 17033:2018 – Plastics. Biodegradable mulch films for use in agriculture and horticulture. Requirements and test methods.

[36] Marí, A.I., Pardo, G., Cirujeda, A., and Martínez, Y. (2019) Economic Evaluation of Biodegradable Plastic Films and Paper Mulches Used in Open-Air Grown Pepper (Capsicum annum L.) Crop, *Agronomy*, Vol.9, No.1, p.36

[37] *A European Strategy for Plastics in a Circular Economy*, accessed 9 November 2018, https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1516265440535&uri=COM:2018:28:FIN

[38] *TUV Austria webpage: OK compost certification,* http://www.tuv-at.be/certifications/ok-compost-industrial-ok-compost-home/

without a rigorous scientific basis— as previously discussed, the marine certification is particularly complicated in this regard. The soil certifications broadly align with the new EN 17033 standard but were developed before this standard was introduced. Din Certco[39] also provide a certification using the same criteria for soil and industrial composting.

FIGURE 9. European Certifications for Biodegradable Plastics

Labels	Reference Standard	Test Conditions	Biodegradation Test Threshold
	EN 13432	Ambient temperature (20°C – 30°C)	90% in 12 months[3]
	ISO 17556[1]	Between 20°C and 25°C	90% in 2 years[4]
	ASTM D7081 (withdrawn)	30 +/- 2oC	90% in 6 months
	EN 14987[2]	Between 20°C and 25°C	90% in 56 days

Notes:

1. This is the test method for aerobic biodegradability of plastics in soil.
2. This is the test method for biodegradability of plastics in waste water treatment plants—used as a proxy for fresh water environments.
3. Test threshold the same as EN 13432
4. Test threshold the same as EN 17033

5.3 Future Standard Setting for Biodegradable Plastics in Denmark

This following section takes the information from the previous sections on biodegradability and looks at it in the Danish context. This identifies how standards for testing in open environments may apply in Denmark and the implications. Several example products are discussed and recommendations are presented based on the current knowledge base.

5.3.1 Biodegradation in Danish Conditions

Although test methods are mostly designed to approximately simulate conditions for biodegradation it is useful to determine how close these conditions might be to the average in Denmark. One of the key aspects to focus on is temperature; the average for different environments in Denmark is shown in Table 3. For sea, air and soil temperatures the year-round average is around 10°C with a high of around 18°C in summer and close to zero in Winter (see monthly data in Appendix A.2.0). This is compared with example testing conditions of over 20°C. This is not a criticism of the tests themselves as they are designed to create optimised

[39] *Din Certco webpage: Biodegradability in Soil,* http://www.dincertco.de/en/dincertco/produkte_leistungen/zertifizierung_produkte/umwelt_1/biodegradable_in_soil/biodegradable_in_soil.html

environmental conditions to promote microbial growth and activity which will indicate intrinsic biodegradability—as long as the test is conducted in a temperature range in which the microorganisms that are expected to be present will operate (i.e. high temperature thermophilic microorganisms at ~58°C and low temperature mesophilic microorganism at ~25°C), it can be assumes that biodegradation will occur. Fungal and bacterial activity is known to slow down as temperatures lower with the growth rate halving between 20°C and 10°C and between the optimal range of 25—30°C and zero the activity rate is 14 times lower.[40] Activity, particularly amongst the fungi population, will still happen in sub-zero temperatures, but at a much reduced rate.

What these standard lab tests do not provide is an indicator of the environmental fate; this is where testing in those environments (or at least finding ways to accurately simulate these) is used to determine what might happen in reality. Temperature is also known to be a large influence over the speed of the biodegradation process with its direct link to microbial activity. A recent study of a common starch blend polymer in soil showed a minerization rate of only just under 30% at 15°C compared with just under 80% at 28°C within one year[41]. A regression model was developed as part of the study to estimate the time to full mineralisation of this material at any[42] soil temperature and Italian average soil temperatures of 14°C were used as an example. This estimated that it would take 82 days to mineralise a 15 µm thick film. Using the 10°C average for Denmark in the author's equation shows that the same material would take 150 days. Extrapolating further, a typical mulch film thickness of 25 µm could take 251 days, although this is still below the 2 year threshold used in EN 17033.

A key component of the regression analysis is the relationship between available surface area and the mass of the material—this is why thinner films will biodegrade more quickly as more of the material is immediately available to the microorganism. The actual testing that the model was based on used pellets with a surface (cm2) to mass (mg) ratio of 1:68, whereas films of this material have a surface to mass ration of 1:1. This shows that design is just as important as the material and the conditions that are present. In this way it may be possible to begin to develop design guidelines as, for example, in order for this material to biodegrade in Danish soil conditions within two years, the maximum surface to mass ratio should be 5—for Italy this would be 8.5.

The evidence base to facilitate this type of analysis and decision making is limited at present, and for the marine environment there is even less. There are also other factors which will also affect (perhaps to a lesser extent) biodegradation speed such as the type of soil and therefore the types of microorganisms present and humidly levels.[43]

[40] Pietikäinen, J., Pettersson, M., and Bååth, E. (2005) Comparison of temperature effects on soil respiration and bacterial and fungal growth rates, *FEMS Microbiology Ecology*, Vol.52, No.1, pp.49–58

[41] Pischedda, A., Tosin, M., and Degli-Innocenti, F. (2019) Biodegradation of plastics in soil: The effect of temperature, *Polymer Degradation and Stability*, Vol.170, p.109017

[42] The authors state that the validity of the model for temperatures outside the tested

range (15-28 °C) is questionable, but a few degrees either side may still be valid.

[43] Tang, Z., Sun, X., Luo, Z., He, N., and Sun, O.J. (2017) Effects of temperature, soil substrate, and microbial community on carbon mineralization across three climatically contrasting forest sites, *Ecology and Evolution*, Vol.8, No.2, pp.879–891

TABLE 3. Average Temperatures in Denmark

Environment	Actual Conditions	Example Test Conditions
Sea (surface)	10°C[1]	30 +/- 2°C[3]
Air	8.5°C[1]	20°C – 30°C[4]
Soil (10cm depth)	10°C[2]	

Notes:

1. Copenhagen annual average
2. Annual average for Herfølge in 2005
3. OK Marine Certification
4. OK Soil Certification

5.3.2 Industrial Composting

The current standard of for compostable packaging EN 13432 has been in place and largely unchanged for almost 20 years. Scientific understanding of the process of biodegradation, the facilities themselves and the materials being tested have all changed since that time. There is potential for the standard to be updated at the same time as the Essential Requirements of the Packaging and Packaging Waste Directive are also updated – EN 13432 is the standard linked to the definition of being biodegradable under the Directive.

The EU study into "Relevance of Biodegradable and Compostable Consumer Plastic Products and Packaging in a Circular Economy"[44] recommends that EN 13432 (and consequently EN 14995) be updated to reflect new understanding by incorporating the following requirements:

- A requirement to separately test and meet the criteria for biodegradation of all organic constituents[45] which are present in the material at a concentration between 1% and 15%.
- The introduction of a nitrification inhibition test and an earthworm toxicity test (these are also requirements specified in the recent EU fertiliser Regulation amendments, therefore are already recognised as important for agriculture applications).[46]
- A requirement that substances of very high concern (SVHC) shall not exceed a concentration limit of 0.1 % in the material of the carrier bag.[47]

These are minimum extra requirements to strengthen the standard, but as identified in Section 7, these do not reflect the practice that currently takes place in the majority of organic waste treatment in Denmark. The standards themselves specifically state that it is assumed that a further aerobic composting process is undertaken after any anaerobic process which is not currently or expected to be common practice in Denmark. It is also not a strict requirement of EN 13432 that biodegradability under anaerobic conditions is determined and therefore products can and are certified without this test taking place.

This standard is therefore not a reliable way of ensuring that compostable plastics on the Danish market are performing effectively in organic waste treatment. Based on this, it is recommended that Denmark (as a minimum) introduce a requirement that all compostable plastic products on the market in Denmark must also be tested under the anaerobic conditions specified in EN 13432 (both biodegradation and disintegration tests).

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[44] Eunomia Research & Consulting (2020) *Relevance of Biodegradable and Compostable Consumer Plastic Products and Packaging in a Circular Economy*, Report for DG Environment, January 2020 (DRAFT, UNPUBLISHED)

[45] Chemical constituent that contains carbon covalently linked to other carbon atoms and to other elements, most commonly hydrogen, oxygen or nitrogen.

[46] REGULATION (EU) 2019/1009 https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32019R1009&from=EN#d1e40-1-1

[47] This also includes those on the candidate list - https://echa.europa.eu/candidate-list-table

5.3.3 The Open Environment

Beyond controlled environments such as industrial composting it may be considered desirable to have products that are biodegradable once they enter the open environment. This is usually because of one of two situations;

- The item is littered or otherwise mismanaged; or,
- The item is designed to enter the environment or will do as an inevitable result of use.

Biodegradable plastics are often suggested as a potential solution to both of these scenarios in order to reduce the persistence of plastics in the environment.

5.3.3.1 Littering

A focus group from Scotland in 2007 showed that most participants felt that it was acceptable to litter 'biodegradable' items as these were seen as harmless – although participants did not distinguish between organic food waste and biodegradable plastics.[48] This study appears to suggest that the driver for littering is not apathy, but misinformation. A more recent focus group from Scotland again revealed similar responses and states that the idea of 'degradability' makes litter feel less unacceptable.[49] However, only 19% surveyed for a US study thought it was understandable to litter if the item was biodegradable or could rot away.[50]

The caveat to any survey or focus group based study is that reported 'hypothetical' behaviour is difficult to correlate with actual behaviour, for which empirical observations are necessary. There is also an issue with the term 'biodegradable' which is often used is such studies, but it lacks a common agreement on meaning and does not reference a particular material or product – for one individual this may mean an apple core and for another, a paper bag for example. More recently a summary of two German focus groups on the perceptions of bioplastics found that the actual timeframe a product needs to biodegrade totally differs from what consumers assume and that compostable plastics will not always biodegrade outside of a composting facility.[51] An analysis of tobacco industry focus groups found evidence that tobacco companies thought that biodegradable filters might encourage littering but, filters 'may not degrade as quickly as smokers really want' and would actually highlight the fact that the degradability of filters generally was an issue, would run counter the desire of industry to improve their public perception.[52]

This raises the interesting issue of the public's perception of the timescales for biodegradation. In the open environment this would be difficult, if not impossible to guarantee. The expectation may be for weeks or months rather than the more realistic timeframe of years and it still creates a visual disamenity during that time, plus the material could be harmful to wildlife.

From the limited evidence available it can be concluded that;

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[48] Keep Scotland Beautiful (2007) Public attitudes to litter and littering in Scotland, *cited in* Brook Lyndhurst (2013) *Rapid Evidence Review of Littering Behaviour and Anti-Litter Policies*, Report for Zero Waste Scotland, 2013, http://www.zerowastescotland.org.uk/sites/files/zws/Rapid%20Evidence%20Review%20of%20Littering%20Behaviour%20and%20Anti-Litter%20Policies.pdf

[49] Brook Lyndhurst (2015) *Public Perceptions and Concerns around Litter*, Report for Zero Waste Scotland, 2015, http://www.zerowastescotland.org.uk/sites/files/zws/Litter%20Insights%20final%20web%20March%2015.pdf

[50] S. Groner Associates (2009) *Littering and the iGeneration. City-Wide Intercept Study of Youth Litter Behavior in Los Angeles.*, Report for Keep Los Angeles Beautiful, 2009, http://www.cleanup-sa.co.za/images/Littering%20and%20the%20iGeneration_Youth%20Litter%20Study%20for%20KLAB%20.pdf

[51] Haider, T., Volker, C., Kramm, J., Landfester, K., and Wurm, F. (2019) Plastics of the future? The Impact of Biodegradable Polymers on the Environment and on Society, *Angewandte Chemie International Edition*, No.58, pp.50–62

[52] Smith, E.A., and Novotny, T.E. (2011) Whose butt is it? tobacco industry research about smokers and cigarette butt waste, *Tobacco Control*, Vol.20, pp.i2–i9

- several studies point towards a perception amongst consumers that 'biodegradable' is a positive aspect of a product and that littering such an item would be less impactful;
- that perceptions of the time to biodegrade are likely not in line with reality which suggests actions are not always based upon correct information; and,
- the use of the term biodegradable may lessen the feeling or responsibility for those already predisposed to litter items.

One of the main arguments that can be made against the use of biodegradable plastics (or other materials with such claims) is that they may promote littering, and as discussed, there is some evidence to support this. However, it adds additional confusion for the consumer who is faced with multiple terms such as 'biodegradable' and 'compostable'. Ideally, the labelling of the product should not be ambiguous with regard to the waste disposal method.

5.3.3.2 Biodegradability as a 'Desired Trait'

The other potential for biodegradable plastics is for products that are designed to enter the environment or will do as an inevitable result of use. Examples of these items which are often used in Denmark can include:

- Shot gun shells
- Mulch films/agriculture films
- Blades and wires for grass trimmers
- Plant clips
- Tree protection
- Sport fishing gear
- Plastic parts in fireworks

First and foremost, it is important to recognise that the waste hierarchy should still be respected if at all possible; in this case, preventing the waste in the first place should be a priority. Looking for alternatives or considering whether the item should be subject to a ban (as is the case for a number of products in the EU SUP Directive) may be a viable way for reducing pollution of this items in the first instance. Reuse and recycling should then be considered. Shot gun shells are notable as a particular problem in Denmark, with a recent study finding used plastic shells all along Danish coastlines as a result of hunting activities.[53] As part of the Danish National Plastics Action Plan (drawn up under the previous parliament) a ban on the use of non-biodegradable shot gun shells was proposed. This particular product is therefore investigated in more detail.

Shot Gun Shells

There are two main plastic components of a shotgun shell that may end up in the environment; the outer tube and the 'wad'. These are shown in Figure 10 with two variations of the wad; fibre and a plastic shot cup (haglskåle) which also surrounds the shot. The fibre wad can actually also be made from plastic fibres, but regardless of the material this part of the shell leaves the barrel of the gun along with the shot and therefore is impossible to retrieve. The outer tube either remains in the gun until removed or ejects when using a pump action shot gun[54] and therefore it can end up in the environment as a result of littering behaviour. As littering of this part of the shell is avoidable it should be tackled with approaches in education and potentially a deposit refund scheme.

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[53] Kanstrup, N., and Balsby, T.J.S. (2018) Plastic litter from shotgun ammunition on Danish coastlines - Amounts and provenance, *Environmental Pollution (Barking, Essex: 1987)*, Vol.237, pp.601–610

[54] Pump action shot guns are restricted to two shots (one in the chamber, one in the magazine)

FIGURE 10. Shotgun Shells – Fibre Wad (L), Plastic Shot Cup (R)

In order to legally buy and use a shotgun in Denmark for hunting, a hunting test must be passed, which covers species, game biology, firearms, safety, hunting and regulations. As part of this test, new owners should be taught about the importance of retrieving the shell. The Danish Hunter's Association represents which 93,000 out of the 163,000 hunters in Denmark[55] is also a good way to increase the reach of this message to existing hunters. Introducing a deposit refund scheme for used shell casings would also help to not only reduce littering of the shells, but can be used as a way of increasing the recycling of these items.
The more difficult part of the shell to address is the fibre wad or the plastic shot cup. The Danish Hunter's Association has recently committed to encouraging its members to move towards biodegradable wads/shot cups and is facilitating this process by working with manufacturers and importers.[56] Most fibre wads are mad from natural materials and therefore are likely to biodegrade in shorter timeframes. However, there is often a preference towards the plastic shot cups as these are thought to provide a tighter shot pattern and are therefore more accurate, however this assertion is not always borne out by reality in modern shell designs.[57,58,59]
There are several products on the Danish market which claims to include biodegradable shot cups, but the material is not usually specified and no testing standards are referred to. One exception to this is the GreenShot manufactured by Armusa[60] in Spain, but sold under several

[55] http://www.face.eu/sites/default/files/denmark_en_2.pdf

[56] https://www.jaegerforbundet.dk/om-dj/dj-medier/nyhedsarkiv/2018/slut-med-haglskale-i-plast/

[57] https://www.clay-shooting.com/coaching/ask-the-experts-should-i-use-plastic-or-fibre-wads/

[58] https://www.gunsonpegs.com/articles/cartridges/plastic-vs-fibre-wads-which-is-best

[59] http://www.shotgun-insight.com/fibreVsPlasticSporterShells.html

[60] https://www.cartuchosarmusa.com/copia-de-steel-shot

different brands in Denmark.[61] This uses an injection moulded plastic shot cup made from polyvinyl alcohol (PVA) from the company Plasticos Hidrosolubles[62]. This is a fossil based water-soluble polymer that is most commonly found as the wrapper on cleaning tablets used in dishwashers. This particular supplier has a certification from TUV Austria for industrial composting (EN 13432) although only for the material in film form (at a very thin 0.08 mm thickness) and not as an injection moulded component. Being water soluble should also not be confused with being biodegradable (in the open environment); there is evidence that PVA can accumulate in watercourses and wastewater treatment plants and the speed and extent to which biodegradation may occur is questionable.[63]

The material has no independent certifications for marine or terrestrial biodegradability and Plasticos Hidrosolubles makes the common mistake of claiming 'certification' to a test method (ISO 14851) for biodegradation in an aqueous environment. The test method means nothing on its own without the results or reference to any time limit threshold.

As already identified, there is no current national or international standard for biodegradation in the terrestrial or marine environments (except for mulch films in soil). This current state is recognised in the EU SUP Directive which is why 'biodegradable' products are not exempt at the time, in line with the precautionary principle. The Directive also stipulates that this will be investigated by the European Commission by 2026 and this work is already ongoing.

Nevertheless, this is problematic at present, as there is no credible way of assessing whether products will perform well enough to be considered biodegradable in specific open environments. There is no threshold to meet and no expectation for the length of time to biodegrade.

Mulch Films

Mulch films are widely used in agriculture to protect early stage crop growth, improve crop quality, retain water and minimise spread the spread of weeds and consequently are widely regarded as a successful way of increasing crop yields. It is beyond the scope of this report to fully investigate the agronomic benefits or determine whether alternative practices can provide the same kind of benefits – determining whether biodegradable films are more preferable to a recycling of conventional films is also due to be investigated by the European Commission in a specific study during 2020. This will investigate, amongst other things, the prospect of a European EPR system of these and other agricultural plastics.

In the meantime, there appears to be no justification for Denmark to diverge from the recent standard for biodegradable mulch films for use in agriculture and horticulture— EN 17033.[64]

As described in Section 5.2.1.4, this standard is specific to mulch films and shares the same criteria as the TUV Austria OK Soil certification which can – in theory – be used for any product, but isn't linked to national or international standards. The French standard for biodegradable materials for agriculture and horticulture (AFNOR NF U 52-001) also has the same criteria.

Other Products

Grass trimmer wire appears to be an ideal use of biodegradable plastic as it is designed to slowly wear away into small fragments during use. However, the same cutting properties achieved by using stiff nylon wire are harder to achieve from a plastic that will also biodegrade in the open environment. More rigid plastics, such as PLA, will not biodegrade in low temperatures and many of the materials that are capable of being certified for any form of open environment are thin film based. Because of this, no confirmed evidence of these products existing

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[61] https://www.landogfritid.dk/products/4476/952154

[62] http://watersoluble.green-cycles.com/

[63] Julinová, M., Vaňharová, L., and Jurča, M. (2018) Water-soluble polymeric xenobiotics - Polyvinyl alcohol and polyvinylpyrrolidon - And potential solutions to environmental issues: A brief review, *Journal of Environmental Management*, Vol.228, pp.213–222

[64] *BS EN 17033:2018 – Plastics. Biodegradable mulch films for use in agriculture and horticulture. Requirements and test methods.*

in practice has been found – the exception to this are examples made from oxo-degradable nylon which are likely to fulfil performance requirements, but not the biodegradability requirements. As a minimum, a TUV Austria OK Soil (or similar) certification should be required for these products.

Larger items such as tree guards (see Figure 11) provide their own unique challenge as when they are left in the environment their functional life is only just beginning. Therefore, biodegrading within weeks or months would actually be problematic. There is also a complete lack of study regarding the exact way in which a biodegradable tree guard might behave differently to one made from conventional plastic. They expand with the growth of the tree but are unlikely to suffer any significant biodegradation as the exposure to microorganisms is initially low until such time as they are mechanically degraded from UV exposure and weathering. The length of time before this happens and any subsequent biodegradation timeframe are unknown and cannot be confirmed. Arguably, this type of product should be recovered after its useful life as part of a responsible forestry operation and therefore developing more robust reusable alternatives is likely to be the best option from an environmental perspective.

FIGURE 11. 'Biodegradable' Tree Protector
Source: Eunomia

Fireworks are also known to litter the environment mostly as a result of rockets fired into the sky. Other firework litter that does not leave the ground should be addressed in the same way as any form of deliberate littering. Rockets are more difficult to address as it is almost impossible to locate the debris after it falls from the sky. These types of fireworks have various plastic components and it is unclear exactly which parts are functional and which parts are purely aesthetic—the outer body and nose cones, for example may not necessarily be plastic but are often used to provide bright colours and eye-catching graphics. The low cost, mass produced nature of these products is more likely to be the reason for plastic use over materials such as card which would increase product production costs.

Plasticos Hidrosolubles[65] also produce PVA internal firework components that perform a similar function as a shotgun wad but there is limited evidence that this or any other biodegradable plastics is used more widely in fireworks at present. Again, the rate of biodegradation in likely environments is unknown but will still be measured in years rather than weeks, and hence will

[65] http://watersoluble.green-cycles.com/

do little to reduce the visual impact of these items littering the streets or potential harm to wildlife.

Sport fishing gear has a high degree of plastic content combined with a high likelihood of becoming lost or discarded in use. Accidental loss should be the only focus for biodegradable alternatives—other incentives should be used to help prevent deliberate loss. A number of fishing line alternatives have been developed in the past, but appear to suffer from the same issue of product performance as a strimmer wire.[66]

The accidental loss of fishing lures is relatively common place especially for beginners and US company Meridian (now known as Danimer) began producing a biodegradable PHA fishing lure in 2015 reportedly with an OK Marine certification.[67] The only current certification that exists for this material is a 19 μm film[68] and therefore it is unclear what the current status of the product is although it appears to have been discontinued.

It appears many biodegradable alternatives that have appeared on the market for different products have largely failed to gain a significant market share. Performance issues or negative perceptions seem to be barriers and there may be a degree of scepticism around the ability to biodegrade. Developing standards for this will help, but if certain plastic products are a particular issue in the environment then other legislative mechanisms may be needed to move the market towards anything other than conventional plastic.

5.3.4 Recommendations for Denmark

When addressing the issue of plastics designed to enter the environment or as an inevitable result of use (not products that have a waste management route), it is beneficial to design an approach that can be used to assess the best strategy for reduction. Biodegradable plastic should not be the first choice to solve the problem of plastic pollution, but rather the final choice if all other means are exhausted. From the perspective of the circular economy it is more important to focus on reducing the need for the product or capturing the material value in some way. Labelling and marketing a product as biodegradable should also not affect the behaviour of the user i.e., they would act the same regardless—shot gun shell cups may be a possible example as these end up in the environment anyway.

To that end, Figure 12 demonstrates the logical process to go through in order to decide how certain products that enter the environment should be dealt with.

If there are certain products that have been identified as suitable for the use of biodegradable materials (which could include any type of material and no just plastics) it is important to define and regulate how these are sold and marketed in Denmark—it is advisable to keep this list as small as possible due to the fact that there are no internationally agreed standards to adopt that can guarantee that, once in the environment, the product will not still have an negative impacts. What does exist are several examples of tests that can reduce this impact and at least make sure that no harmful substances enter the environment. To that end it is recommended that Denmark introduce its own national standard for biodegradation in the open environment that either references or adopts other tests. This should include as a minimum:

1. A test for biodegradation in soil
2. A test for disintegration and biodegradation in sea water/marine sediment
3. A limit on heavy metals
4. All biodegradation tests are carried out on organic constituents which are present in the material at a concentration of greater than 1%
5. A limit on SVHCs
6. Ecotoxicity tests on plants and invertebrates
7. Specific requirements and guidelines for product labelling

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[66] https://www.anglersmail.co.uk/news/biodegradable-line-call-79948

[67] https://bassanglermag.com/mhgs-biodegradable-fishing-lure/

[68] http://www.tuv-at.be/green-marks/certified-products/

8. A list of products/applications for which the standard is applicable with the expectation that no other products can use it.

Points 4 to 6 should be in line with the recommendations for an update to EN 13432 in Section 5.3.1.

There are three possibilities for references regrading biodegradation in soil; the French standard for biodegradable materials for agriculture and horticulture (AFNOR NF U 52-001); EN 17033 and the OK Soil certification tests. These all have the same test with temperature of 25°C and 90% biodegradation required within two years. A lower time threshold could be applied, but the implications from a product perspective are unclear i.e. would a lower threshold remove all products from the market that are capable of providing the necessary functional properties? This is a distinct possibility as thickness of material has a direct correlation to speed of biodegradation (as discussed in Section 5.3.1) and therefore rigid versions of the same materials will take longer. None of these standards include a disintegration test at present, but it may not be necessary to conduct one if this is conducted for sea water.

Specifying a reference standard for sea water testing is more challenging. ISO 19679 and ISO 18830 are the only international test methods for biodegradation in marine sediment and ASTM D6691 from the US is the only test method for sea water (referenced in the OK biodegradable Marine certification)—these tests could be refenced in a Danish standard. However, within these test methods there are no time limit thresholds of biodegradation targets to meet (not since ASTM D7081 was withdrawn in 2014) as they just describe the test procedure. As discussed in Section 5.2.1.3, this is the precise subject of research and debate at present. Setting a 90% biodegradation target within 6 months (in line with ASTM D7081 and OK biodegradable Marine) should be regarded as a minimum expectation. Again, reducing this time threshold may result in reduced functional properties that essentially prevent certain applications from being used. Consultation with industry stakeholders around what time limits are feasible should be undertaken to assess the effect. Any standard that is developed with specific thresholds should also be updated in line with any international standards that appear at a later date in order to maintain relevance with the latest scientific understanding.

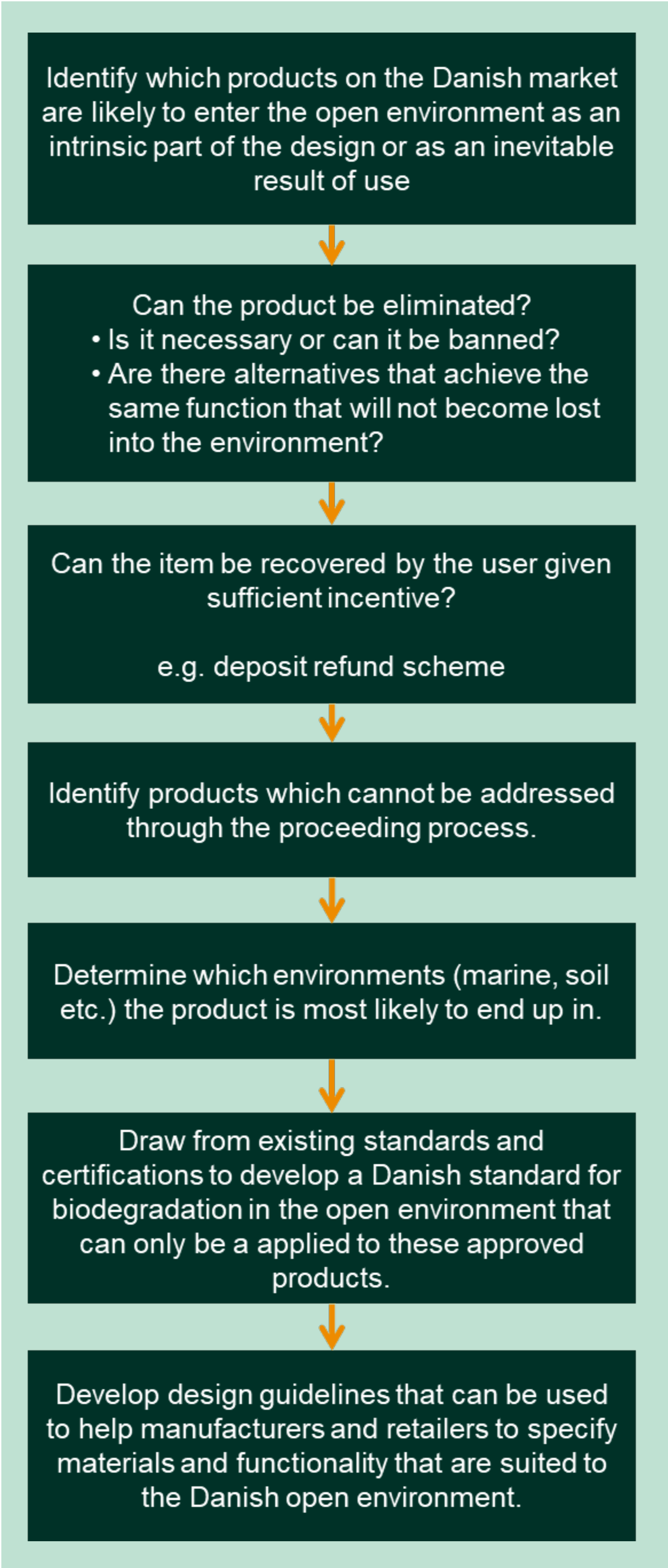

FIGURE 12. Decision Process for Biodegradable Products

Summary of Standards and Certifications

There are no international Standard Specifications (which specify tests and requirements to validate that biodegradation takes place in a particular timeframe) for biodegradation in marine environment. These only exist for industrial composting and for the specific application of mulch films in soil.

Standard tests are generally conducted at between 20°C and 30°C—the average annual temperature for sea surface, soil and air in Denmark is around 10oC. This does not mean biodegradation will not take place, but it will be significantly slowed. This means that the risk to wildlife is still present over that time. Understanding the implications of this will help with specific design requirements that are tailored to the Danish environment.

Some private certifications exist which could be used as minimum requirement whilst standards are being developed. However, it is recommended that these are only used for particular products that cannot be prevented from entering the open environment by other means. An example of this may be shot gun shell cups although there may be alternatives that remove the need for plastic in this application altogether.

Where items can be easily recovered or prevented from littering, the focus should be on incentivising appropriate behaviour especially in light of the lack of certainty around biodegradation performance in the environment.

6. Market Assessment

6.1 Key Materials

On overview of the key bio-based and biodegradable plastics on the market is shown in Table 4. These materials have been identified as they have the largest market share globally – more details are shown in section 6.2.1.2.

The common biodegradability certification at a typical thickness is shown in the table. It is important to note that not all polymers sold will be certified in this way, as this depends on both the company and thickness that the polymer is sold at. If a polymer is certified as compostable, it also does not necessarily mean that an end product made from this polymer is compostable. The common certifications listed in this table are therefore indicative only, to give the reader an idea of the varying levels of biodegradability of the polymers.

The average cost for each of the key plastics is also included in the table. For comparison, the average price for virgin LDPE and HDPE are approximately €1.4/kg and virgin PET approximately €1.2/kg. Recovered plastics are typically cheaper, with recovered LDPE and HDPE €0.3 - 0.5/kg and recovered PET €0.06 - 0.2/kg[69] (with coloured PET cheaper than clear PET). A large number of polymers on the market are blends of the polymer types listed below, sold under proprietary brand names.

6.1.1 Bio-based and Biodegradable

6.1.1.1 Polylactic Acid (PLA)

PLA is a 100% bio-based and biodegradable plastic that can biodegrade in industrial composting plants. The chemical structure of a PLA monomer is shown in Figure 13. PLA is produced by fermenting a carbohydrate rich feedstock to produce lactic acid, and then dehydrating this to a lactide, before undergoing polymerisation.

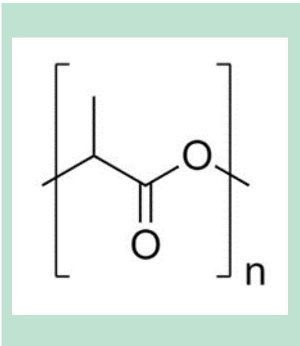

FIGURE 13. Chemical structure of PLA

It is relatively cheap compared to other bio-based and biodegradable plastics. It can be used as an alternative to conventional plastic in many circumstances, particularly as a replacement for PET but other polymers too. It is approved for food contact applications, making it suitable for food packaging. It is transparent, which makes it particularly useful for packaging which requires the consumer to be able to see the product. The material also has high breathability, making is well suited to products that require oxygen, e.g. salad leaves. PLA is regularly used

[69] (2013) *Plastic, recovered plastics market | WRAP UK*, accessed 5 December 2019, http://www.wrap.org.uk/content/plastic

as a lining for paper cups and plates.[70] Heat-stable PLA can also be produced, making it possible to use in coffee cups. It is also available in foam form, making it a compostable replacement for expanded polystyrene foam packaging.
As well as packaging, PLA is also used for textiles and consumer goods. One example of PLA use in consumer goods is the Sony Walkman; in 2002 Sony became the first company to use PLA for a whole product casing. Additives were included to improve the durability of the plastic and put off biodegradation during the product's lifetime – this makes it unlikely that the PLA will then degrade in a suitable time frame and brings question to the fact a biodegradable polymer was used. This is a relatively isolated example, and from market assessments, it does not seem there has been a significant penetration of PLA into the consumer goods market.
Natureworks currently have the highest production capacity for PLA. Other notable market leaders include Total Corbion.[71]

6.1.1.2 Polyhydroxyalkanoates (PHAs)

PHAs are a family of very diverse plastics, including PHB, PHBV, PHV and PHH. The chemical structure of PHB and PHV monomers are shown in Figure 14. As shown, only the side change differs in the structure, with PHB having a methyl group and PHV a methylene. All PHAs have a similar structure, but with a different side chain.

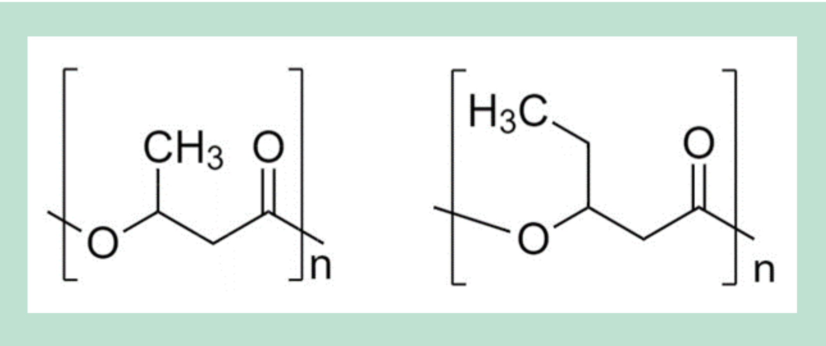

FIGURE 14. Chemical structure of P3HB (left) and PHV (right) monomers[72]

They are all 100% bio-based and it is said that they are able to biodegrade in a wide variety of environments, including industrial and home composters, soil, fresh water and sea water. They are fairly expensive, and therefore are not as common as cheaper bio-based and biodegradable alternatives such as PLA.
The properties of PHAs can largely be selected in the manufacturing process, thus they are suitable for a wide variety of applications. They generally have good barrier properties, similar to those of conventional plastics PET and PP. Their main drawback is they are generally quite brittle compared to other plastics, however this can be monitored and controlled during production to optimize the product. Despite a wide range of properties, they are generally used for thin materials such as films or coatings due to their high price – generally costs associated with production are 5-10 times higher than conventional plastics.[73]

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[70] Jamshidian, M. et al (2010) Poly-Lactic Acid: Production, Applications, Nanocomposites, and Release Studies, *Comprehensive Reviews in Food Science and Food Safety*, Vol.9, No.5, pp.552–571.

[71] Barrett, A. (2018) *The NatureWorks Saga*, accessed 11 October 2018, https://bioplasticsnews.com/2018/06/05/natureworks-saga-thai-fiasco/

[72] Lazonby, J. *Degradable plastics*, accessed 29 October 2019, http://essentialchemicalindustry.com/polymers/degradable-plastics.html

[73] Raza, Z.A., Abid, S., and Banat, I.M. (2018) Polyhydroxyalkanoates: Characteristics, production, recent developments and applications, *International Biodeterioration & Biodegradation*, Vol.126, pp.45–56

TABLE 4. Types of Bio-based and/or Biodegradable Plastics and Key Information[74]

Plastic type	Typical bio-based carbon content	Common biodegradability certification	Feedstock	Market leader	Cost (€/kg)[75]
Bio-based and Biodegradable					
PLA	100%	OK compost industrial	Sugarcane, sugarbeet, corn, potato, wheat	Natureworks	2 €/kg
PHAs	100%	OK compost industrial & home, OK biodegradable soil, water & marine	Sugarcane, sugarbeet, corn, potato, wheat	Danimer Scientific	5 €/kg
Starch Blends	25-100%	Varies lots. e.g. Mater-Bi: OK compost home & industrial & OK biodegradable soil.	Varies e.g. corn, potatoes, wheat	Novamont	2-4 €/kg
Bio-PBS(A)	20-100%	OK compost home & industrial	Sugarcane, sugarbeet, corn, potato, wheat	Mitsubishi Chemicals	4 €/kg
Bio-based and non-Biodegradable					
Bio-PET	20-30%	N/A	Most often sugarcane but possible with sugarbeet or starch	Indorama	No information
Bio-PAs	30-100%	N/A	Sugarcane, sugarbeet, corn, potato, wheat, or castor seed oil	Rennovia	+10-20% on conventional PAs
Bio-PE	100%	N/A	Sugarcane, sugarbeet, corn, potato, wheat	Braskem	+20-40% on conventional PE
PEF	100%	N/A	Sugarcane, sugarbeet, corn, potato, wheat	Avantium / BASF	No information
Bio-PP	30%	N/A	Sugarcane, sugarbeet, corn, potato, wheat	FKuR	+80-100%
PTT	37%	N/A	Sugarcane, sugarbeet, corn, potato, wheat	DuPont	4 €/kg
Fossil-based and biodegradable					
PBAT	0-50%	OK compost industrial	Petro-sources	BASF	No information
PBS(A)	0-20%	OK compost home & industrial	Petro-sources	Mitsubishi Chemicals	No information
PVA	0%	Not known	Petro-sources	N/A	No information

[74] Eunomia Research & Consulting, and Mepex (2018) *Bio-based and biodegradable plastic: An Assessment of the Value Chain for Bio-Based and Biodegradable Plastics in Norway*, Report for Norwegian Environment Agency, 2018, https://www.eunomia.co.uk/reports-tools/bio-based-and-biodegradable-plastics-norway/

[75] FBR BP Biorefinery & Sustainable Value Chains, FBR Sustainable Chemistry & Technology, Biobased Products, van den Oever, M., Molenveld, K., van der Zee, M., and Bos, H. (2017) *Bio-based and biodegradable plastics : facts and figures : focus on food packaging in the Netherlands*, Report for Wageningen, 2017, http://library.wur.nl/WebQuery/wurpubs/519929

6.1.1.3 Starch blends

After bio-PET, starch blends are the most widely produced bio-based plastic. The starch is typically blended with another biodegradable material, and therefore can have any number of properties dependent on the chosen composition. They are widely used as foam filler and foam trays, as well as compostable biowaste bin liners.

The most common starch blend on the market is Mater-Bi, a biodegradable plastic produced by Novamont. It is available in different biodegradability grades, including a soil biodegradable plastic, and industrial and home compostable plastics. These are most widely used as the liner for household food waste bins. In agriculture it is also used as a mulch film.

Novamont have also received an 'Environment Technology Verification' certificate for biodegradation in the marine environment for two of their products – Mater Bi AF03A0 and Mater-Bi AF05S0. This indicates that, in testing, high levels of biodegradation were achieved in a simulated eulittoral zone in 195 days (76.4% and 110.8%[76] respectively), and in a simulated sublittoral zone in 259 days (biodegradation of 93.2% and 92.6% respectively). The test uses a temperature of 28°C – a temperature arguably too high for many eulittoral and sublittoral zones – as outlined in section 4.2. Novamont suggest that this material could be used for items prone to ending up in the sea, such as fishing equipment and single use carrier bags.

6.1.1.4 Polybutylene Succinate (Adipate) (PBS(A))

The chemical structure for PBS is shown in Figure 15. PBS is made using succinic acid and 1,4-butanediol - both of which can be 100% bio or fossil-based. PBSA also uses adipic acid as a feedstock – which can also be bio or fossil-based. They can be used in a wide variety of applications, but at current is mostly used for films, single use bags or food/cosmetics packaging. Bio-PBS is relatively new to the market, becoming commercially available in 2016. It is currently only produced by Mitsubishi Chemicals.

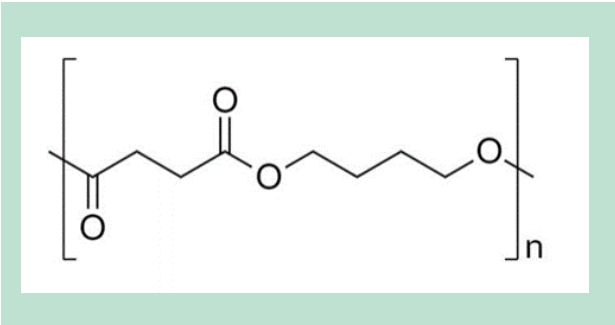

FIGURE 15. Chemical structure of PBS monomer

6.1.2 Bio-based and Non-biodegradable

6.1.2.1 Bio-polyethylene Terephthalate (bio-PET)

Bio-PET is the most common bio-based plastic, with global production capacity reaching over 560,000 tonnes in 2018.[77] It is a drop-in bio-based, non-biodegradable option for conventional PET. The chemical structure of a PET monomer is shown in Figure 16.

The polymer is produced from the chemical building blocks monoethylene glycol (MEG) and purified terephthalic acid (PTA) – with 32% MEG and 68% PTA in the final product. MEG can be bio-based or fossil-based, which is why one can produce a drop in from conventional PET.

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[76] The biodegradation value being above 100% is due to the 'priming' effect that is common in biodegradation testing – a phenomenon where a humidified portion of soil or compost begins to degrade at an accelerated rate when the test material is added.

[77] European Bioplastics (2018) Bioplastics Facts and Figures 2018

Bio-PET is currently made of up to 32% biomass (MEG), although there are ongoing efforts to make 100% bio-based PET commercially available by producing bio-based PTA. The market has previously been driven by Coca-Cola, who lead the Plant PET Tech Collaborative.

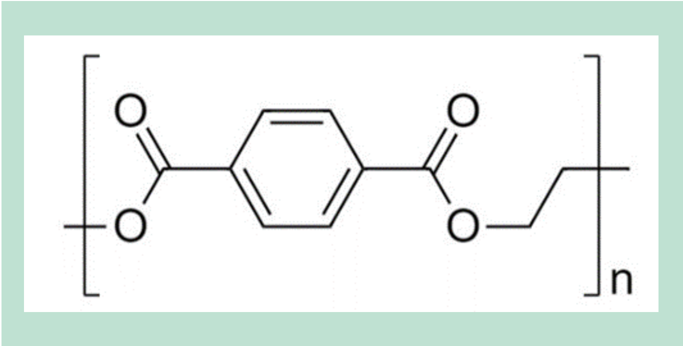

FIGURE 16. Chemical structure of PET / bio-PET

6.1.2.2 Bio-polyethylene (bio-PE)

Bio-PE is a very popular drop-in bio-based plastic, however unlike bio-PET, it is 100% bio-based. The chemical structure for bio-PE is shown in Figure 17. It is made of repeating ethene units, produced using bio-ethanol. Conventional PE is simply made of fossil-based ethanol.
As it is a drop-in polymer, it can be used in the same applications as conventional PE. It is extremely versatile, although is most often used for single use bottles, food packaging and carrier bags.
Bio-PE is very expensive compared to conventional PE – with prices 20-40% higher in 2016 - and therefore has not shown much market growth in previous years.

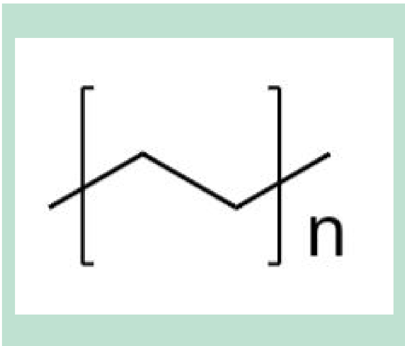

FIGURE 17. Chemical structure of PE / bio-PE[78]

6.1.2.3 Polyethylenefuranoate (PEF)

PEF is a very new bio-based plastic to enter the market. It is not yet commercially produced. It is 100% bio-based, and is reportedly much cheaper than the proposed process for 100% bio-based PET.[79] PEF is also reported to have better CO2, water and oxygen barrier properties than PET, meaning that it is better suited to some packaging applications. PEF also has better mechanical properties than PET, for example it has a 60% higher tensile modulus, meaning that there are opportunities to lightweight packaging using PEF.[80] PEF can be recycled in the

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[78] Davidson, J. (2014) Multiscale modeling and simulation of crosslinked polymers

[79] Barrett, A. (2013) Bottles from Furfural, accessed 11 October 2018, https://bioplasticsnews.com/2013/12/17/bottles-from-furfural/

[80] Polyethylene Furanoate (PEF) - The Rising Star Amongst Today's Bioplastics, accessed 11 October 2018, https://omnexus.specialchem.com/selection-guide/polyethylene-furanoate-pef-bioplastic

PET recycling stream up to 2%, with no reported effect on the PET performance. It could also have its own dedicated recycling stream in future.[81]

6.1.2.4 Bio-Polypropylene (bio-PP)

Bio-PP currently contains approximately 30% bio-based content and is a drop-in for fossil-based PP. It is made up of repeating propene monomers – traditionally a by-product of oil refining, however can also be made 30% bio-based.

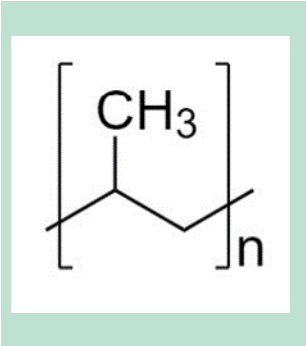

FIGURE 18. Chemical structure of PP / bio-PP

It is suitable for a wide variety of applications, is fairly rigid and resistance to fatigue. IKEA has recently announced that they will use bio-PP in all its plastic products, and are working with Neste to make 100% bio-PP commercially available, with the intention of moving to 100% bio-PP by 2030.[82] LyondellBasell and Neste have recently announced a new commercial operational bio-PP facility, which reportedly has over 30% renewable content[83] – although this may be marginal.

6.1.2.5 Bio-polyamides (Nylons/bio-PA)

PAs, or nylons, are mostly used in textiles and engineering. Engineering includes the automotive industry, machinery, electronics, consumer goods, films and coating. The automotive industry currently holds the largest share of bio-PA, as it is often used in vehicles instead of glass fibre to reduce weight but still maintain strength. The PA market in Europe is being driven by the EU's carbon dioxide limits, which put pressure on vehicle manufacturers to reduce weight.

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[81] Guzman, D. de (2017) *PEF to be integrated in European PET recycling*, accessed 25 October 2018, https://greenchemicalsblog.com/2017/05/24/pef-to-be-integrated-in-european-pet-recycling/

[82] Barrett, A. (2018) Ikea and Neste Go Bioplastics, accessed 15 October 2018, https://bioplasticsnews.com/2018/06/08/ikea-and-neste-go-bioplastics/

[83] *LyondellBasell and Neste announce commercial-scale production of bio-based plastic from renewable materials*, accessed 1 October 2019, https://www.lyondellbasell.com/en/news-events/products--technology-news/lyondellbasell-and-neste-announce-commercial-scale-production-of-bio-based-plastic-from-renewable-materials/

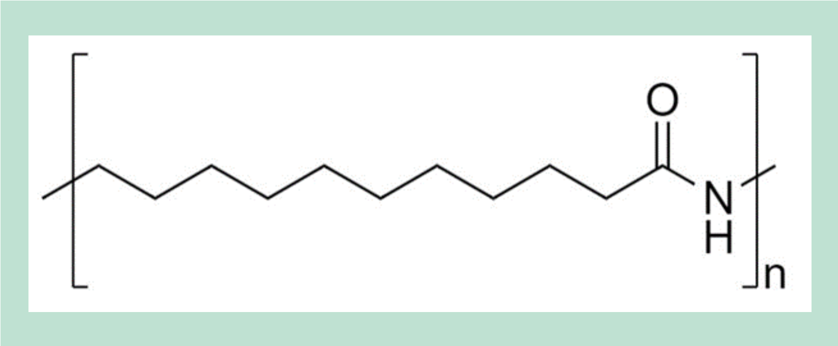

FIGURE 19. Chemical structure of Nylon-11

6.1.2.6 Polytrimethylene terephthalate (PTT)

PTT is used solely in carpet fibres. It is favoured as it is more durable and resilient than traditional polyester and feels much softer. It is hydrophobic, therefore naturally very stain resistant. PTT is also cheaper than Nylon, giving it an economic advantage.[84] As with many other bio-based polymers, the introduction of these into recycling streams (e.g. if PTT carpet was put in the recycling stream for conventional PP carpet) can cause contamination issues for the recyclers. PTT could, however, be effectively recycled if it was to be collected in a pure stream.[85]

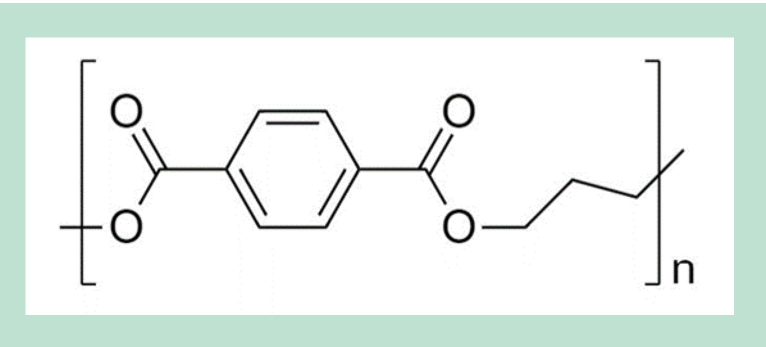

FIGURE 20. Chemical structure of PTT

6.1.3 Fossil-based and Biodegradable

6.1.3.1 Polybutylene adipate terephthalate (PBAT)

PBAT is the market leader for fossil-based, biodegradable plastic materials. Most is produced by BASF under the brand name ecoflex, which holds OK Compost Industrial certification.[86] It is also widely used in blends with other compostable materials. It is very tough and has high flexibility, which lends itself to being combined with more rigid biodegradable plastics in products such as water bottles. It is not water soluble, meaning that it is a good coating for paperboard. Another common application is in flexible films (including carrier bags), as well as in compounds for medical packaging.

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[84] *What You Didn't Know About Triexta, the New Carpet Fiber*, accessed 15 October 2018, https://www.thespruce.com/triexta-ptt-carpet-fiber-2908799

[85] Resch-Fauster, K., Klein, A., Blees, E., and Feuchter, M. (2017) Mechanical recyclability of technical biopolymers: Potential and limits, *Polymer Testing*, Vol.64, pp.287–295

[86] *BASF Certified - the compostability of ecoflex®*, accessed 16 October 2018, https://www.plasticsportal.net/wa/plasticsEU~en_GB/portal/show/content/products/biodegradable_plastics/ecoflex_compostability

The chemical structure of PBAT is as shown in Figure 21. It is depicted as a block co-polymer here due to the common synthetic method of first synthesizing two copolymer blocks and then combining them. However, it is important to note that the actual structure of the polymer is a random co-polymer of the blocks shown.

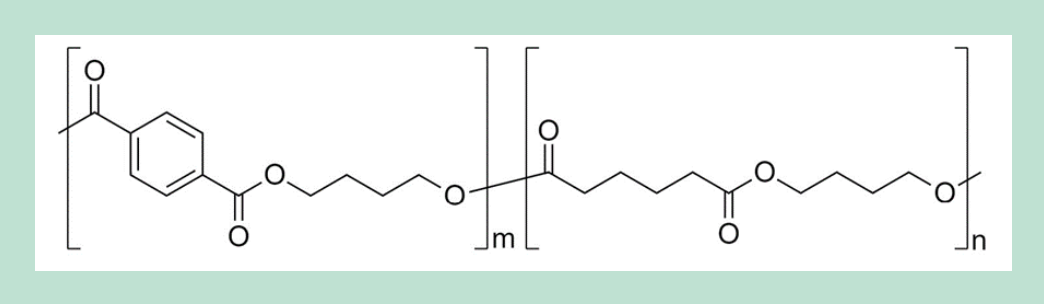

FIGURE 21. Chemical structure of PBAT

6.1.3.2 PBS(A)

As outlined above, PBS(A) can be 100% bio-based or 100% fossil-based. At present, it is unknown how much of the market is bio-based compared to fossil-based PBS(A).

6.1.3.3 Polyvinyl Alcohol (PVA)

PVA is another fossil-based polymer. It is water soluble and is therefore often used for dissolvable items such as dishwasher tablet casing and bait casing for recreational fishing. It is also breathable, so often used as a backing sheet in feminine hygiene products and nappies.
It has received controversial reviews as it is water soluble but its degradation in a water or marine environment is not verified.[87,88] There are some types of PVA which have received compostability certifications, however.[89]

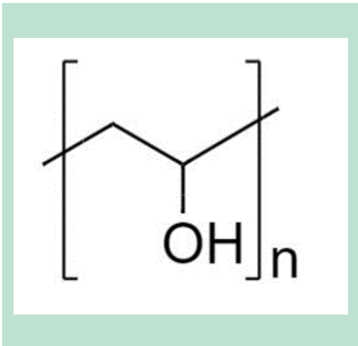

FIGURE 22. Chemical structure of PVA

6.2 Market Size

The market size for bio-based and biodegradable plastics is explored in the next section. It should be noted that **market data is generally very limited**, and often different sources provide conflicting data. This is largely a result of the market being dominated by large plastic

[87] Julinová, M., Vaňharová, L., and Jurča, M. (2018) Water-soluble polymeric xenobiotics - Polyvinyl alcohol and polyvinylpyrrolidon - And potential solutions to environmental issues: A brief review, *Journal of Environmental Management*, Vol.228, pp.213–222

[88] Kawai, F., and Hu, X. (2009) Biochemistry of microbial polyvinyl alcohol degradation, *Applied Microbiology and Biotechnology*, Vol.84, No.2, p.227

[89] *GreenCycles® technology | Water soluble plastic GreenCycles®*, accessed 4 November 2019, http://watersoluble.green-cycles.com/greencycles-technology/

manufacturers whose data is commercially sensitive, and retailers only selling small quantities of end-products.
The following section includes an estimate of the total bio-based and/or polymers and end products on the market globally and within Denmark. This is estimated by looking at global production capacities and through discussions with stakeholders.

6.2.1 Global Market

6.2.1.1 Size

Although exact production or sales data for bio-based and biodegradable plastics is hard to come by, facility production capacity data is available. This gives an indication of the size of the market, as well as which polymers are dominating. The most well-trusted global production data available is reported on annually by European Bioplastics. Although the data is well-respected, the data source has changed twice in the past ten years – in 2015 and 2017 - to improve accuracy. **This means that the three datasets (2008-14, 2015-16 and 2017-18) are not comparable.**

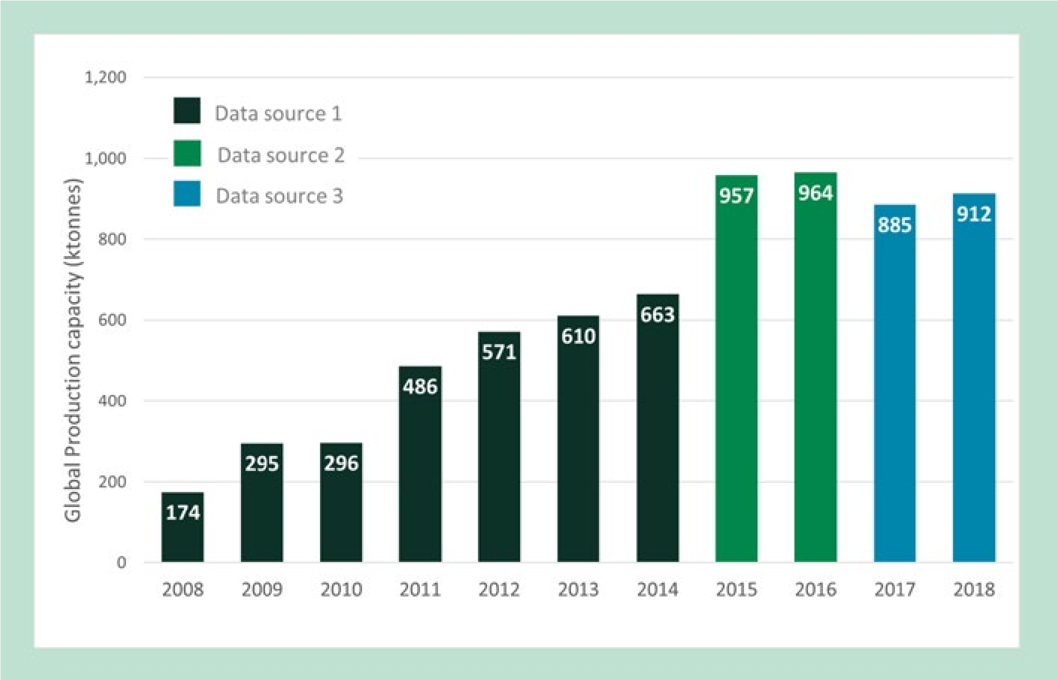

FIGURE 23. Reported global production capacity of biodegradable plastics, 2008 to 2018[90,91,92,93,94,95] *Note that change in data sources and methodologies mean that no trend can be inferred between 2014 and 2017*

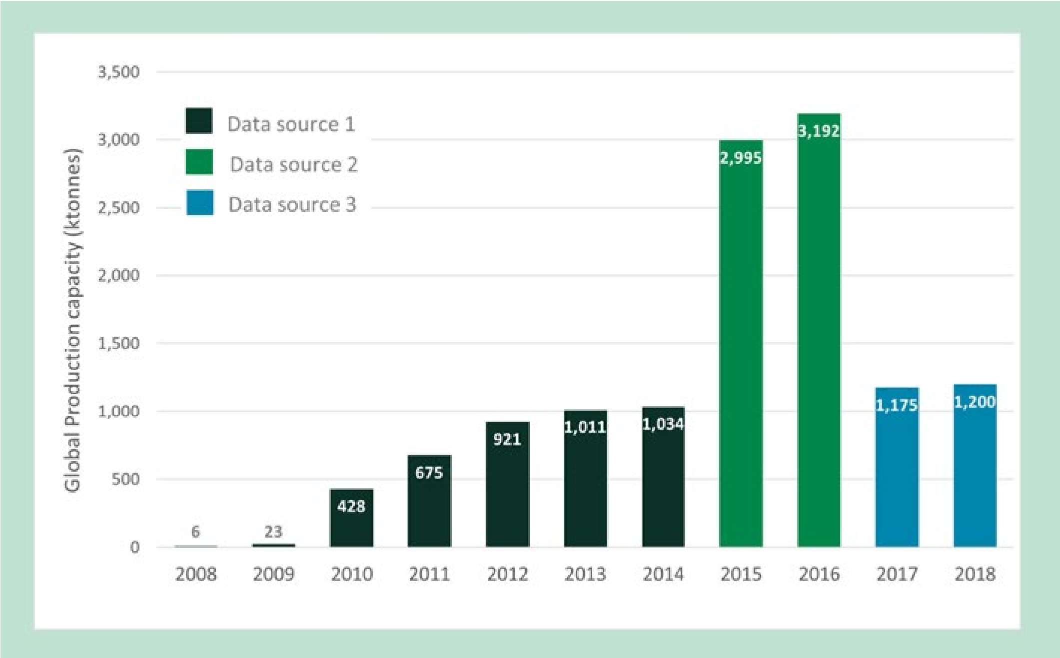

FIGURE 24. Reported global production capacity of bio-based plastics, 2008 to 2018[96] No*te that change in data sources and methodologies mean that no trend can be inferred between 2014 and 2017*

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[90] European Bioplastics (2010) *Bioplastics Facts and Figures 2010*, accessed 15 May 2019, http://www.plastemart.com/upload/literature/bioplastic-capacity-to-surpass-one-mln-ton-2011-biodegradable-polymers.asp

[91] European Bioplastics (2011) *Bioplastics Facts and Figures 2011*, accessed 15 May 2019, http://www.plastemart.com/upload/literature/europe-strong-bioplastic-growth-led-by-bio-polyethylene-terephthalate-pet.asp

The most recent comparable data shows there was a 3.05% increase in production capacity for biodegradable plastics from 2017 to 2018 and a 2.13% increase in bio-based plastic production capacity. Through discussions with key stakeholders it has been determined that this increase has been fairly consistent since 2008, with an average annual increase of 2-3%.[97] It has been predicted that, for biodegradable plastic facilities, **70% of the production capacity is reached**.[98] This was calculated by comparing the reported monetary value of the global market to the value of the market that would be reached if facilities were producing at full capacity. The value of the market if facilities were running at full capacity was calculated using the price of biodegradable plastics per tonne in 2016[99] and the percentage of global production capacity by plastic type in 2016.[100] **The global quantity of biodegradable polymers produced is thus predicted to be 640,000 tonnes.**

Data is not available to calculate the capacity utilization of bio-based polymer facilities. It is assumed that the capacity utilization is between 70-80%, an assumption based on the biodegradable plastic utilization and the average economy-wide capacity utilization.[101] This predicts the global quantity of bio-based polymers produced to be 840-960 ktonnes.

The **global quantity of biodegradable and bio-based polymers expected on the market is 1.48-1.60 million tonnes** for 2016.

The tonnage of end products on the market is typically less than that of raw material, reportedly approximately 80%, suggesting there **was 1.18-1.28 million tonnes of bio-based or biodegradable products on the global market** in 2016.

The total amount of plastics predicted to be on the global market in 2016 was 335 million tonnes,[102] meaning that bio-based and biodegradable plastics hold 0.4% of the global market by weight.

6.2.1.2 Global market by polymer type

The global market by polymer type is as shown in Figure 25 – where biodegradable polymers (including both fossil and bio-based) are shown in blue and non-biodegradable, bio-based polymers shown in green.

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[92] European Bioplastics (2013) Bioplastics Facts and Figures 2013

[93] European Bioplastics (2014) Bioplastics Facts and Figures 2014

[94] European Bioplastics (2017) Bioplastics facts and figures 2017

[95] European Bioplastics (2018) Bioplastics Facts and Figures 2018

[96] ibid

[97] Eunomia Research & Consulting, and Mepex (2018) *Bio-based and biodegradable plastic: An Assessment of the Value Chain for Bio-Based and Biodegradable Plastics in Norway*, Report for Norwegian Environment Agency, 2018, https://www.eunomia.co.uk/reports-tools/bio-based-and-biodegradable-plastics-norway/

[98] Eunomia Research & Consulting (2020) *Relevance of Biodegradable and Compostable Consumer Plastic Products and Packaging in a Circular Economy*, Report for DG Environment, January 2020

[99] FBR BP Biorefinery & Sustainable Value Chains, FBR Sustainable Chemistry & Technology, Biobased Products, van den Oever, M., Molenveld, K., van der Zee, M., and Bos, H. (2017) *Bio-based and biodegradable plastics : facts and figures : focus on food packaging in the Netherlands*, Report for Wageningen, 2017, http://library.wur.nl/WebQuery/wurpubs/519929

[100] European Bioplastics (2017) Bioplastics facts and figures 2017

[101] The Federal Reserve (2019) *Statistical Release - Industrial Production and Capacity Utilisation*, accessed 26 September 2019, https://www.federalreserve.gov/releases/g17/current/

[102] Plastics Europe (2017) *Plastics – the Facts 2017 - An analysis of European plastics production, demand and waste data*, 2017, https://www.plasticseurope.org/application/files/5715/1717/4180/Plastics_the_facts_2017_FINAL_for_website_one_page.pdf

As shown, the global production capacity for bio-based and/or biodegradable plastics is currently 57% non-biodegradable polymers. Bio-PET dominates this area, with 26% of the global market – as shown in Figure 25. Bio-PA and bio-PE also hold a large share, with 12% and 9% respectively.
Biodegradable polymers hold 43% of the total bio-based and biodegradable markets. Of the polymers that are biodegradable, starch blends and PLA are the most common, with 18% and 10% of the market respectively.

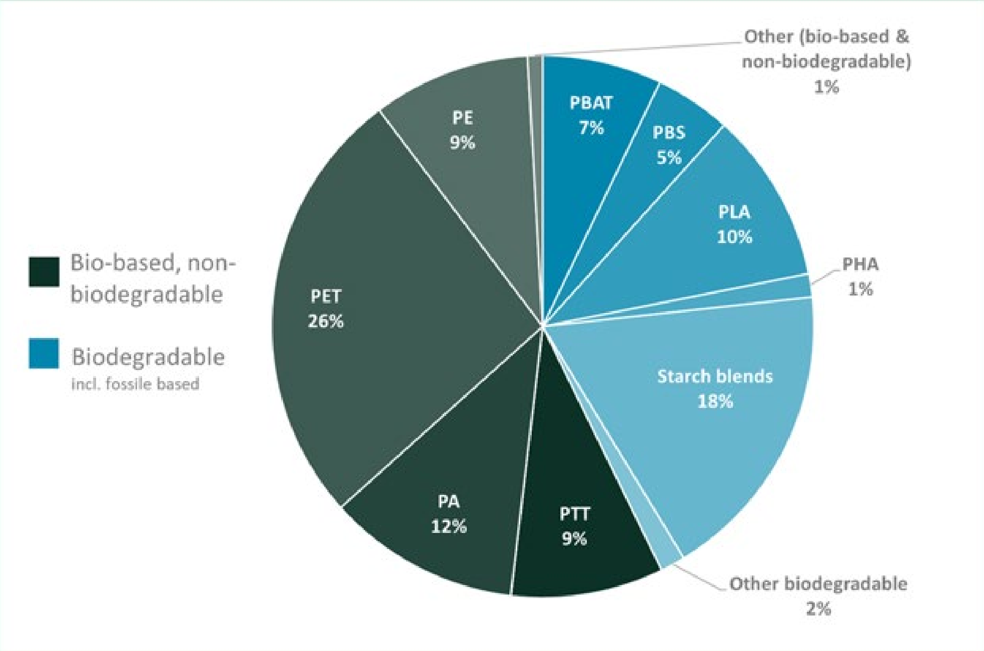

FIGURE 25. Split of the global production capacity of bio-based or biodegradable plastics, by polymer type[103]

Summary of the Current Global

The size of the market is hard to measure, and data is hard to find.

It has been predicted that there are 1.18-1.28 million tonnes of bio-based or biodegradable products on the global market.

Bio-based and biodegradable plastics made up 0.4% of the total plastics market in 2016

[103] European Bioplastics (2018) Bioplastics Facts and Figures 2018

6.3 Applications

6.3.1 Common Market Areas

Bio-based and biodegradable plastics can be found in many market areas, including packaging, textiles, automotive, consumer goods, agriculture, construction and electronics. Figure 26 shows the global market of these materials by product group in 2018. This shows that packaging accounts for the majority of the bio-based and/or biodegradable plastics market. The key difference between the two markets here is that whilst flexible packaging dominates the biodegradable market, ridged packaging dominates the bio-based market. This is because flexible packaging (which, in this case, includes all types of bags) generally lends itself more to being biodegradable in the context of composting—it is certainly harder for ridged packaging to meet the requirements of EN 13432 for industrial composting. Agricultural products such as mulch films are also a key market for biodegradable plastics but which do not feature in the bio-based market (likely due to price). The automotive and transport sector is a growing market for bio-based plastics as car manufacturers seek to find alternative feedstocks for plastic interiors and finishes. Biodegradable plastics would be unsuitable for this market which requires durability and a focus on end-of-life recycling.

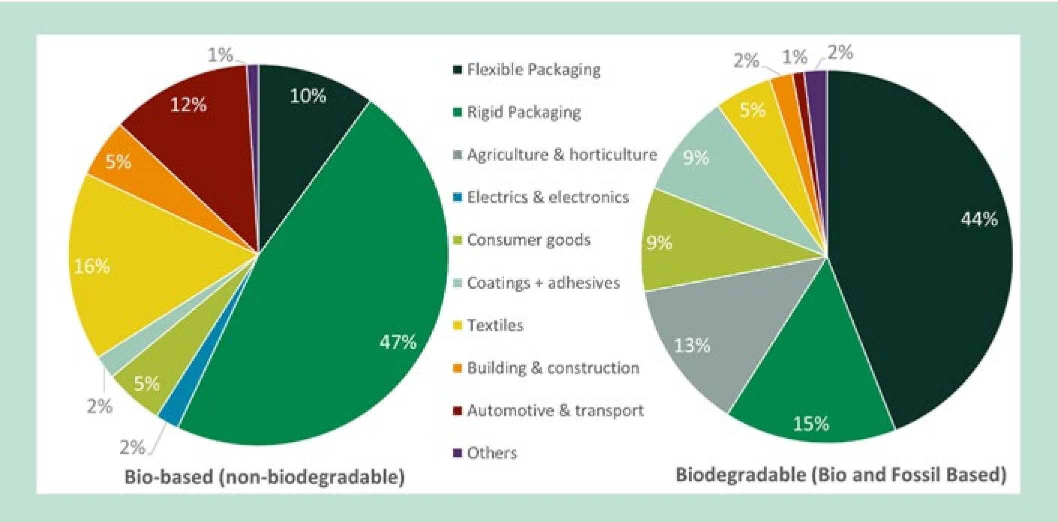

FIGURE 26. Global Market Applications of Bio-based and Biodegradable Plastics, by Product Group (2018)[104]

6.3.2 Common Applications

Data regarding the quantity of each end product on the market is limited for both bio-based and biodegradable products, as the data is often commercially sensitive. They are also sold in relatively small quantities to end-users. The following section seeks to outline an indication of the common applications of both biodegradable and bio-based plastics.

6.3.2.1 Biodegradable Products

Little data is available on the quantity of each end product on the market, as the data is often commercially sensitive. As such, it is not possible to determine a completely accurate and up to date, ordered list of the most common applications and the quantities on the market.
The Nova Institute reported in 2015 that the top applications, in order, were shopping bags, biowaste bags, disposable tableware, rigid packaging, other flexible packaging (not including shopping or biowaste bags), consumer goods, fibre products and agricultural and horticultural

[104] European Bioplastics (2018) Bioplastics Facts and Figures 2018

applications.[105] This is the only data available on EU sales by application, but due to the nature of the market—several niche applications—there is a lack of specific detail.
Through analysing both data on the products that are certified (from 2019) and the proportion of product groups on the market (from 2015), the ten most common applications on the European market have been identified - outlined in Table 5.
For carrier bags, biowaste bags, rigid packaging, other flexible packaging and agricultural films, data was available on the proportion of these products on the EU market in 2015.[106] This allowed calculation of an indicative quantity on the European market.
The other applications listed in the table were determined through analysing the share of the individual product certifications. This is as a proportion of product certifications put on the market, rather than as a proportion of financial value or actual tonnes on the market. The indicative values have been calculated by looking at the share of product certifications from TUV Austria. The list of ten most common applications has also been verified through discussions with stakeholders.

TABLE 5. Most common applications of certified compostable plastics on the European market

Application	Indicative quantity on EU market, ktonnes[4]	Share of product certifications[5]
Carrier bags	65 – 74	29%
Biowaste bags	54 – 62	28%
Rigid packaging (food and non-food)	16 – 18	4%
Other flexible packaging (food and non-food, not incl. carrier or biowaste bags)	8 – 9	12%
Agricultural films	7 - 8	2%
Single use trays and plates[1]	Data not disaggregated: Disposable tableware (incl. trays, plates, cups and cutlery) 10 - 12	6%
Single use cups[2]		4%
Single use cutlery[3]		2%
Bags for loose products (vegetables and other)	Unknown	3%
Coffee pads, filters and capsules	Unknown	3%

Notes:

1. Plates will be banned across Europe under the SUP Directive Article 5
2. May be subject to national bans or restrictions under SUP Directive Article 4
3. Will be banned across Europe under the SUP Directive Article 5
4. Calculated using total quantity on EU market as calculated within this report, plus proportion of EU market data in 2015 – where available - from Nova Institute (2016) Market study on the consumption of biodegradable and compostable plastic products in Europe 2015 and 2020
5. TUV Austria: Certified Products, as of 25 June 2019, http://www.tuv-at.be/certified-products/

[105] Nova Institute (2016) *Market study on the consumption of biodegradable and compostable plastic products in Europe 2015 and 2020*

[106] Nova Institute (2016) *Market study on the consumption of biodegradable and compostable plastic products in Europe 2015 and 2020*

Across Europe, carrier bags make up 29% of certified products.[107] It is expected that this value is less within Denmark as they reportedly use less single use carrier bags than the rest of Europe.
Carrier bags and biowaste bags combined make up 68% of the product on the market by weight in 2015, so clearly dominate the European market.
There is also a large number of certified compostable single use cutlery items and plates on the European market. These products will be banned under the SUP Directive
Indicative sales data is reported on 'Northern Europe' in 2015 - which includes Sweden, Finland and Switzerland as well as Denmark. The type of products sold on this wider market are expected to be representative of the market within Denmark. Of the biodegradable plastic products sold in Europe in 2015, the following quantities were sold in Northern Europe:[108]

- 10% of biodegradable organic waste bags;
- 3% of shopping bags;
- 11% of rigid packaging;
- 17% of single-use tableware; and
- 33% of coated paper packaging.

This indicates that Northern Europe held a large share of the biodegradable coated paper packaging market within Europe, as well as the single-use tableware market. There have been no large changes to the Northern European market since 2015, so it is expected that the share is currently similar. It should be noted, however, that single-use trays and cups **may be subject to national bans** under SUP Directive Article 4.[109] **Single-use cutlery and plates will be banned** across Europe under SUP Directive Article 5.

Summary of the Current Market in Europe

Packaging is the most common market area for bio-based and biodegradable plastics with ridged and flexible packaging dominating respectively.

Carrier bags and biowaste bags are the most common applications for biodegradable products in Europe

[107] *TUV Austria: Certified Products*, accessed 25 June 2019, http://www.tuv-at.be/certified-products/

[108] Eunomia Research & Consulting (2020) *Relevance of Biodegradable and Compostable Consumer Plastic Products and Packaging in a Circular Economy*, Report for DG Environment, January 2020

[109] European Commission (2019) Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment

6.4 Market in Denmark

For the past several years, governmental discussions around resource use in Denmark have focused on building a circular economy, with an Advisory Board established in 2016 and a circular economy strategy published in 2018.[110] Following this strategy, the previous Danish government's plastic action plan was published in December 2018, further emphasising building a circular economy for plastics.[111] Bio-based and biodegradable plastics are mentioned in the action plan primarily in terms of the existing knowledge gap on many aspects of these materials, and the resulting uncertainty as to whether bio-based and/or biodegradable plastics should form a significant part of the solution to the plastic pollution problem.

Knowledge building is a theme in the Danish plastic market in general at present. Both the Danish Plastic Industry association[112] and one of the trade associations for waste[113] have held seminars aiming to inform attendees about bio-based and biodegradable plastic and their relevance to the plastic and waste industries, respectively. A necessary focus has been on clearing up confusion around the difference between bio-based and biodegradable plastic – a confusion which recently resulted in a reduction in the number of municipalities using compostable bags for food waste (see Section 6.4.1.1).

6.4.1 Biodegradable Products

The market in Denmark is relatively small compared to other countries within Europe. It is estimated that there are 6,500 tonnes of biodegradable products on the market[114] within Northern Europe (including Denmark, Norway, Finland and Sweden).

There is a small market for biodegradable plastics in Denmark. Although data is very hard to access, with no national studies having been carried out to date in the country, desk-based research and interviews with stakeholders suggests that the single biggest use of biodegradable plastic in Denmark is in the form of compostable food waste bags. Copenhagen city council hands out approximately 130 tonnes of compostable food waste bags each year, produced by the Norwegian company BioBag, and additional councils in Denmark account for around an additional 70 tonnes of biodegradable food waste bags, resulting in 200 tonnes of compostable food waste bags on the market for the household sector (see Appendix A.3.1 for the methodology used for these estimations).

Additionally, based on further research of company data and estimations by the research team, there is a market for other film-based biodegradable packaging[115], e.g. carrier bags, larger food waste bag liners for the service sector and dog waste bags, which is estimated to be around 300 tonnes per year (see Appendix A.3.2 for details of the methodology). Rigid single-use PLA packaging[116] is also available on the Danish market, at an estimated minimum market size of 50 tonnes per year (see Appendix A.3.3 for details). According to communication with the Danish importers of these products, both film and rigid biodegradable products

[110] Miljø- og Fødevareministeriet og Erhvervsministeriet (2018) *Strategi for cirkulær økonomi*, September 2018, https://mfvm.dk/fileadmin/user_upload/MFVM/Miljoe/Cirkulaer_oekonomi/Strategi_for_cirkulaer_oekonomi.pdf

[111] Miljø- og Fødevareministeriet (2018) *Plastik uden spild – Regeringens plastikhandlingsplan*, December 2018, https://mfvm.dk/fileadmin/user_upload/MFVM/Publikationer/NY_Regeringens_plastikhandlingsplan_full_version_FINAL_0123-2019.pdf

[112] https://plast.dk/2019/02/bioplastic-coference-2019-see-presentations-and-pictures/

[113] https://dakofa.dk/element/hvad-goer-vi-med-problemboernene-i-skraldespanden-kompositter-og-bioplast/

[114] Eunomia Research & Consulting (2020) *Relevance of Biodegradable and Compostable Consumer Plastic Products and Packaging in a Circular Economy*, Report for DG Environment, January 2020

[115] e.g. Plant2Plast and BioBag

[116] e.g. Plant2Plast

are primarily sold to the service or public sectors, rather than to retail, though as some of the sales are to large distributors, e.g. Multiline, where the final user is not known.
Purchasers for large events and festivals also import single-use plastic (bio-based and/or biodegradable) directly from abroad, in particular from US suppliers. The extent of this practice is not known. Interviewees in the retail sector, representing approximately 65% of the retail market, report that biodegradable plastic is not intended to be used in own-brand packaging, sold as single-use packaging or used e.g. for thin-gauge fruit and vegetable bags and for carrier bags (see further information in Section 6.4.1.1). There is therefore limited access to biodegradable products for the regular consumer.
Finally, there are niche applications in Denmark. One coffee brand[117] exclusively uses biodegradable plastic capsules for its coffee and also uses PLA for its take-away coffee cup lids and there is reported usage of biodegradable films in agriculture and horticulture[118], as well as for plant pots, though it is not known how widespread these are. One biodegradable PVA wad (a component of an ammunition shell) is also on the market[119] and there are reported instances of biodegradable plastic coffin ornaments being sold in Denmark, though the company that used to produce these appears to have closed down.

6.4.1.1 Market Trends and Influences

The future of the market for biodegradable plastics is unclear in Denmark. Of the stakeholders interviewed, some believe that the confusion around the meaning of "bioplastic" as well as the global focus on the issue of plastic marine litter has meant a diversion either towards other single-use non-plastic biodegradable products or towards reusable plastic containers, e.g. for drinks.[120] On the other side, some believe that there is still a market for biodegradable plastic, particularly for PLA single-use takeaway food containers.
The image of compostable food waste bags was heavily damaged in 2018 due to the "revelation" that Copenhagen's compostable food waste bags contained 70% fossil-based plastic (further evidence of the conflating of the terms 'biodegradable' and 'bio-based'). Biobag, the company that produced the bags, had never claimed that their bags were bio-based, and despite the fact that the bags remained certified to the EN 13432 composting standard, they were immediately seen as "less green" than expected.[121]
Following the publication of the bag testing report in spring 2018, Vestforbrænding carried out an internal evaluation to reassess their recommendation to use compostable bags. Their result was an updated recommendation to stop using these bags. The reasons included price, increased difficulty of removal of compostable bags during the pre-treatment stage, usability and householder experience and the potential for recycling conventional plastic bags (see Section 7.2 for further discussion on waste management of food waste liners).[122] In 2018, Vestforbrænding tendered for a supplier of non-compostable liners, with a contract initially for 2019 plus up to three optional 12 month extensions.

[117] Peter Larsen Kaffe

[118] Trioplast and BASF

[119] Green Shot. As at the time of writing, the only importer of the wad in Denmark is Land & Fritid, who have published further information about the wad on their website: https://www.landogfritid.dk/greenshot. Other non-plastic fibre-based biodegradable wads are also on the Danish market.

[120] A well-established deposit refund scheme makes a refund and/or return scheme for cups e.g. at festivals and theme parks more palatable in Denmark.

[121] https://ing.dk/artikel/koebenhavnske-bioposer-lavet-70-pct-fossil-plast-212171

[122] Internal communication seen by the research team.

As a direct result of Vestforbrænding's recommendation, ten municipalities within Vestforbrænding's area, covering 150,000 households, have switched from compostable bags to conventional plastic bags in the last year.[123]
In fact, the only municipality in Vestforbrænding's area that has not switched is Copenhagen city council. As a result of the fossil-based content found in the compostable bag, the municipality also initiated an evaluation to ascertain which liners to use in future. The results of the evaluation, carried out by COWI, were considered in committee meetings in spring 2019 and a decision was made to carry on using compostable food waste bags[124] – the contract to supply these was sent to tender in September 2019.

In summary, the evaluation considered four types of plastic bags:[125]

- compostable[126], partially bio-based
- (partially) bio-based non-compostable plastic
- non-compostable fossil-based plastic, (partially) made from recycled content
- non-compostable fossil-based plastic.

Additionally, paper bags were briefly considered, but due to a previous study in 2014, where householders showed a strong preference for compostable bags, paper bags were disregarded as an option for this evaluation. Due to the small market for the (partially) bio-based non-compostable plastic bags, these were also not considered further, leaving three types of bags for detailed consideration.

The results in brief:

- The compostable bag was determined to have lower CO2 emissions associated with its production and waste management. Based on COWI's evaluation, the committee also concluded that a compostable bag would degrade completely in soil, without leaving microplastics behind. However, this conclusion was a mis-reading of the report, which only refers to studies that found 90% degradability during a time period of up to two years.
- The compostable bag was also overall more expensive, at an increase of 10% on the total cost of collection compared to the total cost when supplying non-compostable bags.
- Householders were thought to find the non-compostable bags more reliable, more sturdy and to be associated with fewer bad odours. On the other hand, contamination rates of up to four times higher when using non-compostable compared to compostable bags have been found in surveys by other municipalities.

[123] Based on a telephone survey of municipalities by the research team. Many of these stories have also made the news. See e.g. See e.g. https://hilleroed.lokalavisen.dk/nyheder/2018-06-13/-Madaffald-Bio-poser-skiftes-ud-med-plastposer-2343952.html in Hillerød, https://ballerup.dk/dagsorden/teknik-og-miljoeudvalget-06-06-2018 in Ballerup, https://vallensbaek.dk/nyheder/service/nye-poser-til-indsamling-af-madaffald in Vallensbæk and https://www.tv2lorry.dk/lorryland/kommuner-om-bioposer-fulde-af-plastik-skandalost-og-en-ommer for an overview of municipality responses.

[124] https://www.kk.dk/indhold/teknik-og-miljoudvalgets-modemateriale/08042019/edoc-agenda/b3340b88-ccfd-4ca0-9b58-6c966b5ca3b3/b4567fbd-945f-4bca-8b92-62d73d21079e

[125] COWI (2019) *Opsamling på Viden om Indsamlingsposer til Bioaffald*, Report for Københavns Kommune, January 2019, https://www.kk.dk/sites/default/files/edoc/Attachments/22568190-31237848-1.pdf

[126] in Danish, "compostable" is not frequently used to describe these types of bags. "Biodegradable" is the Danish word used in the report, but given what bags are available on the Danish market, it is reasonable to assume that only compostable types of biodegradable bags are considered

On balance, on the basis of the above, the recommendation and adopted decision was to continue using compostable bags but to include a minimum of 50% bio-based material in the tender for the new supply of compostable bags.
As only 45% of municipalities currently collect food waste, there is a large potential for more compostable plastic bags, if more municipalities follow in Copenhagen's footsteps. Odense commenced a roll-out of food waste collection in October 2019 but is providing conventional plastic bags for this. The municipality decided on conventional plastic bags due to the potential for recycling these bags in future and as the municipality did not believe there would be increased benefits in respect of the householder from using compostable bags.[127]
In relevant trade associations, there are strong voices advocating against the use of biodegradable plastic, including the Danish Waste Association, the Danish Plastic Industry association and two major retailers (representing 60% of the market for groceries). The primary reason is the issue of waste management and risk of contamination of the plastic recyclate (See Section 7.2) – and it therefore seems unlikely that biodegradable (or more specifically, compostable) plastic will be promoted by these actors.
Specifically, these organisations state the following on bio-based and biodegradable plastics:

Danish Waste Association (Dansk Affaldsforening)[128]:

- Although using recycled content should be a priority, bio-based plastic are relevant to use where virgin fossil-based material would otherwise be used.
- Biodegradable plastic only has limited scope for use, e.g. in food waste liners and cellophane wrapping that frequently ends up as litter, such as around chewing gum and cigarette packets. Technological development to improve degradation is required.
- Biodegradable plastic should not be used in non-takeaway food packaging that is frequently sorted for recycling in the home, due to contamination of the recyclate.

Danish Plastic Industry Association (Dansk Plastindustri) – Forum for Circular Plastic Packaging[129]:

- Biodegradable plastic should not be used for plastic packaging due to contamination of the recyclate, but does have a role in products intended to be left in environments where it can biodegrade, e.g. in agricultural film.
- Bio-based plastic, e.g. in PP, PET and PE, is appropriate for plastic packaging that is intended to be recycled. The biomass source should be sustainably farmed.
-

Salling Group (retailer)[130]:

- Reducing plastic packaging is the overall priority, alongside ensuring recyclability of the plastic packaging that remains.
- Emphasises using recycled content in plastic packaging.
- Biodegradable and bio-based plastic should not be used in packaging and should not be present in products on store shelves – due to, respectively, waste management concerns and a belief that ”food should not be used for packaging".

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[127] Personal communication between the research team and the municipality.

[128] https://www.danskaffaldsforening.dk/sites/danskaffaldsforening.dk/files/media/documents/plast_i_en_cirkulaer_oekonomi_feb_2017/bioplastik.pdf

[129] https://plast.dk/wp-content/uploads/2018/11/Recommendations-and-actions-ENG-Forum-for-Circular-Plastic-Packaging-NOVEMBER-2018.pdf

[130] https://sallinggroup.com/ansvarlighed/klima-baeredygtighed/plastik/plastik-principper/ and personal communication.

- It is possible that some packaging on products sold by Salling Group from international suppliers contain biodegradable coating – there is a lack of standardisation and consistent labelling across the EU.

Coop (retailer)[131]:
- Emphasise reducing the use of plastic packaging and removing single-use plastic products from shelves where possible.
- Packaging should be recyclable within the Danish waste management system and should use recycled or bio-based plastic where possible.
- Biodegradable plastic should not be used – because it is often fossil-based, because appropriate waste management channels do not exist in Denmark and because Coop does not believe that current certifications for degradability are strict enough. If better products can be developed, including for example some that are certified to standards higher than OK Home Compost, then Coop may reconsider stocking specific products.

Niche applications may then be where the current potential lies for an increase in biodegradable plastic in Denmark. For examples, estimates suggest that there are 20-30 tonnes of non-biodegradable plastic wads in ammunition shells in use each year. As the government has already announced an intended ban on non-biodegradable shells (with support from relevant interest associations), this is likely to be a growing market.

6.4.2 Bio-based Non-biodegradable Products

As with biodegradable products, it is difficult to measure the quantity of bio-based products on the market in Denmark.
As outlined above, in September 2019 Copenhagen City Council decided to use compostable bags with a minimum of 50% bio-based material for their household food waste collections. Other municipalities have not followed in Copenhagen's footsteps so far, and are choosing conventional plastic bags over bio-based or biodegradable alternatives.

There are several niche examples of bio-based products on the market within Denmark:

- Danish toy company Dantoy specialises in providing bio-based toys from bio-PE.[132]
- Arla Dairy plan to sell bio-PE milk cartons in Denmark by the end of 2019. This comes after them experimenting with using PLA but finding the plastic did not have sufficient technical properties.[133] They plan to use sugar cane or forest waste as a feedstock for the bio-PE, and the company claim that the milk bottles produce 25% less carbon dioxide into the atmosphere compared to the previously used fossil-based plastic.[134]
- Styropack, a Danish company part of the Durch Synbra Group, produce BioFoam® – a foamed PLA with similar properties to expanded polystyrene (EPS). They provide a 100% PLA product, which is certified compostable, as well as a 10% PLA and 90% EPS product called 'BioFoam® Inside'. The latter product is not compostable, due to the mixing of PLA

[131] https://ansvarlighed.coop.dk/vores-fodaftryk/emballage/ and personal communication

[132] *BIO - Dantoy bioplastic line*, accessed 7 November 2019, https://dantoy.dk/en/bio/

[133] FORCE Technology (2014) *Anvendelse og potentiale for brug af bioplast i Danmark*, Report for Danish Environmental Protection Agency (Miljoestyrelsen), 2014, https://www2.mst.dk/Udgiv/publikationer/2014/12/978-87-93283-40-4.pdf

[134] (2019) *Arla makes over one billion pieces of packaging more sustainable across Europe*, accessed 7 November 2019, https://www.arla.com/company/news-and-press/2019/pressrelease/arla-makes-over-one-billion-pieces-of-packaging-more-sustainable-across-europe-2869447/

with a non-compostable product, and only has 10% bio-based content.[135] As it is only 10% bio-based content, it does not meet any bio-based certification criteria.

Danish company Haldor Topsoe have teamed up with Braskem to open a bio-based MEG plant – see section 6.6.1.1 for more details. It is unclear whether this will influence the bio-PET industry in Denmark at this stage.

Summary of the Current Market in Denmark

There are an estimated 550 tonnes of compostable plastics used in Denmark annually which is primarily comprised of biowaste and carrier bags.

There is no market data on any other types of biodegradable plastic, but applications are expected to be very niche and not contribute in a large way to the overall market at this time.

6.5 Future of the Market

6.5.1 Projections

It is predicted that key growth areas will be for plastics with a novel chemical structure, in comparison to drop-ins, as they have additional functionality. Due to current policy and petrochemical prices, a polymer being bio-based is simply not enough for it to break through in the market. Additionally, published predictions for the future of the market are unreliable and ever-changing.

Overall, the global production capacity of bio-based and biodegradable plastics is currently growing at 2-3% per year, which is the same rate as conventional plastics.[136] A business as usual projection for 2019 - 2024 is shown in Figure 27. There are several key assumptions that have been used to produce this graph:

1. The global quantity of biodegradable plastics produced in 2018 is 640 ktonnes (production capacity utilisation[137] of 70%);
2. The global quantity of bio-based plastics produced in 2018 is 900 ktonnes (production capacity utilisation of 75%);
3. Growth for both markets is, on average, 2.5%.

[135] *BioFoam - Få en grøn profil med Styropacks bionedbrydelige materiale*, accessed 7 November 2019, https://styropack.dk/products/biofoam/

[136] Eunomia Research & Consulting, and Mepex (2018) *Bio-based and biodegradable plastic: An Assessment of the Value Chain for Bio-Based and Biodegradable Plastics in Norway*, Report for Norwegian Environment Agency, 2018, https://www.eunomia.co.uk/reports-tools/bio-based-and-biodegradable-plastics-norway/

[137] Production capacity utilisation is the amount of product produced by a facility compared to the maximum capacity of the facility, for example a facility that *could* produce 100 ktonnes annually but only produces 80 ktonnes would have a production capacity utilisation of 80%.

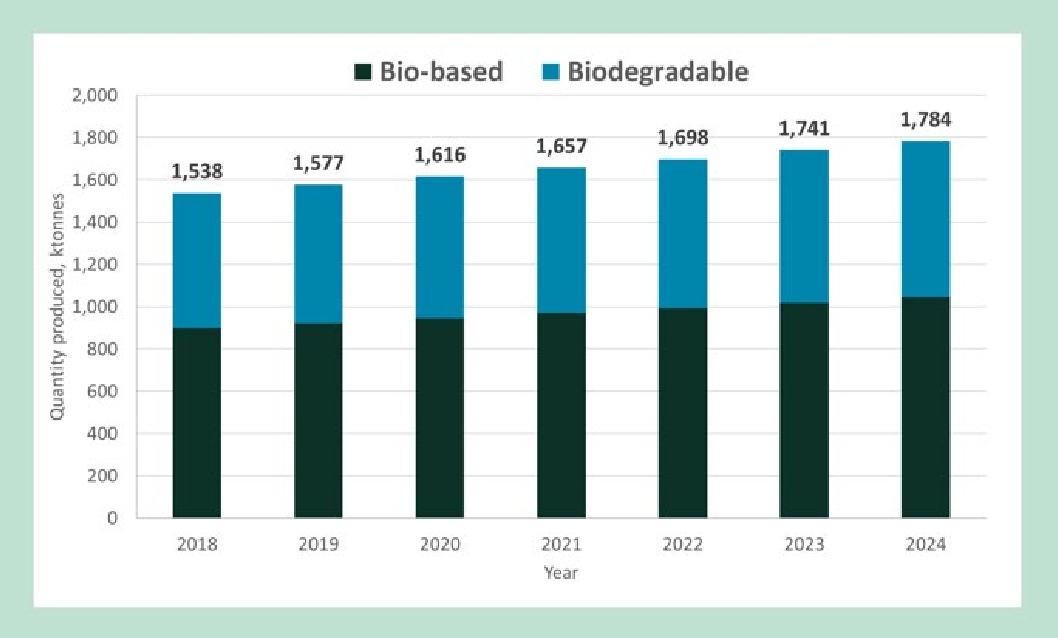

FIGURE 27. Global projection of the bio-based and biodegradable market, 2018 to 2024

6.5.2 Influences

There are many potential market drivers, for example increased pressure from consumers for products to be 'environmentally friendly', policy measures and corporate social responsibility voluntary agreements. The key market drivers are outlined below.

There are targets and directives across the EU that will influence the plastic market in Denmark. The EU's Plastic Strategy[138] for example, has the objective for all packaging placed on the EU market to be reusable or recyclable by 2030. These targets currently include the composting of plastics.

Some products are due to be banned under the European Single-Use Plastics (SUP) Directive[139], at present there is no exemption for biodegradable or bio-based plastics as the aim of the Directive is to reduce the impacts of littering – which biodegradable plastics may even increase, at least in the short term, due to consumers believing they will disappear in a short space of time.

Unlike many other countries, Denmark has not published a dedicated bioeconomy strategy but instead has two broader policy frameworks "Growth Plan for Water, Bio and Environmental Solutions" and "Growth Plan for Food". The first Growth Plan, launched in 2013, has 40 'actions', including:

1. Provide excellent opportunities for research, testing and market maturation of new biobased high-value products such as bioplastics and other advanced biotech products; and
2. Promote a European market for biobased, renewable products.

The second Growth Plan is focused on food rather than other materials, however part of its first key objective is to improve resource efficiency and the utilization of biomass.

As outlined in section 6.4.1, the biodegradable plastics market in Denmark is relatively small. There are more instances, however, where bio-based plastics are being researched and/or used in Denmark.

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[138] European Commission *Press release - Plastic Waste: a European strategy to protect the planet, defend our citizens and empower our industries*, accessed 25 September 2018, http://europa.eu/rapid/press-release_IP-18-5_en.htm

[139] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1562859783264&uri=CELEX:32019L0904

The Danish toy company LEGO have announced that they intend to use 'sustainable' materials in all of their products by 2030, and have a line commercially available that is made of bio-based PE. This currently only accounts for 1-2% of their sales, however is set to increase in the future. LEGO are also part of the PEF consortium 'PEFerence' – who aim to make PEF commercially available. The consortium currently has plans to open a 50 ktonne facility to produce PEF starting materials, with it expected to open in 2023/4.[140] The facility is not expected to be based in Denmark; however, it is likely that LEGO will use PEF in their end products in the following years.
Haldor Topsoe – a Danish company – have gone into partnership with Braskem in order to produce bio-based MEG; a building block of bio-based PET. A pilot plant is now operation in Lyngby, Denmark. It is said that by 2020, samples of the bio-based MEG will be available.[141]

Summary of the Future Market Potential in Denmark

Current there are no policy drivers within Denmark that are likely to incentivise significant growth in the biodegradable or bio-based plastic market as growth strategies do not contain any binding targets at present.

It seems likely that the biodegradable plastic market will not gain much traction within Denmark and will grow at (or even below) market average.

It is plausible that bio-based plastic will grow above the market average within Denmark, due to Danish investors and production facilities.

6.6 Manufacturing

6.6.1 Production Facilities

The following section summarises what is known about the production facilities for the raw materials and the polymer production.

6.6.1.1 Raw Materials

There are a multitude of production facilities making raw materials for the building of bio-based and biodegradable polymers, with the primary processing being dominated by 10-15 major companies. Some of these are petrochemical companies which also produce bio-based materials, and others are simply bio-based processors.
There are several biorefineries in Denmark, however these primarily produce biofuel.[142] It is worth noting that there is a bio-based MEG facility in Lyngby (Denmark).[143] This facility is run

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[140] (2018) *PEF pilot phase set to be extended*, accessed 11 October 2018, https://www.avantium.com/press-releases/pef-pilot-phase-set-extended/

[141] (2019) *Braskem and Haldor Topsoe startup demo unit for developing renewable MEG - Bio-based News* -, accessed 27 September 2019, http://news.bio-based.eu/braskem-and-haldor-topsoe-startup-demo-unit-for-developing-renewable-meg/

[142] Nova Institute (2017) Biorefineries in Europe 2017

[143] (2019) *Braskem and Haldor Topsoe startup demo unit for developing renewable MEG - Bio-based News* -, accessed 27 September 2019, http://news.bio-based.eu/braskem-and-haldor-topsoe-startup-demo-unit-for-developing-renewable-meg/

by Braskem and Haldor Topsoe. This means that within Denmark only bio-based feedstocks are produced, rather than polymers themselves. There may be small-scale product production facilities, however these have not been picked up through the research conducted for this report. There are no large scale product facilities.

6.6.1.2 Polymers

The global production of bio-based and biodegradable plastics is dominated by several key industry players. In an everchanging market these producers, their facility locations, and their capacity, change rapidly. Several key players are shown in Table 6. This list has been taken from The Norway Report.

There have been no changes to global polymer production capacity between 2018-19 for the producers mentioned in The Norway Report. Neste and LyondellBasell have also entered the bio-based plastic market, producing bio-PP and bio-PE. The production capacity of their facility has not been announced, but the products are commercially available.[144] Greendot holdings – Terratek® producers – have received significant funding to increase their production capacity, but plans are not yet publicly available.[145]

TABLE 6. Bio-based and/or Biodegradable Plastic Producers

Company	Brand name	Type of plastic	Production Locations	Production capacity (ktonnes / year)
Arkema SA	Rilsan®	PA	France, USA, China	N/A
Avantium	YXY	PEF	Belgium	50 by 2023
BASF	ecoflex®	PBAT	Germany	74+
	ecovio®	PBAT & PLA blend		
Braskem	I'm greenTM	Bio-PE	Brazil	200
DowDuPont	Hytrel® RS	polyester- copolymer	Switzerland	N/A
	Zytel® RS	PA (Nylons)		
	Sorona® EP	Bio-PTT		
Danimer Scientific (formerly Meridian)	Nodax™	PHA	USA	~90[146]
FKuR	Biograde	Cellulose Acetate	N/A	N/A
Greendot holdings	Terratek®	Starch blend	N/A	N/A
Neste and LyondellBasell	Circulen	Bio-PP and -LDPE		
NatureWorks	Ingeo	PLA	USA	200

[144] (2019) *Neste and LyondellBasell announce commercial-scale production of bio-based plastic from renewable materials - Bio-based News* -, accessed 1 October 2019, http://news.bio-based.eu/neste-and-lyondellbasell-announce-commercial-scale-production-of-bio-based-plastic-from-renewable-materials/

[145] (2019) Green Dot Bioplastics Secures $6.5 Million to Expand Material Portfolio and Increase Production Capacity, *Green Dot Bioplastics*

[146] Trump, P.V. (2019) *Why 2019 may be a promising year for PHA*, accessed 1 October 2019, https://www.plasticstoday.com/packaging/why-2019-may-be-promising-year-pha/45669703260085

Company	Brand name	Type of plastic	Production Locations	Production capacity (ktonnes / year)
Novamont	Mater-Bi	Starch blend	Italy	100
Plant PET Tech Collaborative	PlantBottle™	PET	N/A	N/A
Plantic Tech	Plantic	PE / PET copolymers	Australia + Germany	N/A
Total Corbion	Luminy®	PLA	Thailand	75[147]
Yield10 Bioscience Inc. (formerly Metabolix)	Mirel	PHA	Spain	N/A
	Mvera	PHB		

6.6.1.3 Quantity

Each polymer on the market requires a certain amount of bio-based and fossil-based feedstock to be produced. Outlined in Table 7 is the amount of starch needed to produce one tonne of polymer, as well as the total starch to produce the predicted quantity of each polymer on the market. Also detailed is the type and quantity of petro-based material needed to make the polymer if relevant and data is available. Only information on starch as a bio-based feedstock is included, as it is the most common feedstock for bio-based products – as outlined in Section 6.2.1.2**.**

As an understandable comparison, the quantity of potatoes that would be necessary to produce this amount of starch has been included. This is an incorrect assumption as not all bio-based products are made from potatoes, but is meant to be indicative. For comparison, the worlds potato production was estimated at 388,191,000 tonnes in 2017.[148] It typically takes 4 - 6.5 tonnes of potatoes to produce 1 tonne of commercial starch.[149]

Bio-PE has a low feedstock efficiency, meaning that it requires a large amount of feedstock to produce a relatively small amount of plastic.[150] PLA has a relatively good feedstock efficiency, meaning less starch/sugar is required to produce one tonne.

[147] (2018) *Total Corbion PLA starts-up its 75,000 tons per year bioplastics plant - Bio-based News -*, accessed 1 October 2019, http://news.bio-based.eu/total-corbion-pla-starts-up-its-75000-tons-per-year-bio-plastics-plant/

[148] FAOSTAT, 2019

[149] *International Starch: The Production of High Quality Potato Starch*, accessed 31 October 2019, http://www.starch.dk/isi/starch/tm5www-potato.asp

[150] Eunomia Research & Consulting, and Mepex (2018) *Bio-based and biodegradable plastic: An Assessment of the Value Chain for Bio-Based and Biodegradable Plastics in Norway*, Report for Norwegian Environment Agency, 2018, https://www.eunomia.co.uk/reports-tools/bio-based-and-biodegradable-plastics-norway/

TABLE 7. Tonnes of each bio-based raw material to produce the amount of polymer predicted to be on the market

Polymer	Starch required per tonne of plastic[151], tonnes	Total starch required, tonnes	Petro-based product required, tonnes
PBAT	No information	No information	No information
PBS (100% bio-based)	1.95	261	N/A
PBS (100% fossil-based)	No information	No information	No information
PLA	1.67	500	N/A
PHA[152]	3.24	132	N/A
Starch blends	Varies	Varies	Varies
PTT[153]	3.25	870	
Bio-PA[154]	3.49	1,178	
Bio-PET[155]	0.85 (+ 0.87 PTA)	658	670 PTA
Bio-PE	4.95	1,368	N/A
Total	N/A	4,967	N/A

6.6.1.4 Land use

The land required to produce the expected quantity of polymers on the market in 2016 has been calculated, using data on land use from the Institute for Bioplastics and Biocomposites[156] - see Appendix A.4.0. The land use for polymers has been calculated for five different feed-stocks – sugar cane, sugar beet, corn, potato and wheat. The land use per tonne of PBAT and for starch blends was not available – so these have not been included in the total land use. As PBAT and starch blends account for 25% of the market, this is a key limitation.

[151] Institute for Bioplastics and Biocomposites *Biopolymers facts and statistics 2017*, https://www.ifbb-hannover.de/files/IfBB/downloads/faltblaetter_broschueren/Biopolymers-Facts-Statistics_2017.pdf

[152] Assuming that all PHAs have the same land use requirement as PHB

[153] Assuming that all is 100% bio-based

[154] Assuming that all is PA-6

[155] For bio-PET with 32% bio-based content. 100% bio-based would be roughly three times more land intensive

[156] Institute for Bioplastics and Biocomposites *Biopolymers facts and statistics 2017*, https://www.ifbb-hannover.de/files/IfBB/downloads/faltblaetter_broschueren/Biopolymers-Facts-Statistics_2017.pdf

FIGURE 28. Predicted land use to produce the quantity of bio-based and biodegradable plastics expected on the market

	Land use, hectares				
	Sugar cane	**Sugar beet**	**Corn**	**Potato**	**Wheat**
PBAT			No information		
PBS (100% bio-based)	12,000	12,000	28,000	32,000	75,000
PBS (100% fossil-based)	24,000	25,000	56,000	66,000	151,000
PLA	48,000	54,000	111,000	132,000	312,000
PHA[157]	12,000	13,000	28,000	33,000	77,000
Starch blends			No information		
PTT[158]	80,000	83,000	185,000	217,000	506,000
Bio-PA[159]	115,000	125,000	260,000	310,000	736,000
Bio-PET[160]	62,000	62,000	139,000	163,000	379,000
Bio-PE	127,000	130,000	293,000	343,000	796,000
Total	**456,000**	**478,000**	**1,044,000**	**1,229,000**	**2,880,000**

100% fossil-based PBS has been included in the table, but not included in the total, to highlight that sometimes for a drop-in polymer, the fossil-based polymer actually has a higher land requirement than the bio-based polymer.
As shown, the total land use (excluding for PBAT and starch) is predicted by Eunomia to be between 0.45 – 2.88 million hectares, dependent on which feedstock is used. Wheat has a much higher land use requirement than sugar cane.
The total land used for agricultural practices was 4.9 billion hectares in 2016.[161] This shows that the land use for bio-based and biodegradable polymers (excluding PBAT and starch blends) is 0.009 – 0.06% of the total global agricultural area.
European Bioplastics reported that in 2018 approximately 0.81 million hectares of land would be needed to grow sufficient feedstock to reach the predicted production capacity of 2.11 million tonnes. This seems like a reasonable prediction in accordance with the above findings.
The amount of people that could be fed using this agricultural area varies widely dependent on diet, however based on the 'average world diet' it has been reported that 6 people can be fed annually per hectare of land.[162] This suggests that the land used to grow feedstock for bio-based and biodegradable polymers – as reported by European Bioplastics - could, in theory, feed an additional 4.9 million people.

However, speculation like this should be taken with caution as there are a great many factors which will influence this including that:

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[157] Assuming that all PHAs have the same land use requirement as PHB

[158] Assuming that all is 100% bio-based

[159] Assuming that all is PA-6

[160] For bio-PET with 32% bio-based content. 100% bio-based would be roughly three times more land intensive

[161] FAOSTAT

[162] Cassidy, E.S., West, P.C., Gerber, J.S., and Foley, J.A. (2013) Redefining agricultural yields: from tonnes to people nourished per hectare, *Environmental Research Letters*, Vol.8, No.3, p.034015

- it is not clear how much feedstock is primary or secondary or how this might change in the future;
- land use per person fed varies a considerably and is dependent on diet/location; and,
- it implies that all the land used to grow feedstocks is also suitable for growing nutrient rich food.

Summary of Manufacturing of Bio-based Plastics

The quantity of starch required to produce all bio-based and biodegradable plastics expected to be on the market is marginal compared to the total starch market.

The land use required to produce the expected amount of bio-based and biodegradable polymers on the market (excluding starch blends and PBAT) is 0.009 - 0.06% of total global agricultural land.

7. Waste Management of Compostable and Bio-based Plastics

7.1 Europe

7.1.1 Overview

There are many different waste management practices across Europe, and practices vary even within a certain country.

Plastic use is increasing across Europe, but so too is plastic recycling, with 33% of post-consumer plastic waste now recycled – doubling from the amount sent in 2006.[163]

Household food waste is also increasing across Europe, with estimates of 47 million tonnes produced in 2012 across waste streams.[164] It is unclear what proportion of households across Europe receive separate food waste collections, however the collection of household food waste is becoming increasingly important in many countries.

With so many different waste management options in place, it is difficult for consumers to know how to correctly dispose of bio-based and/or biodegradable plastics. Drop-in polymers can be effectively recycled with their conventional counterpart where recycling is offered; for example, bio-PET can be processed in exactly the same way as conventional PET. However, bio-based plastics which do not have a fossil-based counterpart, and compostable plastics, are more challenging.

Compostable plastics should be disposed of in an industrial composting facility. However, many facilities do not actually accept these plastics as they are hard to distinguish from conventional plastics – a contaminant that causes quality issues in compost. Equally, compostable plastics are a contaminant in conventional plastics recycling - this will be outlined in more detail in this section.

7.1.1.1 Organic Waste Treatment Methods

There are broadly three different kinds of organic waste treatment systems commonly used across Europe:

- Anaerobic Digestion (AD);
- In Vessel Composting (IVC); and
- Open Air Windrow (OAW).

The processes within each of these treatment systems is not standardized, so the conditions and timeframes, for example, vary dramatically between anaerobic digesters.

Anaerobic digestion is often considered to be the preferred method for processing household food waste as the process generates biogas, an extremely high value output in both economic and environmental terms. Many countries have renewable energy subsidies, which give the biogas a high economic value. As such, many AD facilities depend heavily on income from biogas generation, and less so on the weighty biomass output.

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[163] Plastics Europe (2019) *Plastics - the facts 2019*, 2019, https://www.plasticseurope.org/application/files/1115/7236/4388/FINAL_web_version_Plastics_the_facts2019_14102019.pdf

[164] Stenmarck, Å., Jensen, C., Quested, T., et al. (2016) *Estimates of European food waste levels*, Report for European Commission, 2016, http://edepot.wur.nl/378674

There are two key variations of the AD process relevant to the issue of compostable plastics; wet and dry processes. Denmark mainly use a wet process, along with the UK and Norway, where the pulped biomass output is a slurry-like digestate. In many countries this slurry-like digestate is applied to agricultural land before maturation – however often lacks nutritional content compared to mature compost[165] Italy and Austria, on the other hand, use a dry AD process. This process has much lower water content and generally includes a secondary composting stage to stabilize the digestate – adding nutritional content.

Wet AD processes particularly struggle with plastic contamination, as there are pipes and pumps which can easily become blocked by plastic films. Also, wet AD processes typically do not stay at high temperatures for as long as in a dry process, as it is more costly to heat the water content.

The lack of a secondary composting stage in wet AD also means that the times often aren't sufficient to fully biodegrade compostable plastics, and most processes don't align with the test conditions within EN 13432. It should be noted, however, that woody materials take much longer to break down in AD than other organic materials, and are often screened out and reprocessed. It could be argued that biodegradable plastics that do not degrade due to insufficient time could be re-processed in the same way.

Plastic contamination in the resulting output is an issue in both wet and dry AD. This can arise as the screening and debagging processes aren't 100% efficient and plastic remnants persist. It could be argued that it is better for products likely to contaminate to be compostable, as these are less likely to persist in the soil.

IVC is used through Europe for treating both food and garden waste. It is a controlled, aerobic composting process. The IVC processes is still troubled by plastic contamination, but there are fewer mechanical issues than in wet AD – issues are primarily relating to the quality of output. The primary output of an IVC is the compost, and therefore it is important that minimal plastics are in the final product.

Many processing facilities, particularly wet AD, have screening and debagging processes to try and minimize contamination. This is particularly prevalent in wet AD facilities, as plastics are likely to get blocked in the pipes and pumps. Debagging typically consists of food waste liners being shredded open, before being removed in the screening stage along with any other plastic contaminants. This process is not 100% effective, as the shredding can actually result in microplastics being left in the biomass. This is the case with both conventional and compostable plastics. In regards to the quality of output, it is thus preferable for the plastic to be compostable, as it can degrade in the process.

OAW is used primarily for household garden waste and agricultural wastes. As no animal by-products are allowed to be composted using this method, it is unsuitable for household food waste. This technically means that compostable plastic packaging that has been contaminated with animal by-products should also not be sent to OAW.

7.1.1.2 Collection and Treatment in Europe

There are large differences in the provision of both separate collection and treatment capacity for organic waste in Europe. The European Compost Network report that approximately 30 million tonnes of biowaste is processed across Europe each year through composting or AD. The majority of this is green waste rather than food waste, as many countries still do not offer separate food waste collections. Composting accounts for the processing of most organic wastes, with 90% of food and garden waste across Europe going to compost facilities.[166]

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[165] European Commission, Directorate-General for the Environment, Autriche, Bundesministerium für Land- und Forstwirtschaft, U. und W., and Applying compost: benefits and needs, (eds.) (2003) *Applying compost: benefits and needs : seminar proceedings, Brussels, November 2001*, Vienna: Federal Ministry of Agriculture, Forestry, Environment and Water Management

[166] *Treatment of bio-waste in Europe*, accessed 6 December 2019, https://www.compostnetwork.info/policy/biowaste-in-europe/treatment-bio-waste-europe/

A literature review has been carried out[167] to determine which of the 28 Member States (+Norway) collect food waste at the kerbside and if so, whether this is as mixed organic waste or a separate stream, as shown in Figure 29. Also investigated was the proportion of Member States that have mandatory food waste collections which is currently 54%, although mandatory separate collection of organic waste will be a requirement for all Member States by 31 December 2023. It was found that no (or extremely limited) food waste collections occur in Bulgaria, Croatia, Cyprus, Estonia, Latvia, Portugal, Romania, Slovakia and Spain. Italy, Germany, UK, Sweden, Luxembourg, Belgium and Finland all carry out the separate collection and processing of food waste.

Of the countries with information available, it was found that only Belgium, Latvia, Luxembourg, Malta, Portugal, Sweden, Denmark and the UK use AD predominantly, with another nine countries either prioritising composting and no data available for other countries.

Many countries still rely on MBT to separate organic waste from residual, rather than separate organic waste collections. This is reportedly common in Bulgaria, Croatia, Cyprus, Estonia, Latvia and Portugal.

It was not possible to determine the prevalence of screening and debagging at organic waste treatment plants across Europe, or whether those that primarily use AD typically use a wet or dry process.

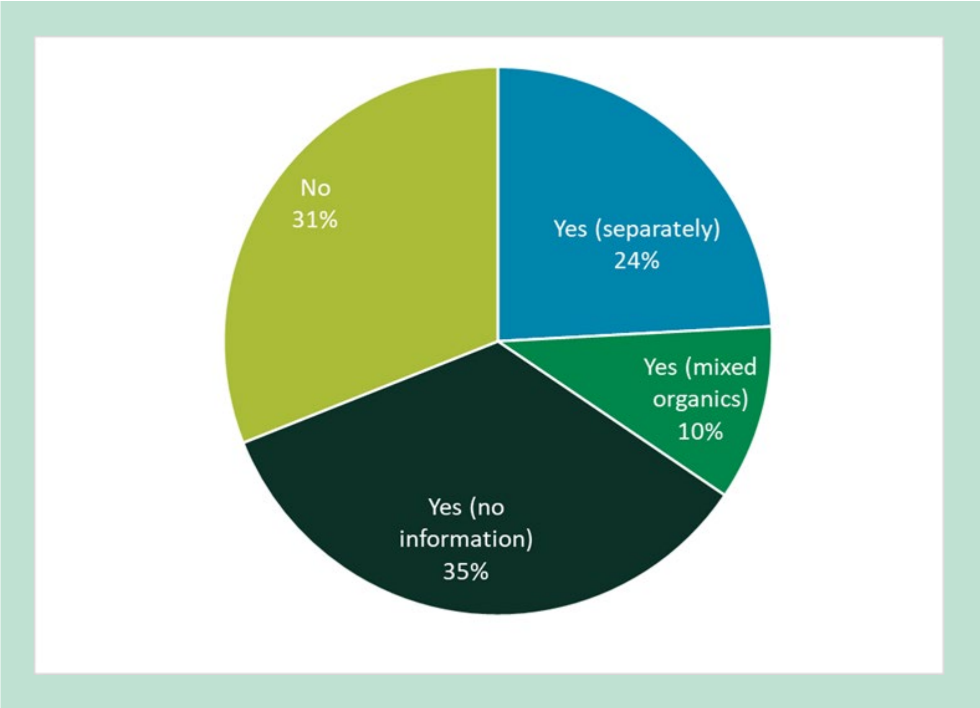

FIGURE 29. Proportion of EU member states (+Norway) that collect food waste at the kerbside

7.1.2 Case study: Italy and Germany

The following section focuses on comparing two key countries: Italy and Germany. The countries have been chosen as they have a widely different acceptance of compostable plastics; Italy has widespread use of compostable plastics, primarily for the purpose of increasing food waste capture, and the plastics are accepted by composters and processed effectively. Compostable plastics in Germany, however, are not widely accepted and there are issues with these being processed effectively.

[167] Much of this information has come from datasheets from the European Compost Network (https://www.compostnetwork.info/), with gaps filled from data held by Eunomia as well as country specific websites

In Italy, a dry AD process is used, generally with a secondary composting stage to stabilize the digestate. Italy has a minimum requirement that compost should mature for at least 90 days (which can be up to twice as long as German compost). Digestate can only be sold as a product if it has undergone this secondary composting stage, otherwise it is still considered a waste (whereas in most other countries it can be applied directly to land). This increases the nutrients in the product so more effectively 'recycles' the nutrients, and is also in line with the requirements of EN 13432 for treatment in aerobic conditions.

In Germany, renewable energy subsidies have driven the business model for AD, and as such, biogas generation is focused on rather than digestate. Digestate is essentially a byproduct of the process, rather than an output whose quality is optimised. Almost all AD facilities in Germany are used to process agricultural waste rather than household waste – although there are reports that the AD market for food waste is growing in Germany.[168] Plastic contamination is typically not a problem in agriculture waste, but is more prevalent in household food waste. This means that AD facilities in Germany are less likely to be experiencing plastic contamination, and that their facilities are less well equipped to deal with such contamination.

The vast majority of German household organic waste is treated by in composting plants rather than AD. Germany also use the 'Rottegrad' classification system which grades compost maturity levels for certain applications. Mature compost is generally used for higher value (horticultural) applications, such as gardening, landscaping, greenhouses and tree nurseries, whereas fresh compost (Frischkompost) is typically applied directly to agricultural land — the latter can be composted for as little as 6-8 weeks. The agronomic benefits—or perceived lack thereof—of fresh compost is the subject of much debate in Germany and elsewhere. A literature review of the issues around compost stability by WRAP from the UK —but with a focus on Germany where much of the research has been conducted—concluded that "Agricultural and field horticultural trials have not shown significant agronomic problems when less mature composts have been used."

This practice and the relatively short composting time is unlikely to be compatible with the conditions specified in EN 13432 that are required to ensure full biodegradation takes place before the compost is applied to land. This shows why the German composting industry is reluctant to embrace the widespread use of compostable plastics at this time when their processing time is generally incompatible and that the fresh compost output still provides the required agronomic benefits.

7.1.3 Contamination of Plastics Recycling with Compostable Plastics

Compostable plastics often look very similar to conventional plastics, making it very difficult for end-users to distinguish between materials. The plastics industry is concerned that the disposal of these compostable plastics in conventional plastic recycling streams will negatively impact the product, or even disrupt the process. This is confirmed by a position paper from SUEZ[169], which highlights the following:

> **" In general, any compostable plastic mixed with recyclable plastics will reduce the mechanical properties of the recyclates. This means that it will degrade the quality and reduce the recycling opportunities. (...) An increase in the diversity and the mix of plastics only complicates sorting operations".**

[168] http://adbioresources.org/news/running-an-ad-plant-lessons-from-germany

[169] SUEZ (2019) *SUEZ recommendations concerning Bio-sourced and Compostable Plastics*

It is therefore important to understand what level of compostable plastics in conventional plastic recycling is acceptable and whether this level likely to be surpassed in the case of increased use of compostable plastics, causing an issue for the conventional plastic recycling industry.

7.1.3.1 Problems Caused by Contamination

The amount of compostable plastic that is considered “acceptable” is likely to differ for different types of plastic. The research reviewed for this project is outlined in Table 8.
The majority of research that has been carried out is regarding the contamination of rigid PLA in PET recycling, as PLA has the largest market share of rigid bio-based/biodegradable plastics, and the two materials look and feel very similar to one another[170]; however, as outlined in section 7.1.3.2 it is less likely that compostable contaminants will end up in a rigid plastic stream.
Issues with the recycling refer to either mechanical properties or appearance issues with the output. A key issue with appearance reported amongst many of the in Table 8 studies is yellowing of the output material—a particular problem for clear, food grade PET. Mechanical issues arise mostly due to differences in physical properties, such as melting and glass transition temperatures. For example, when PLA is in PET recycling it is held at a temperature approximately 100°C above its melting point for a long period of time, due to the higher melting point of PET. This causes PLA fragments to become sticky, resulting in agglomerated PLA flakes that can clog machinery and cause outputted pellets to form clusters.[171]
Generally, it is shown that the acceptance of compostable contamination in 3-D plastics is much lower than for 2-D plastics. For example, PLA contamination in PP film is reportedly acceptable up to 3-5%, and up to 10% in a mixed plastic film stream, 1-2% of PLA in recycled PET yarn is acceptable, yet at only 0.1 - 0.3% of PLA in rigid PET bottle recycling.

7.1.3.2 The Likelihood of Contamination

The likelihood of contamination is based on the amount of compostable plastic in the collected stream, and the efficiency of the sorting process at the processing facility.
The typical process at a conventional plastic sorting site is:

1. Bag opening (if necessary) and primary screening to remove small impurities;
2. Ballistic separation and/or wind sifting, to separate 2-D and 3-D materials;
3. Optical sorting of 3-D materials; and
4. (sometimes) hand sorting of 2-D materials to collect large plastic films.
5. (lees often) floatation sorting of plastic films

The optical sorting of 3-D materials, usually Near Infrared (NIR), uses positive identification of target polymers, rather than rejection of impurities. This means that compostable plastics will be left with other impurities as the target material is removed. This also means that if compostable plastics become more widespread it is possible to calibrate the NIR sorting machines to positively identify compostable plastics for recycling—this will only happen if there is a market demand for these materials and currently this is only taking place in limited volumes for PLA in one plant in Belgium.[172]
For 2-D materials such as films, contamination is more likely as NIR is not used to separate these materials. This is either done by hand or using floatation tanks that rely of the density of

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[170] Martien van den Oever, Karin Molenveld, Maarten van der Zee, Harriëtte Bos, (2017), Bio-based and biodegradable plastics - Facts and Figures, Wageningen Food & Biobased Research, http://dx.doi.org/10.18174/408350

[171] Alaerts, L., Augustinus, M., and Van Acker, K. (2018) Impact of Bio-Based Plastics on Current Recycling of Plastics, *Sustainability*, Vol.10, No.5, p.1487

[172] http://www.looplife-polymers.eu/drupal/

materials for separation. Compostable 2-D films are less likely to be identified as a contaminant, and therefore may end up in the mixed film stream. However, as outlined above, there is evidence to show that this stream can accept a higher contamination before mechanical properties are affected.

The actual presence of compostable plastics in conventional plastic recycling collections has been studied by the Italian Composting Association CIC and the Plastic Packaging Recovery Organisation COREPLA[173]. The study consisted of 1,500 compositional analyses of separately collected plastics prior to sorting from 19 sites in 2016 and 17 sites in 2017. The sites were all in Italy – a country which has widespread use of compostable plastics. Results show an average contamination rate of 0.84% of compostable plastics in separately collected conventional plastics in 2016, and 0.85% in 2017. This seems to suggest that even pre-sorting, the contamination level of compostable plastics is low.

TOMRA, who specialise in advanced sorting, have stated that it typically finds 0.1% or less compostable plastic contamination in rigid plastics after sorting[174].

TABLE 8. Contamination of Compostable Plastics in Recycling

Author	Findings
Wageningen University[175]	0.3% PLA in PET recycling causes issues
Alaerts et al[176]	At 0.1% PLA can cause issues with appearance in PET bottle recycling
At 0.3% PLA can cause mechanical issues in PET bottle recycling	
CONAI[177]	1-2%[1] of PLA in recycled PET yarn is acceptable
Van den Oeve et al[178]	10% of Starch based films or PLA films are acceptable in a sorted plastic film mixture, with no significant negative effect on mechanical properties
Samper et al[179]	Up to 5% of PLA or PHB does not have a negative impact on the recycling of PP film
Germany Ministry of Food and Agriculture	3% of PLA in PP (film) recycling is acceptable

Notes

1. Possible higher tolerance due to textiles

[173] M. Centemero, *Accordo di programma tra Assobioplastiche, CIC, CONAI, Corepla, Resoconto sintetico delle attività di Monitoraggio*, 2017

[174] Interviews with Juergen Priesters, Business Development Directoor at TOMRA Sorting GmbH

[175] E.U. Thoden Van Velzen, M.T. Brouwer and K. Molenveld, *Technical quality of rPET*, Wageningen University 2016

[176] Alaerts, L., Augustinus, M., and Van Acker, K. (2018) Impact of Bio-Based Plastics on Current Recycling of Plastics, *Sustainability*, Vol.10, No.5, p.1487

[177] CONAI, WG Biodegradable Packaging Recovery Project, *Final Report,* 2012

[178] M. Van den Oever, K. Molenveld, M. Van der Zee, H. Bos,, *Bio-based and biodegradable plastics - Facts and Figures,* Wageningen University, 2017

[179] M.D. Samper, D. Bertomeu, M.P. Arrieta, J.M. Ferri, J. López-Martínez, *Interference of Biodegradable Plastics in the Polypropylene Recycling Process,* Materials **2018**, 11, 1886

Summary of Waste Management of Compostable and Bio-based Plastics in Europe

Organic waste treatment in Europe is varied, and each of the processes available (composting, anaerobic digestion) have different input requirements and acceptability of compostable plastics.

Italy has good acceptance of compostable plastics and their composting and AD facilities can effectively deal with them; this is from a combination of the dry AD process with secondary maturation phase and that composting facilities are required to run for at least 90 days.

Germany, however, have less acceptance of compostable plastics as their AD facilities are focussed on biogas production, and there are no regulations on compost maturity—the use of 'fresh compost' is widespread which is unlikely to provide the time for compostable plastics to fully biodegrade.

There is evidence to suggest that compostable plastics in conventional plastic recycling can reduce mechanical and aesthetic properties. The effects of this are more pronounced in high quality streams such as food grade PET and less so for mixed plastic films.

Compostable plastics can be identified and removed from plastics recycling and even in Italy where these materials are widespread, the contamination levels are not generally high enough to cause specific concerns at this stage.

7.2 Denmark

Municipalities are responsible for collecting all household waste. Householders pay for residual waste collection based on volume and/or collection frequency and in a few instances on weight. Kerbside collection is almost exclusively from 180+L wheeled bins, frequently with two or four compartments for residual/food waste and/or dry recycling. Recycling is not collected fully co-mingled in any municipality, though collection of 2 or 3 mixed materials such as metal and rigid plastic is common.

As shown in Figure 30 as at 31 December 2018, at least 70% of municipalities have a kerbside collection scheme or local bring sites (i.e. bring banks) for paper, card/cardboard, glass, metal and plastic for both houses and flats. The proportion of municipalities with a kerbside collection scheme is highest for paper (90% of all municipalities) and lowest for glass (55% for houses and 60% for flats).[180]

[180] https://genanvend.mst.dk/projekter/projektbibliotek/2015/kortlaegning-af-kommunale-affaldsordninger-for-husholdningsaffald-1/

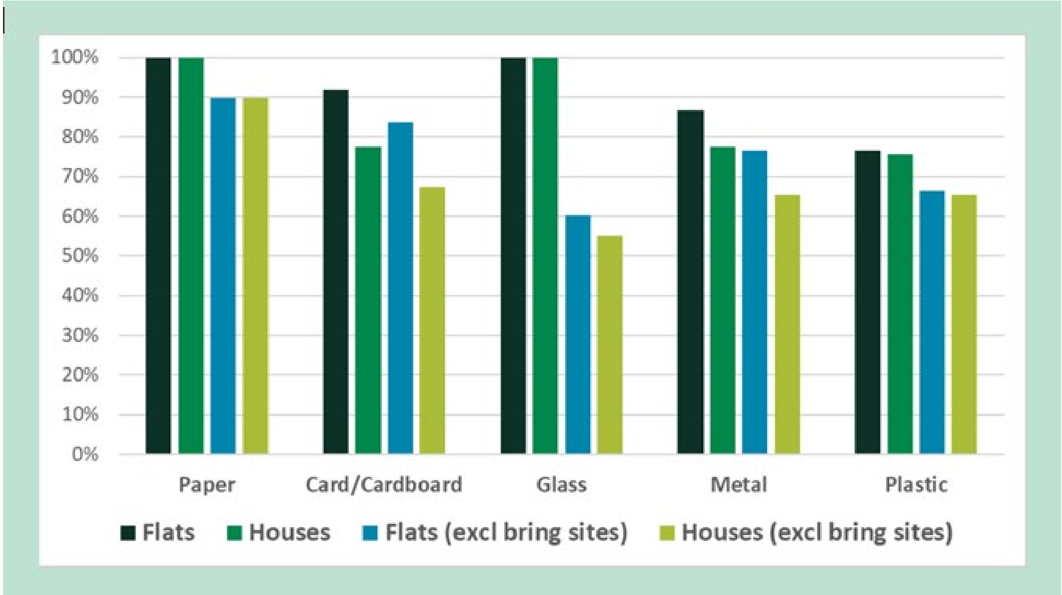

FIGURE 30. Percentage of municipalities with kerbside collection or local bring sites for dry recycling

Residual waste is incinerated in combined heat and power (CHP) plants, usually owned by municipalities or municipal waste companies. Denmark's overall recycling rate (based on waste collected for recycling) was 68% in 2017, the year for which the most recent data is available.[181] As shown in Figure 31, the recycling rate has increased slightly over the previous four years, from 66% in 2013. During this same period, waste generation in Denmark has increased from 10.5 million tonnes to 11.7 million tonnes. Household waste generation has remained at a similar level, with 3.35 million tonnes generated in 2013 and 3.49 million tonnes generated in 2017. The recycling rate for household waste (based on waste collected for recycling) has increased from 40% to 46%, largely due to the continuous roll-out of kerbside collection schemes for organic waste and dry recycling.

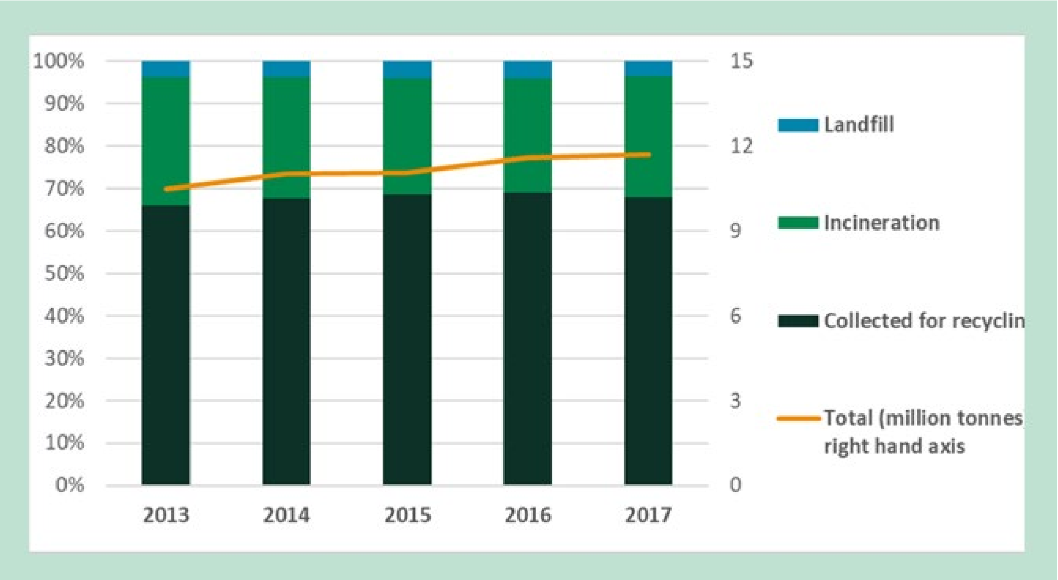

FIGURE 31. Recycling, Incineration and Landfill in Denmark, 2013-2017

[181] Miljøstyrelsen (2019) *Affaldsstatistik 2017, September 2019,* https://www2.mst.dk/Udgiv/publikationer/2019/09/978-87-7038-109-3.pdf

Municipalities are obliged to provide a collection service or to assign a disposal facility for commercial, industrial and construction & demolition waste for incineration and landfill (also on a pay-as-you-throw basis) and commercial businesses are, with some exceptions, obliged to use these. Municipalities are not allowed to run a kerbside collection for commercial dry recyclables, except for commercial businesses that are located in the same buildings as residential properties and that produce waste of similar composition to household waste. Businesses are required to separate waste that can be recycled, though this does not include food waste.

7.2.1 Plastic Collection

Around 75% of municipalities provide plastic waste kerbside collections or local bring site, though there is large variation between municipalities as to whether the plastic is collected separately or co-collected with other materials, and whether materials collected are rigids only or also films. The remaining 25% of municipalities accept plastic at recycling centres. A summary of collection schemes for plastic in flats and houses in Denmark is included in Table 17 in Appendix A.5.0. Figure 32 summarises this information by providing the proportion of municipalities that collect rigids only, films only and, where both types of plastic are collected, whether these are collected separately or in a mixed fraction – this includes all schemes, whether kerbside collection, at local bring banks or at recycling centres. Roughly one-third of municipalities collected rigid plastic only, one-third collects rigids and films together and one-third collect rigids and films together. In municipalities where only bring sites, either local bring banks or recycling centres, are available, rigids may be limited to plastic bottles and may not include pots, tubs and trays. At the kerbside, all types of commonly recycled rigid plastic packaging is usually accepted.
Where collection schemes are not in place, householders are able to bring their plastic waste to a HWRC. All plastic that is not collected separately is incinerated with the residual waste.

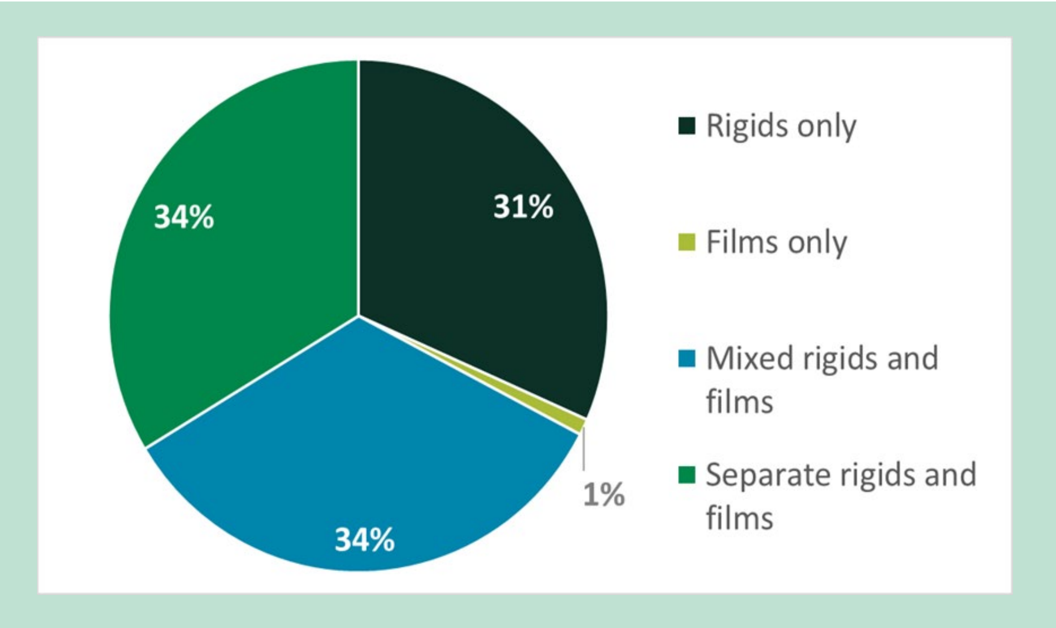

FIGURE 32. Types of plastic collected by municipalities (total: 98 municipalities)

340,000 tonnes of plastic waste are produced by households and businesses each year (year unknown)[182] (of which 218,000 tonnes (2017) are packaging)[183]. Of these, 84,000 tonnes, or 38% (2017) are collected for recycling. The actual recycling rate is likely half of this, once losses during the recycling processes are taken into consideration, as will be required in the updated European methodology for calculating recycling rates.[184] The Danish deposit scheme collected 16,000 tonnes of single-use plastic bottles for recycling in 2017.[185]
Co-collected household plastic waste is typically sorted initially at local waste sorting facilities. Once sorted into separate material streams, plastic waste, including single-stream collected plastic, is typically exported to sorting plants in Germany (e.g. Alba) or Sweden (e.g. Swerec). There is some capacity for sorting plastic waste in Denmark, but it is far from enough to cover the increasing volumes collected. Cleaner fractions, such as PET from the Danish deposit refund scheme or from industrial processes, can be sold directly to reprocessors in Denmark or abroad. A large part of the commercial or industrial collected plastic is LDPE transport packaging which can be sold directly for recycling in Germany and the Netherlands.

7.2.2 Food Waste Collection

Just under half of all Danish municipalities currently collect food waste separately from a total of 1.37 million households. In 2017, 324,000 tonnes of food waste was collected separately, including 62,000 tonnes from households.[186] As shown in Table 9 and Figure 33, the majority of the food waste is collected in conventional plastic bags as of autumn 2019, with 430,000 households' food waste collected in compostable bags, representing around 200 tonnes of biodegradable bags used a year (see Appendix A.3.1 for the methodology used to estimate the tonnage of compostable bags).[187] Three municipalities (with 85,000 households) use paper bags and four (148,000 households) allow a free choice of bag.

The majority of household, service sector and industry food waste is pre-treated and sent to anaerobic digestion facilities where it is frequently mixed with manure slurry (animal waste from agriculture). Small anaerobic digestion plants for manure slurry are common in Denmark, with more than 90 of these in operation around the country. In total, around 12 PJ of energy was produced by anaerobic digestion facilities in 2017.[188] There are also anaerobic digestion plant that exclusively treat food waste from households and commercial businesses. The total number of facilities that treat household food waste is not known. More anaerobic digesters are also in planning stages.

[182] Miljø- og Fødevareministeriet (2018) *Plastik uden spild – Regeringens plastikhandlingsplan*, December 2018, https://mfvm.dk/fileadmin/user_upload/MFVM/Publikationer/NY_Regeringens_plastikhandlingsplan_full_version_FINAL_0123-2019.pdf

[183] https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_waspac&lang=en

[184] Miljø- og Fødevareministeriet (2018) *Plastik uden spild – Regeringens plastikhandlingsplan*, December 2018, https://mfvm.dk/fileadmin/user_upload/MFVM/Publikationer/NY_Regeringens_plastikhandlingsplan_full_version_FINAL_0123-2019.pdf

[185] https://www.danskretursystem.dk/wp-content/uploads/2018/05/Aarsrapport-Dansk-retursystem-2017-1.pdf

[186] Miljøstyrelsen (2019) *Affaldsstatistik 2017, September 2019,* https://www2.mst.dk/Udgiv/publikationer/2019/09/978-87-7038-109-3.pdf

[187] Telephone survey with municipalities by the research team.

[188] https://biogasbranchen.dk/om-biogas/faellesanlaeg

TABLE 9. Types of bag used for municipal household food waste collections

Type of bag used for food waste collection	Number of municipalities	Number of households
Compostable plastic	9	430,383
Conventional plastic	30	711,570
Paper	3	84,690
Free choice	4	147,594
Total	45[189]	1,374,237

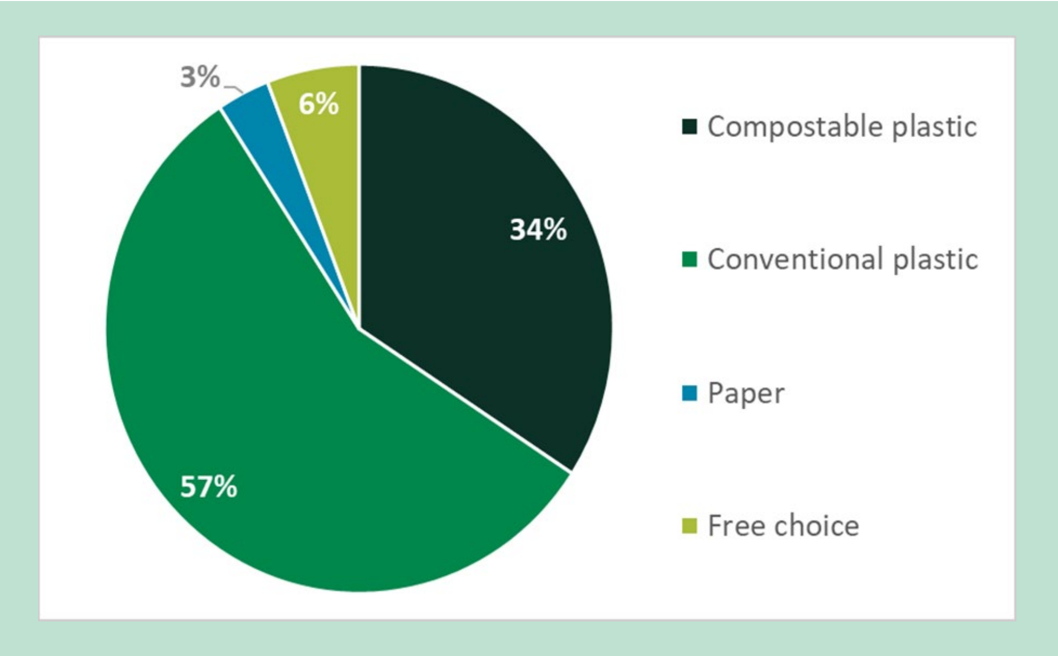

FIGURE 33. Type of food waste bag used, by number of households with food waste collection

Prior to anaerobic digestion, food waste is pre-treated by shredding to remove bags and other impurities and create a biopulp that can be sent to a digester. Although there are various technologies in use, both to open the bags, shred the waste and separate out impurities, in terms of removing impurities, recent analyses have not reported a clear difference in efficiency.[190] There are at least 11 pre-treatment facilities in Denmark that receive household food waste.[191] Commonly, these facilities also receive food waste from commercial sectors, such as cafes, restaurants and supermarkets. Average estimates of reject rates for organic waste received are typically 2-5% for waste from commercial kitchens; 10-20% for household food waste; and 15-30% for packaged food waste.[192]

These rejects are typically sent for incineration. We are aware of one case where rejects are recycled, namely from Ragnsells' two facilities that remove conventional plastic bags that

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[189] One municipality (Frederiksberg) is double-counted as it uses conventional plastic bags for flats and compostable for houses.

[190] COWI (2019) Fremme af efterspørgslen af organisk affald til genanvendelse. Krav til kvaliteten efter forbehandling, Report for Miljøstyrelsen, May 2019 and personal communication with Bigadan.

[191] https://genanvend.mst.dk/projekter/projektbibliotek/2015/kortlaegning-af-kommunale-affaldsordninger-for-husholdningsaffald-1/

[192] COWI (2019) Fremme af efterspørgslen af organisk affald til genanvendelse. Krav til kvaliteten efter forbehandling, Report for Miljøstyrelsen, May 2019

household food waste is collected in. These bags are sold to Dansk Affaldsminimering, which is able to granulate and sell the material for recycling.

The 2018 Danish legislation on Waste to Soil prescribes limits for physical impurities in biopulp.[193] These are: 0.5% by weight of dry matter for pieces larger than 2 mm; 0.15% by weight of dry matter and 1 cm2 per percent dry matter in 1L of biopulp for plastic pieces larger than 2 mm. In compost, the limit is 0.5% of dry matter. The facilities interviewed during this project and during another project earlier this year are all able to comply with the limits for physical impurities.[194] In terms of plastics specifically, the visual physical impurities are the limiting factor, not the weight.

In addition to the anaerobic digestion facilities already mentioned, there is one facility, Solum in west Zealand, which has a 5 month post-digestion composting stage. This plant receives both food waste collected in conventional plastic bags and compostable bags but does not remove these prior to the digestion stage. Instead the conventional plastic bags are removed after the digestion stage. The facility reports that the compostable bags are digested fully during the composting stage.

The resulting digestate from the biogas facilities and compost from Solum is spread on agricultural land directly, subject to the contamination limits mentioned earlier.

7.2.3 Compostable Plastic in Danish Waste Management

Stakeholder interviews were conducted with a number of actors in the waste management sector, including municipalities, pre-treatment and anaerobic digestion facilities and a plastic recycler. None of the stakeholders interviewed reported significant problems with the volume of compostable plastic currently received.

7.2.3.1 Plastic Recyclers

Dansk Affaldsminimering receives lower-grade household plastic waste after a mixed fraction has been pre-sorted by a municipal waste company. The company reports no problems with compostable plastic in the packaging waste from households. The recycler does not expect an increased amount of compostable plastic in the household waste stream and is therefore not concerned that it could create problems for the quality of the recyclate in future. Compostable plastic is primarily used for food waste bags and single-use plastic items in the service sector, both of which are unlikely to end up in the household plastic waste fraction. The recycler has received some one-off batches of large volumes of compostable plastic, e.g. PLA cups from a festival in Denmark, which are not able to be recycled together with conventional plastic as PLA is not a target material in plastics recycling in Denmark currently.

7.2.3.2 Food Waste

Solum, which receives household food waste both in conventional and compostable plastic bags, as well as some organic waste and biodegradable plastic products from the service sector (which is not bagged), treats the received waste in an aerobic digestion plant followed by composting the digestate for five months. The facility reports that the compostable plastic food waste bags are composted effectively during this latter stage. Conventional plastic bags from food waste are removed after the composting step. There are no reported issues with plastic, whether conventional or compostable, in the remaining compost and therefore there are no concerns should there be an increase in compostable plastic in the food waste received.

Two further biogas facilities—Nature Energy and Solrød Biogas—either mix food waste from households with manure from agriculture or receive a mix of household and industrial food waste. The food waste received has been pre-treated in a pulping or shredding pre-treatment

[193] https://www.retsinformation.dk/Forms/R0710.aspx?id=202047

[194] COWI (2019) Fremme af efterspørgslen af organisk affald til genanvendelse. Krav til kvaliteten efter forbehandling, Report for Miljøstyrelsen, May 2019

plant prior to arrival and plastic bags (both conventional and compostable) used for the collection of household food waste have been removed. If there are some remnants of plastic, compostable or conventional, in the digestate, these are not an issue in terms of spreading of the resulting output on agricultural land, as they are below the allowable limits – this is particularly the case where the amount of food waste treated is small compared to the manure. Both facilities report no concern about a potential increase in compostable plastic in the waste stream – although they would not like to receive more of it, they are confident that they can remove enough of any additional compostable plastic so they are still able to meet the limits.

One pre-treatment facility owned by Affald Plus receives food waste from several municipalities, including one which utilises compostable bags for collecting the waste. As part of the pulping process, the bags are all removed prior to the waste being sent to anaerobic digestion plants for treatment. Compostable bags are more frequently found in the biopulp than conventional plastic bags, as the bags curl up and are caught in the sifts. However, the receiving plant does not report any issues with contamination in the resulting digestate.

A 2017 analysis looked at contamination due to compostable, conventional plastic and paper bags for household food waste collection.[195] Although the sample sizes are very small, the analysis suggests that compostable bags remain in the biopulp as impurities more frequently than conventional plastic bags, However, that the overall level of impurities is not necessarily higher when using a compostable bag, as there are more non-bag impurities in the samples collected using a conventional plastic bag.

The same analysis also conducted a literature review of degradation of compostable bags and concluded that the compostable bag would not be able to be digested during the typical 30 day duration of a thermophile anaerobic digestion process and that any remaining particles would be unlikely to be more than 50% degraded even 9 months after being spread on land in digestate. This suggests, that the key to reducing the impact of any increase in compostable plastics is to continue improving and customising the pre-treatment stage, rather than relying on compostable material degrading once spread on fields.

Summary of Waste Management of Compostable and Bio-based Plastics in Denmark

The majority of food waste in Demark is processed in a ‘wet’ AD that is generally incompatible with compostable plastics due to the short processing duration and reported issues with becoming stuck in machinery.

AD plants in Denmark are also mostly focused on receiving agricultural waste and mainly receive household waste as a ‘pulp’ after pre-treatment and removal of all types of plastics—these rejects are usually sent for incineration.

Any remaining plastic contamination is currently though to be minimal and not a particularly pressing problem for Danish AD plants at present—this may be a result of low market penetration of compostable plastics in Denmark but plants are also confident that an increase would not be problematic in the future.

With the EU requirement that organic waste is separately collected from 2024, more plants may operate purely by receive household organic waste (rather than predominately agricultural). This may result in some of the problems found in other countries

[195] COWI (2017) Posekvalitetens og materialets betydning for indholdet af fysiske urenheder i biopulp, Report for Kerteminde Forsyning, December 2017

where (all types of) plastic contamination is a significant issue in maintaining compost quality.

For the same reason, plastics recyclers in Denmark also remain unconcerned about compostable plastic contamination. As the primary application for the material is in bags, these are less likely to contaminate the high value rigid plastic streams and there is no driver to see this change in the future.

8. LCA as a Tool to Compare Bio-based and Biodegradable Plastics with Conventional Plastic

In the following section the latest Life Cycle Assessments (LCAs) on bio-based and biodegradable plastics are discussed in the context of their potential environmental benefit.
Firstly, the concept of LCA as a tool is introduced, then the methodology briefly explained along with the opportunities within the methodology for legitimate variation in method. The limitations of LCAs and the assumptions are explained and their usefulness in the context of this report disused. The following two sections are split into an analysis of LCA studies on bio-based plastics and of biodegradable plastics.
This split is necessary because the scope of LCA studies on bio-based plastics focus on the material being produced and comparative studies are mostly between materials (an emphasis on feedstocks); studies on biodegradable plastics on the other hand usually have a focus on specific product applications (an emphasis on performance). Although, in this analysis, bio-based plastics and biodegradable plastics are discussed separately the overlap between the two still needs to be considered as many bio-based plastics often claim to be biodegradable to some degree and most biodegradable plastics are bio-based. This overlap is addressed within the discussion on end of life disposal options for the bio-based plastics and within the biodegradable plastic section.
Finally, the predicted future improvements in feedstock production are discussed within the context of future LCA studies and basing decisions for the future on current results.

8.1 Life Cycle Assessment

LCA is one of the tools which can be used to evaluate the environmental impact of bio-based and biodegradable plastics in comparison to conventional, fossil fuel based, non-biodegradable plastics. They are hugely important when making decisions on new materials and products, especially when the motivation is improved environmental performance, and can also be used to identify how a product or materials environmental performance can be improved.
They do however need to be viewed within the context of their limitations. In this section, the methodology behind LCAs is briefly discussed, followed by an analysis of possible variation between studies and their comparability.

8.1.1 Methodology

The principle aim behind any LCA study is to quantify the material and energy required to make a product or material, the waste and emissions produced and assess the associated environmental impacts. In the context of this report, comparative LCAs which compare one material or product against another, have been utilised with a focus on those studies which compare conventional plastic and an alternative, such as, biodegradable or bio-based plastic.
Some studies also compare conventional plastics to non-plastic material such as paper, these studies have been utilised in this report but the focus has remained on biodegradable or bio-based plastic alternatives.
The results of an LCA study consist of a series of Environmental Impact Categories which represent the environmental issues of concern. Each study will decide which Impact Categories it will use; common Environmental Impact Categories include: climate change, fossil fuel depletion, eutrophication, acidification, human toxicity and land use.

The chosen Environmental Impact Categories are often presented in a side-by-side numerical comparison between plastics. Most studies leave the assessment here with the end product consisting of a list of more positive and more negative indicators between compared products. This is arguably the most robust analysis but requires further interpretation to determine the environmentally preferable choice. Sometimes normalisation is used to determine which Impact Categories are the most important. This, combined with weighting, produces an easy to understand single score, but introduces a lot of uncertainty in the process and is why public declarations should not include such a step.

8.1.2 Variation

There are various frameworks available to structure an LCA, with the most common being ISO 14040/44 standards. These standards recommend a methodology but are not prescriptive enough to prevent any significant scope for variation and are not a guarantee of valid assumptions or results. For this reason, care must be taken when comparing separate LCA studies or generalising results from several studies.
Possible variations between studies can include the;

- system boundaries i.e. the size and nature of the product system being assessed;
- the scope of study, including time and geographical setting;
- the quality and validity of the data used;
- the key driving assumptions relevant to a particular study, such as the average weight of a shopping bag; and,
- the chosen environmental impact categories or indicators that are used to assess the environmental impacts.

Because the ISO standards allow for these variations, two LCA studies comparing the same products can produce very different results. This is why it is generally expected that comparative assessments that are disclosed to the public are subject to external peer review. This helps to remove biases and check for methodological inconsistencies. Either way, the results can only be viewed through the lens of the assumptions that have been chosen – a review panel may not be in a position to determine whether these assumptions are appropriate, but will ensure than they are consistently applied.
Finally, care must also be taken when comparing LCA studies produced years apart from one another—as discussed, LCA is very context dependant and timeframe is a particular important aspect of this. Techniques and assumptions are also constantly improving and so the same study even five years earlier may (justifiably) produce different results.

8.2 Bio-Based Plastics

As explained in more detail in other sections of this report, bio-based plastics are plastics whose raw material or feedstock isn't fossil fuel based. Typical feedstocks include crops, such as corn and by-products of other processes, such as whey, and starch. There are currently hundreds of types of bio-based plastics in development and many different feedstock options. As discussed above, most bio-based plastics are also biodegradable to some degree, and vice versa. Therefore, the impacts associated with the production of bio-based plastics are also relevant to biodegradable plastics and should be borne in mind when reading the biodegradable plastic section of this report.
The JRC are currently undertaking a comprehensive study of biodegradable and bio-based plastic LCAs. This study is on-going but the published meta-analysis[196] lists the relevant scientific literature and provides a detailed analysis of five product case studies; beverage bottles,

[196] Nessi S., Bulgheroni C., Garbarino E., Garcia-Gutierrez P., Orveillon G., Sinkko T., Tonini D., and Pant R. (2018) ***Environmental sustainability assessment comparing through the means of lifecycle assessment the potential environmental impacts of the use of alternative feedstock (biomass, recycled plastics,***

flexible food packaging, mulching film, insulation board and automotive interior panel. In this section, the most recent research comparing the environmental impact of bio-based plastics with conventional plastics is presented. The main trends are discussed using case studies from the JRC report, with feedstock production impacts and global warming environmental impact indicator discussed in detail. These trends are the summarised with a discussion of the factors external to the LCA which should be considered.

8.2.1 Main Trends

The JRC are currently undertaking a comprehensive study of LCAs and the published, details five case studies. In this section, the JRC meta-analysis case studies[197], along with relevant other examples, are used to demonstrate the main trends coming out of LCA studies investigating the impact of bio-based plastics when compared with conventional plastics.

Feedstock Production Impacts

The JRC case studies found the 'polymer production' lifecycle stage to have the greatest % impact of all the lifecycle stages on Environmental Impact Categories, as shown in Table 10. The 'polymer production' stage is defined as all processes preceding transport of polymer for article production. More specifically, some studies, for example the report of Biodegradable plastics by Umweltbundesamt[198], compute that it is impacts resulting from the feedstock production element of polymer production that have by far the greatest effect on the Environmental Impact Categories than any other life-cycle stage when compared to conventional plastics. The Impact Categories most commonly affected include:

- Land use, which calculates the direct and indirect impacts of land use change from other uses to feedstock production;
- Eutrophication, which refers to the run off nutrients, typically pesticides and fertilisers, into water. This can cause excessive plant growth, depleting the water of oxygen and harming the associated biosphere;
- Acidification, which calculates the impact on the pH level of water bodies, such as oceans, which can have detrimental impact to ocean organisms such as coral reefs; and
- Toxicity, which can include human toxicity, ecotoxicity and the production of carcinogens.

In the JRC case study on beverage bottles[199] it was found that bio-based PET plastic had a higher environmental impact than conventional plastic bottles in all Environmental Impact Categories, including climate change, and only had a lower environmental impact in ozone depletion, resource use and water use Environmental Impact Categories. The same is true in the JRC case study[200] on flexible packaging film. An example, from the Umweltbundesamt report[201], compares bio-based polyethylene (PE) plastic derived from sugar cane grown in Brazil

(CO2) for plastic articles in comparison to using current feedstock (oil and gas), Report for European Commission, December 2018

[197] bid

[198] Systemadmin_Umwelt (2013) *Study of the Environmental Impacts of Packagings Made of Biodegradable Plastics*, March 2013, https://www.umweltbundesamt.de/publikationen/study-of-environmental-impacts-of-packagings-made

[199] ibid

[200] Nessi S., Bulgheroni C., Garbarino E., Garcia-Gutierrez P., Orveillon G., Sinkko T., Tonini D., and Pant R. (2018) *Environmental sustainability assessment comparing through the means of lifecycle assessment the potential environmental impacts of the use of alternative feedstock (biomass, recycled plastics, (CO2) for plastic articles in comparison to using current feedstock (oil and gas)*, Report for European Commission, December 2018

[201] Systemadmin_Umwelt (2013) *Study of the Environmental Impacts of Packagings Made of Biodegradable Plastics*, March 2013, https://www.umweltbundesamt.de/publikationen/study-of-environmental-impacts-of-packagings-made

and an equivalent fossil fuel-derived European plastic, both of which were modelled to be processed in Germany. The results are outlined in Table 11.

TABLE 10. Bio-Based PET Beverage Bottle Lifecycle Stages and Associated Contribution to LCA Scenario

Life cycle stage	Environmental Impact Indicator			
	Particulate Matter	Climate Change	Resource Use – fossils	Human toxicity – cancer
Polymer Production	96.8%	85.2%	76.6%	52.3%
Transport	1.2%	5.7%	3.5%	3.0%
End of Life	1.2%	0.2%	14.1%	44.1%
Article Production	0.9%	8.9%	5.7%	0.9%

TABLE 11. Bio-based PE vs conventional PE study results

Environmental impact of bio-based PE lower than conventional PE	Environmental impact of bio-based PE higher than conventional PE
Climate change	Acidification potential
Consumption of fossil fuel resources	Terrestrial eutrophication
Summer smog	Aquatic eutrophication
	Human toxicity
	Water consumption
	Total primary energy demand
	Land use

These results echo those of the JRC report with feedstock production heavily impacting all bio-based plastic environmental impact categories other than the 'climate change' and 'consumption of fossil fuel resources' categories. These higher impacts are easily explained as conventional plastics, extracted from fossil fuels, have no associated cultivation and therefore none of the impacts stemming from agriculture.

In addition, the choice of feedstock is important. It matters greatly whether a feedstock is considered to be a 'prime crop' or a by-product of another process. For a 'prime crop' feedstock, such as corn, it is assumed that all environmental impacts of the feedstock production are in scope of the study. On the other hand, if the feedstock is categorised as a waste or residue, it is assumed to have no feedstock production environmental impacts. The bio-based plastics made from these waste feedstocks therefore often perform vastly better in LCA analysis as the input material come 'burden free'. Economic allocation is often used to categorise feedstocks as either product or residues and wastes. These economic allocations are complex assumptions and are time variable due to their basis on market assumptions.

For example, in a comparison calculated as part of the Umweltbunesamt report[202], between a bio-based PLA with a lactic acid feedstock, a bio-based PLA with a ligno-cellulose feedstock and an equivalent conventional plastic, Table 12; the lactic acid is assumed to be derived from prime agricultural products such as maize, whereas the ligno-cellulose is assumed to be derived from a by-product of grain production. The environmental impact of the grain production is assumed to be accounted for by the primary use of the grain and is therefore out of the scope of the study and the feedstock production impacts calculated as nil—the way the boundaries of the study is set, therefore make a large difference to the outcome. For example, in the

[202] Systemadmin_Umwelt (2013) *Study of the Environmental Impacts of Packagings Made of Biodegradable Plastics*, March 2013, https://www.umweltbundesamt.de/publikationen/study-of-environmental-impacts-of-packagings-made

Umweltbunesamt study[203], no impacts resulting from cultivation were modelled for the ligno-cellulose PLA, whereas cultivation impacts were modelled for sugar beet PLA. For Environmental Impact Indicators such as 'Land Use: Farmland', and 'Aquatic Eutrophication', where a large percentage of the impacts are from the cultivation lifecycle stage, the net impacts for lignocellulose PLA in comparison to lactic acid PLA will often be much lower. This is a further example of how these studies are also often time specific as the boundary may change if the 'waste' becomes in demand and valuable and thus is a 'co-product' with associated environmental impacts.

TABLE 12. Bio-based PLA lactic acid feedstock vs bio-based PLA ligno-cellulose feedstock vs conventional PS plastic

Environmental impact of bio-based PLA lower than conventional PS	Environmental impact of bio-based PLA higher than conventional PS
Climate change	Terrestrial eutrophication
Consumption of fossil fuel resources	Aquatic eutrophication
Summer smog	Water consumption
	Total primary energy demand
	Land use
	Acidification potential
	Human toxicity

Predictions and assumptions on the availability of by-products or wastes in the future are difficult to make. Without any clear policies in Europe guiding both the production of biomass and the use of it, for both bio-based plastics and biofuels, no firm predictions can be made. The Umweltbunesamt report[204] calculated that for 2020, if the predicted bio-based plastic production in 2020 is double the 2015 baseline, the land required for feedstock would be 1.37 million hectares. Whereas the land required for biofuel production in 2020 will be 120 million hectares of land in order to meet 2020 biofuel targets, concluding that biofuel production is therefore the major future consideration when considering the future availability of feedstock. A report in 2010[205] for DEFRA, estimated that globally, due to ineffective land use, 150-800 million hectares of land is available for biomass production without encroaching on areas of high ecological or social value. The report stressed that current land use and farming practices will need to change for this 'low impact' land to be utilised and predictions need to be made as to how quickly this will happen. In conclusion, it is difficult to assess the availability of feedstock for future production of bio-based plastics because of the lack of firm policies in Europe for both biofuels and bio-based plastic and the lack of clarity on future efficiencies in farming.

Global Warming Environmental Impact Category

Results are less consistent between case studies in the 'global warming' or 'greenhouse gas' Environmental Impact Categories between bio-based plastics and conventional plastics with contradictory conclusions evident between studies. This is because these categories are affected by many different life cycle stages and study boundaries e.g. feedstock production location and assumptions used. Examples of influencing factors include:

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[203] Systemadmin_Umwelt (2013) *Study of the Environmental Impacts of Packagings Made of Biodegradable Plastics*, March 2013, https://www.umweltbundesamt.de/publikationen/study-of-environmental-impacts-of-packagings-made

[204] Systemadmin_Umwelt (2013) *Study of the Environmental Impacts of Packagings Made of Biodegradable Plastics*, March 2013, https://www.umweltbundesamt.de/publikationen/study-of-environmental-impacts-of-packagings-made

[205] Valpak Consulting Consortium (2010) Bioplastics: Assessing their environmental effects, barriers & opportunities

- **Residual feedstock impacts** refers to the wastes or residues formed as part of feedstock production. Studies vary in how they account for residual feedstock, some including the impacts within calculations but others using a cut off approach so that no impacts associated with the use of residual feedstocks are in scope[206]. This variation in scope between studies reduces the comparability of the resulting 'global warming' impact between studies;
- **Biogenic carbon calculations** vary in detail between studies[207]. There are three possible inputs, each adding an element of sophistication to the calculation: firstly, 'biogenic carbon balance' which accounts for the carbon absorbed from the atmosphere when feedstocks are growing and (potentially) emitted at end of life, and next, 'carbon storage' which takes into consideration a products lifetime and the benefit derived from the delay in releasing of carbon at end of life. Finally, the 'timing of the carbon emissions' which accounts for any additional storage of carbon past a products end of life, such delayed release of carbon due to assumptions of slow breakdown of biodegradable plastics to methane in landfill. At the other extreme, some studies, don't include any consideration of biogenic carbon as long-term storage is too dependent on end of life assumptions. Ignoring this altogether is less common in more contemporary studies as the movement of biogenic carbon is viewed with more importance and the benefits of carbon storage are better understood. These variations in methodology affect the resulting 'climate change' environmental impact category and reduce the comparability of studies;
- **Disposal option assumptions** are particularly important for bio-based plastics which are also biodegradable as, if the material end its life in landfill, due to anaerobic conditions, it may break down to form methane instead of carbon dioxide which has a much higher global warming potential. This is important in the context of Denmark where the percentage of plastics ending up in landfill is much lower than the assumptions in some studies. For example, Chaffee et al 2007[208] in their study of plastic bags, assumed that 82% of bags go to landfill, whereas Denmark currently sends close to 0%, with just under 50% ending life in incineration. Incineration is also important for bio-based plastics because the carbon released by bio-based plastics during incineration is sequestered during feedstock growth meaning there is approximately no net increase in atmospheric carbon. On the other hand, the carbon released from conventional plastics, is derived from fossil fuel and therefore adds to atmospheric carbon and the climate change Environmental Impact Indicator;
- **Direct land use change impacts**, are based on land use change models[209] and are calculated from the assumed previous land use. The accuracy of the assumptions on previous land use as well as the country the feedstock is produced in will all affect the modelled greenhouse gas emissions and therefore the 'climate change' environmental indicator;
- **Indirect land use impacts**, are hard to quantify and trace and require large models which link effects to causes and are thus very uncertain (and subject to varying methodologies) compared with impacts calculated from direct measurements (e.g. CO2 emissions). Because of this, they are not consistently accounted for within LCAs; the JRC report found

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[206] Nessi S., Bulgheroni C., Garbarino E., Garcia-Gutierrez P., Orveillon G., Sinkko T., Tonini D., and Pant R. (2018) *Environmental sustainability assessment comparing through the means of lifecycle assessment the potential environmental impacts of the use of alternative feedstock (biomass, recycled plastics, (CO2) for plastic articles in comparison to using current feedstock (oil and gas)*, Report for European Commission, December 2018

[207] ibid

[208] Prepared for the Progressive Bag Alliance, Chet Chaffee and Bernard R. Yaros, and Boustead Consulting & Associates Ltd. (2014) Life Cycle Assessment for Three Types of Grocery Bags - Recyclable Plastic; Compostable, Biodegradable Plastic; and Recycled, Recyclable Paper

[209] Wicke, B., Verweij, P., Van Meijl, H., Van Vuuren, D.P., Faaij, A.P.C. (2012) *Indirect land use change: review of existing models and strategies for mitigation*, 2012

that they were only included in seven of the twenty-three studies reviewed. The variation in scope of studies therefore reduces their comparability; and

- **Transport distance and type** varies between situations and therefore studies. In the bio-based polyethylene plastic study described above, the transport of sugar cane from Brazil to Germany by ship increased the greenhouse gas emissions and therefore the 'global warming' impact of the bio-based plastic in comparison to conventional plastics. However, it should be noted that the % impact of transport, in comparison to other life cycle stages, is not a major contributor to an increased 'global warming' Environmental Impact Indicator. The case study on bio-based PET beverage bottles in Table 10, highlights this with the % contribution of transport on the climate change environmental impact indicator calculated as 5.7%[210]. The assumptions on feedstock and fossil fuel locations and end country are particular to any study and therefore the impact of transport varies.

The 'climate change' Environmental Impact Category is therefore very dependent on a particular situation and study. To demonstrate this in practice—of the five case studies reviewed in detail by the JRC report— two had a lower environmental impact for conventional plastics when compared to a bio-based equivalent, one had higher and two came out even. A second example is shown in Figure 34 whereby four separate studies comparing bio-based plastic bags—in this case, starch polyester blended bag—with conventional HDPE have very different results with two finding the bio-based bags better and two finding them worse than HDPE for global warming potential.

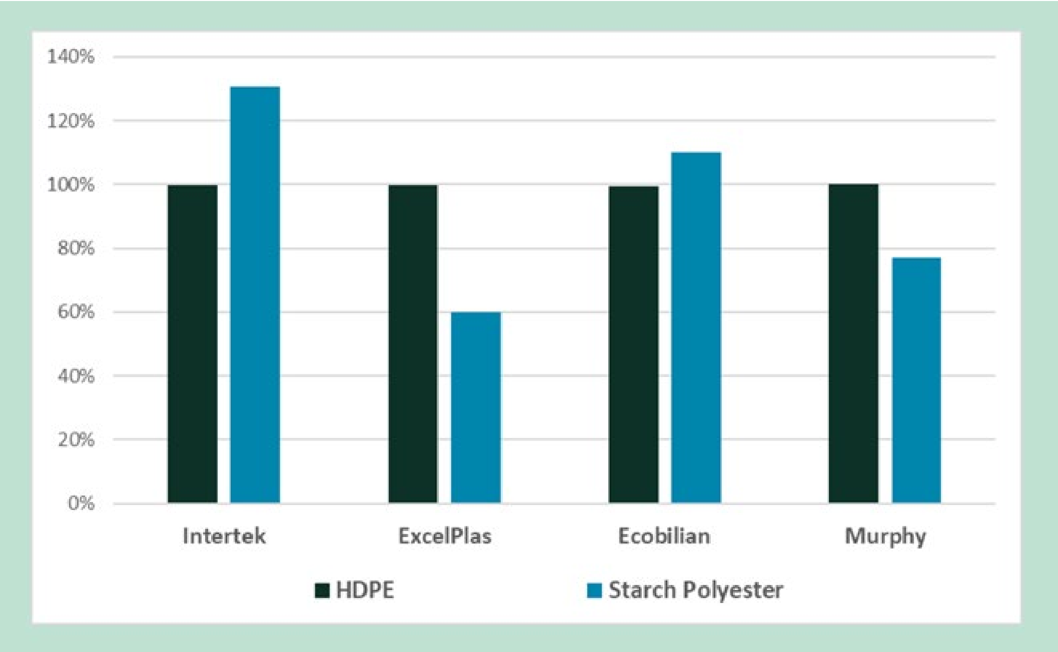

FIGURE 34. Global warming potential of plastic bags in four LCA studies
Source: Adapted from[211]

[210] Nessi S., Bulgheroni C., Garbarino E., Garcia-Gutierrez P., Orveillon G., Sinkko T., Tonini D., and Pant R. (2018) *Environmental sustainability assessment comparing through the means of lifecycle assessment the potential environmental impacts of the use of alternative feedstock (biomass, recycled plastics, (CO2) for plastic articles in comparison to using current feedstock (oil and gas)*, Report for European Commission, December 2018

[211] Intertek Expert Services (2011) *Life Cycle Assessment of Supermarket Carrier Bags: A Review of the Bags Available in 2006*, Report for Environment Agency, February 2011

8.2.2 Bio-Based Plastic Summary

In summary, the over-riding trends in environmental impacts in the vast majority of studies show that there are some advantages to bio-based plastics such as a likely reduced climate change potential and the reduced consumption of fossil resources but there are disadvantages, stemming primarily from feedstock production impacts, such as increased acidification, eutrophication, and human toxicity.

There are some considerations, relevant to the bio-based plastic vs conventional plastic discussion which are out of scope of LCA studies. These effects include indirect agricultural intensification impacts resulting from feedstock production such as biodiversity loss resulting from an increase in monocultures and the unforeseen effects of genetic engineering. Although these effects have not yet been quantified, they are worth considering alongside LCAs as part of the bigger picture.

A final consideration in relation to bio-based plastic is the percentage of the plastic which is bio-based as it is common to also produce plastics with a mixture of bio-based and fossil fuel derived feedstock. It may be in some cases that a blend of bio-based and fossil fuel derived feedstocks produces the plastic with the lowest overall score in the environmental impact categories.

8.3 Biodegradable Plastics

The development of biodegradable plastics has been motivated mostly in the packaging and agricultural mulch sectors. In the packaging sector, it is often seen as a potential part of the solution to littering and environmental plastic pollution (despite the solutions often being certified compostable and thus not specifically designed for littering). It is for this reason that LCAs focusing on biodegradable plastic are usually product specific as the application and thus the end of life option is specific to a particular product and use.

Although this section focusses on biodegradable plastic LCAs, most biodegradable plastics are also bio-based (with notable exceptions such as PBAT). Therefore, the discussions in Section, 8.2, are also relevant with regard to the feedstock. In this section, the main trends associated with biodegradable plastics LCA studies are reviewed followed by a detailed discussion of some of the considerations specific to biodegradable plastics.

8.3.1 Main trends

As with bio-based plastics a full literature review is out of scope of this report. Instead the results of comprehensive meta studies such as, Umweltbundesamt 2013[212], will be summarised with additions from more recent studies, such as the JRC draft report. As previously discussed, these studies are only relevant to a specific situation and product application, therefore it is more difficult to generalise results of biodegradable plastic LCA studies. A biodegradable plastic option may have, legitimately, a different result in an environmental impact category for different applications even if the polymer and product are identical.

By way of an example, three case studies, on single layer flexible films, multilayer flexible films and shape retaining packaging are presented to highlight the variation:

- **Single layer flexible film:** The Umweltbundesamt report reviewed three different studies comparing biodegradable flexible film plastic bags with conventional plastic film bags. Two

[212] Systemadmin_Umwelt (2013) *Study of the Environmental Impacts of Packagings Made of Biodegradable Plastics*, March 2013, https://www.umweltbundesamt.de/publikationen/study-of-environmental-impacts-of-packagings-made

of the three studies, Wellenreuther et al. 2009[213] and Chaffee et al. 2007[214], found that the conventional flexible plastic bag had lower environmental impacts in almost all Environmental Impact Categories in comparison to the biodegradable flexible plastic bag. A product specific study, comparing biodegradable PHA bread bags[215] to conventional plastic bread bags had very similar results and found the biodegradable bread bag to have the highest environmental impact in ten out of eleven environmental impact categories. The causes of these increases, when compared to conventional plastics, for the PHA bread bags study, were traced mainly to the greater thicknesses and resulting higher bag weights, required to perform the same function, and higher end of life impacts. The end of life disposal options were modelled as per the UK average disposal options at the time. These end of life impacts are therefore likely to be reduced in the current Danish context due to a lower percentage of landfill at end of life than modelled.

- **Multilayer flexible film**: The Umweltbundesamt report concluded that the results of studies on multilayer flexible films are more complex than single layer flexible films. One example, Garrain 2007[216], found that biodegradable plastic film, with composting assumed for end of life, when compared to conventional plastics, had a lower score for the climate change and fossil resource Environmental Impact Category but a higher load for eutrophication and acidification. These results differ to those on flexible film bags and is a similar picture to that of typical bio-based plastic LCA studies described in section 8.2 and is due to the biodegradable plastic film also being bio-based and the strong effect of feedstock production on indicators even in a biodegradability focused study.
- **Shape-retaining packagings**: The Umweltbundesamt report reviewed six biodegradable shape-retaining packaging's and found four of the six reviewed to have positive impacts in relation to climate change and resource consumption and negative impacts with respect to acidification and eutrophication. Kauertz 2011[217], is one of the four. They performed an LCA study on biodegradable PLA plastic yogurt pots comparing them to conventional Polystyrene yogurt pots. They found the biodegradable plastic pots had lower environmental impacts in the climate change, consumption of fossil fuels and summer smog categories and higher impacts in the acidification, terrestrial and aquatic eutrophication categories. Kauertz concluded there to be no LCA advantage between the two plastic yogurt pot options The assumptions on end of life options in this study were that 80% of the plastic is recycled and 20% is incinerated. These assumptions mean no biodegradable plastic is modelled to go to landfill and degrading in anaerobic conditions to form methane. The climate change environmental impact indicator is reduced for biodegradable plastics in comparison to if the study was rerun with a percentage of plastic assumed to be landfilled.

This selection of studies demonstrates the variation in results between applications of bio-based plastics. This variation can be accounted for by the detail and associated complexity of modelling an individual application. In the following subsections, the detail behind the complexity is discussed, specifically: plastic thickness, end of life options, the knock-on impacts of organic waste collection and the percentage of plastic which is littered.

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[213] Andreas Detzel, Frank Wellenreuther, and Sybille Kunze (2009) *LCA of Waste Bags on Behalf of European Waste Bag Producers - Extended Summary*, Report for IFEU, June 2009

[214] Prepared for the Progressive Bag Alliance, Chet Chaffee and Bernard R. Yaros, and Boustead Consulting & Associates Ltd. (2014) Life Cycle Assessment for Three Types of Grocery Bags - Recyclable Plastic; Compostable, Biodegradable Plastic; and Recycled, Recyclable Paper

[215] European Bioplastics (2012) *European Bioplastics comments on the study: 'A Life Cycle Assessment of Oxo-biodegradable, Compostable and Conventional Bags'*, July 2012

[216] Daniel Garraín, Rosario Vidal, Pilar Martínez, Vicente Franco, David Cebrián-Tarrasón (2007) *LCA of biodegradable multilayer film from biopolymers*, 2007

[217] Kauertz, Benedikt (2011) *LCA Activia-Becher*, 2011

Plastic thickness

In order to conduct an even comparison, the same functional unit[218] must be defined for a product. For example, for a shopping bag comparison, the functional unit may be 'an X cm3 volume bag, capable of carrying X kg'. This may mean that the thickness of the plastic and therefore the weight of plastic required to meet this functional unit varies between biodegradable plastic polymers and conventional plastic polymers. For example, Wellenreuther 2009[219], compared biodegradable and conventional bags with equal volume. The modelled biodegradable bags had a greater thickness, density and therefore weight and were found to have greater environmental impacts in most categories, including in the 'climate change' impact category.

End of life options

LCA studies need to form assumptions on end of life disposal options for the plastics. These assumptions are difficult as they are based on consumer behaviour and can change quickly over time and are often location specific. The assumptions for end of life options are important for biodegradable plastics because the associated impacts, especially for the 'climate change' environmental impact category which can be significantly affected.

Assumptions around landfilling are the starkest demonstration of this as it is possible for biodegradable plastics break down in landfills to produce methane; a particularly potent GHG. Conventional plastics are inert, they do not break down in landfill and hence produce no GHG; this greatly increases the 'climate change' environmental impact category for biodegradable plastics in comparison. It could be argued that conventional plastics act as carbon storage when landfilled as they could, theoretically, remain in landfill indefinitely and prevent the carbon contained within them becoming atmospheric carbon. Some studies, for example Chaffe et al. 2007, assumed that all biodegradable plastic which ended life in landfill decomposed to either methane or carbon dioxide. This assumption has limited supporting evidence as landfills are heterogeneous, complex environments and current evidence is conflicting as to the extent biodegradable plastics break down—many LCAs will reply on assumptions rather than empirical data in this regard. Incineration, on the other hand, assumes both biodegradable and conventional produce carbon dioxide when burned. As most biodegradable plastics are also bio-based, as explained in Section, 8.2, of this report, the GHG associated with incineration of bio-based plastics, and bio-based biodegradable plastics, results in approximately no net increase in atmospheric carbon dioxide.

The incineration of conventional plastics, does increase atmospheric carbon dioxide and therefore, unlike with incineration of bio-based biodegradable plastics, increases the climate change Environmental Impact Indicator. The last end of life option for biodegradable plastics, excluding littering, is composting or anaerobic digestion. The JRC, for their five LCA case studies, assumed that 90% of the carbon in biodegradable plastics is released as carbon dioxide during composting. The assumptions used for anaerobic digestion are more complex. The JRC calculated, for biodegradable beverage bottles, 35% of the carbon is released and of that 63% is methane and 37% is CO2. Conventional plastics do not have either of these end of life options, leading to differences in end of life option assumptions between conventional plastics and biodegradable plastics. The assumption for end of life options for conventional plastics and the associated assumptions for carbon dioxide emissions for that end of life option, in comparison to composting or anaerobic digestion of biodegradable plastic, will determine the effect on the climate change Environmental Impact Indicator.

[218] A functional unit is the base unit all calculations are related to. It is based on the functionality of a product, for example, the product may be a cup, but the functional unit could be 'holds 500ml of liquid for 1 hour'.

[219] Andreas Detzel, Frank Wellenreuther, and Sybille Kunze (2009) *LCA of Waste Bags on Behalf of European Waste Bag Producers - Extended Summary*, Report for IFEU, June 2009

Co-benefits of Compostable Plastic

One area of increasing focus is the potential for certain compostable plastic products to increase the quantity of organic waste separated from residual waste streams or reducing food waste. Muller et al. 2012[220], studied the impact of compostable organic waste bags in Germany and found a 30% increase in organic waste collected separately in districts using biodegradable bags compared to only 10% in districts which weren't. This increase in the proportion of food waste entering a separate organic waste stream and decrease the associated greenhouse gas emissions associated with non-composted or anaerobically digested organic waste, reduces the 'climate change' environmental indicator for biodegradable plastics. Some biodegradable plastics are also predicted to increase the shelf life of food in applications such as fruit and vegetable bags because of the improved performance of the polymer in characteristics such as increased breathability waste, increasing waste prevention.[221]

Littering

There have been several attempts to include Littering effects in some LCAs and work is ongoing to better quantify the impact, but there is still no established methodology for doing so. A small number of studies have made attempts to quantify the effects of littering. Parker and Edwards, 2012[222], calculated the impact of the degradation of the biodegradable plastic and conventional plastic bags in the environment and quantified the visual impact of littering. The JRC report concluded a quantitative assessment of the effects of littering is not currently feasible but have suggested that the likelihood of a product to be littered could instead be included as 'additional environmental information'. Therefore, there is far from a consensus on a methodology for quantify littering impacts and most studies choose to omit it for this reason.

8.3.2 Biodegradable Plastic Summary

In summary, the results of biodegradable plastics when compared to conventional plastics in LCA studies is complicated with an individual study only being relevant to the particular situation, polymer and application being modelled. There are however some key influencing assumptions or situations specific to an application, which affect the results. These include plastic thickness, end of life options, littering and organic waste. These assumptions will be specific for a particular study and go some way to explaining why the situation is so complex and often contradictory.

8.4 Future Technological Improvements

There is considered to be potential for large efficiencies within current practices for plastic feedstock production. These projected efficiencies will decrease the feedstock production impacts of environmental impact categories for bio-based and biodegradable plastics. For example, a study on bio-based PHB plastic[223] produced from corn grains found that projected efficiencies in corn production could reduce the overall impact of corn production by 72%.

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[220] Muller (2012) *Eco-Efficiency Analysis; Comparative study of bags; Eco-Efficiency Analysis of bags made of different materials for transportation of staple goods, reuse and disposal of organic waste*, 2012

[221] FBR BP Biorefinery & Sustainable Value Chains, FBR Sustainable Chemistry & Technology, Biobased Products, van den Oever, M., Molenveld, K., van der Zee, M., and Bos, H. (2017) *Bio-based and biodegradable plastics : facts and figures : focus on food packaging in the Netherlands*, Report for Wageningen, 2017, http://library.wur.nl/WebQuery/wurpubs/519929

[222] Parker, G., and Edwards, Chris (2012) A Life Cycle Assessment of Oxo biodegradable, Compostable and Conventional Bags, *Intertek Expert Services*, p.46

[223] Narodoslawsky, M. (2015) LCA of PHA Production – Identifying the Ecological Potential of Bio-plastic, *Chemical and Biochemical Engineering Quarterly*, Vol.29, No.2, pp.299–305

The report by Umweltbundesamt[224], contained an LCA comparison between hinged-lid bowls made from lactic acid derived PLA and polystyrene for both the current best practice scenario and a predicted future scenario with improved production techniques. Both scenarios calculated that the lactic acid production lifecycle stage had the greatest overall contribution to the Environmental Impact Indicators. The hypothesised reduction in the impacts of the lactic acid production lifecycle stage therefore modelled a large improvement in the overall impact of PLA production. It is unclear, at this stage, the likelihood of these predicted future efficiencies being realised.

In addition, bio-based plastics are a relatively new material and the scale of their production is currently, relative to conventional plastics, small scale[225]. Bio-based plastic production therefore does not currently benefit from economies of scale and is not fully optimised. The market for bio-based plastic is predicted to grow and, as it does so, the production capacity and efficiency will also. These projected efficiencies, if realised, could tilt the balance on studies which currently favour conventional plastics over bio-based or biodegradable and need to be considered when considering the long-term use of bio-based or biodegradable plastics. Finally, the data sets for LCA's are underdeveloped in relation to the data needed to calculate the impacts of bio-based and biodegradable plastics. Therefore, some of the calculations and methodology behind the LCA studies has not had a chance to be thoroughly tested and mature. European bioplastics called for, in their position paper[226], the data to be improved and made available in a public database. If this happens it will help to improve the assumptions and the accuracy of calculations used.

Summary of LCA as a Tool to Compare Bio-based and Biodegradable Plastics with Conventional Plastic

Plastic use is only predicted to increase. Therefore, the problems associated with all types of plastic are not going away. The purpose of these LCA studies is to help identify which plastic options have the lowest environmental impacts now and provide guidance on how the environmental performance of plastics can be improved throughout their entire life cycles.

To utilise LCAs to their full potential they need to be viewed in the context of the entire system and reviewed in terms of their reliability considering what has been omitted as much as what has been included. This being said, the overriding trend in results for both bio-based and biodegradable plastics is that feedstock production impacts affect the resulting environmental impact categories more than any other lifecycle stage.

Biodegradable plastics add an extra layer of complexity to the bio-based picture and need to be considered on a case by case basis with an understanding of the detail behind the calculations. This is due to studies calculating impacts for very specific applications meaning those results are not easily generalised.

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[224] Systemadmin_Umwelt (2013) *Study of the Environmental Impacts of Packagings Made of Biodegradable Plastics*, March 2013, https://www.umweltbundesamt.de/publikationen/study-of-environmental-impacts-of-packagings-made

[225] European Bioplastics (2019) Position of European Bioplastics Sound LCA as a basis for policy formulation

[226] European Bioplastics (2019) Position of European Bioplastics Sound LCA as a basis for policy formulation

Finally, the predicted large improvements in the efficiency of bio-based feedstock production process over the coming years is a key conclusion—in the same way that fossil based plastics have had many decades to achieve this. When using LCA results as a basis decision making, the timeframe must be considered and if possible, a predicted future scenario developed. This will give a forward-thinking perspective and highlight the potential of bio-based and biodegradable plastics and facilitate fairer comparisons.

Appendix 1. Plastics Lab Testing

TABLE 13. ISO tests for biodegradation of plastic materials

Test number	Title	Description and key features
ISO 14851	Determination of the ultimate aerobic biodegradability of plastic material in an aqueous medium - Method by measuring the oxygen demand in a closed respirometer	Testing is done in aqueous medium Biodegradation measured by consumption of Oxygen 2 months duration
ISO 14852	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium - Method by analysis of evolved carbon dioxide	Testing is done in aqueous medium 2 months duration Biodegradation measured by analysis of evolved carbon dioxide
ISO 14855-1	Determination of the ultimate aerobic biodegradability and disintegration of plastic material under controlled composting conditions - Method by analysis of evolved carbon dioxide	Testing using a compost inoculum 6 months max, 58°±2°C, pH 7.0-8.0, C/N 10-40 Biodegradation measured by conversion of carbon
ISO 14855-2	as above - Part 2: Gravimetric measurement of carbon dioxide evolved in a laboratory-scale test (ISO 14855-2)	As for 14855-1 but with different way of measuring conversion of carbon
ISO 17556	Determination of the ultimate aerobic biodegradability in soil by measuring the oxygen demand	Testing using a soil inoculum 6 months max, 20-28°C Biodegradation measured by consumption of Oxygen

TABLE 14. ISO tests for disintegration of plastic materials

Test number	Title	Description and key features
ISO 16929	Determination of the degree of disintegration of plastic materials under defined composting conditions in a pilot-scale test"	Materials tested in 5x5cm or 10x10cm pieces in pilot scale composting using biowaste mixture Temp can rise to 65°C naturally, 12 weeks duration, C/N 20-30, pH >5 Sample then sieved through 10mm and 2mm sieve
ISO 20200: 2015	Plastics - Determination of the degree of disintegration of plastic materials under simulated composting conditions in a laboratory-scale test"	Qualitative assessment of disintegration 58 ±2°C for max 90 days, if not sufficient, then continue at room temp for max 90 days

Appendix 2. Conditions in Denmark

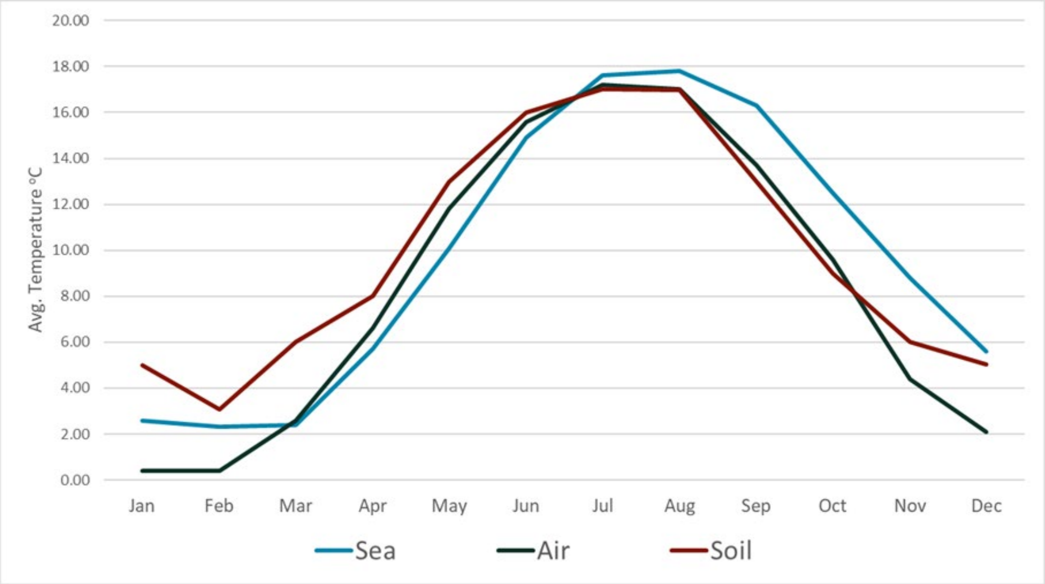

FIGURE 35. Average Temperatures in Denmark
Sources: Sea water (Copenhagen)[227], Air (Copenhagen)[228], Soil (Herfølge)[229]

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227 https://seatemperature.info/february/copenhagen-water-temperature.html

228 https://en.climate-data.org/europe/denmark/capital-region-of-denmark/copenhagen-23/

229 Andersson, K., Nielsen, S., Thørring, H., et al. (2012) Parametric improvement for the ingestion dose module of the European ARGOS and RODOS decision support systems, *Radioprotection*, Vol.46, pp.S223–S228

Appendix 3. Market Estimation Methodology

Appendix 3.1 Compostable Food Waste Bags

A total of 45 municipalities in Denmark have a kerbside collection of food waste for some or all types of properties. This represents 1.26 million households. Based on a telephone survey with all 45 municipalities, the research team identified that nine municipalities use compostable bags for all properties with a collection and one uses compostable bags for flats only (see Table 15 for details).

Copenhagen is one of the municipalities that provides free compostable bags for food waste. A note for a city council committee meeting in spring 2019 states that the council pays around 0.3 kr per bag.[230] Furthermore, Copenhagen hands out around 170,000 packs of 100 bags per household per year, at an approximate weight of 775 g per pack.[231] With just under 300,000 households in Copenhagen, this results in around 58 bags handed out per household and 130 tonnes of bags for all households in a year.

Extrapolating this average per household to all households that receive a kerbside food waste collection results in just under 200 tonnes of compostable food waste bags used across all municipalities per year.

TABLE 15. Types of Bag Used in Kerbside Food Waste Collections

		No. households			
Municipality	**Type of bag used for food waste**	**Compostable plastic**	**Conventional plastic**	**Paper**	**House-holder self-supplies**
Faxe	Compostable plastic	16,054			
Kalundborg	Compostable plastic	21,782			
København	Compostable plastic	294,330			
Køge	Compostable plastic	17,563			
Lejre	Compostable plastic	10,991			
Nyborg	Compostable plastic	15,134			
Odsherred	Compostable plastic	13,882			
Roskilde	Compostable plastic	39,075			
Frederiksberg	Conventional plastic (flats) and compostable plastic (houses)	1,572	50,076		
Hvidovre	Conventional plastic (flats)		13,277		
Albertslund	Conventional plastic		12,547		
Ballerup	Conventional plastic		22,189		
Brøndby	Conventional plastic		15,755		

230 https://www.kk.dk/indhold/teknik-og-miljoudvalgets-modemateriale/08042019/edoc-agenda/b3340b88-ccfd-4ca0-9b58-6c966b5ca3b3/b4567fbd-945f-4bca-8b92-62d73d21079e

231 Interview with stakeholder from Copenhagen council.

Frederikshavn	Conventional plastic		22,595		
Frederikssund	Conventional plastic		19,531		
Furesø	Conventional plastic		16,850		
Gladsaxe	Conventional plastic		13,115		
Gribskov	Conventional plastic		17,586		
Halsnæs	Conventional plastic		14,047		
Hillerød	Conventional plastic		21,223		
Hjørring	Conventional plastic		30,979		
Horsens	Conventional plastic		40,622		
Ikast-Brande	Conventional plastic		18,080		
Ishøj	Conventional plastic		9,420		
Kerteminde	Conventional plastic		10,994		
Kolding	Conventional plastic		41,110		
Næstved	Conventional plastic		28,617		
Randers	Conventional plastic		46,861		
Ringsted	Conventional plastic		15,135		
Rødovre	Conventional plastic		17,985		
Silkeborg	Conventional plastic		40,341		
Slagelse	Conventional plastic		37,746		
Solrød	Conventional plastic		9,085		
Sorø	Conventional plastic		13,267		
Vallensbæk	Conventional plastic		6,371		
Vejle	Conventional plastic		50,864		
Viborg	Conventional plastic		32,796		
Vordingborg	Conventional plastic		22,506		
Billund	Paper			11,938	
Morsø	Paper			9,952	
Thisted	Paper			20,455	
Egedal	Householder self-supplies				16,896
Fanø	Householder self-supplies				1,665
Fredericia	Householder self-supplies				24,268
Holbæk	Householder self-supplies				30,968
TOTALS		**430,383**	**711,570**	**42,345**	**73,797**

Appendix 3.2 Film-Based Biodegradable Plastic Products

Biobag is assumed to be the largest supplier of film-based biodegradable products in Denmark. This is based on desk-based research, discussions with stakeholders and on the fact that Biobag supplies the majority of the Danish municipalities that use compostable food waste bags with these.

Sales data was not available directly from Biobag and the research team has therefore estimated the market size of Biobag using the following methodology:

- The average net profit margin for Biobag Norge and Biobag International[232] for the previous few years (5%) was applied to the net pre-tax profit for Zenzo Group (one of whose

[232] https://www.proff.no/regnskap/biobag-international-as/rognan/engroshandel-annet/IFZG6MH10N6/

brands is Biobag Danmark)[233] (2 million kr) to get an annual revenue for Zenzo Group in 2018 of 40 million kr.

- An assumption was made that 50% of Zenzo Group's revenue is from biodegradable products. Using the same weight:price ratio from the compostable food waste bag estimations (0.3 kr paid per 7.75 g bag – see Appendix A.3.1), a revenue of 20 million kr represents 390 tonnes of biodegradable film-based products. Of these, up to 200 tonnes are compostable food waste bags sold to municipalities. Therefore, there are at least 190 tonnes of additional biodegradable film-based products.
- As there are also other players on the film-based market and the proportion of Biobag products within Zenzo Group turnover could be higher (or lower) than expected, we arrive at a figure of around 300 tonnes of additional film-based products per year.

Appendix 3.3 Other Biodegradable Plastic Products

Another company, which produces a large variety of plastic and non-plastic biodegradable and compostable single-user plastic items provided some sales data to assist with the study.

- According to communication with the company, the company's gross turnover was 13.6 million kr. From the supplied data, one-third of this is PLA or CPLA products and one-third of all is exported, resulting in PLA/CPLA products sold in Denmark with a value of around 3 million kr.
- Based on the product catalogue, a price:weight ratio of 1.6 kr per 15 g product was estimated. Applied to the sales cost, this represents just under 30 tonnes of PLA/CPLA products.
- As there are other suppliers of PLA/CPLA products, the total market size for these single-use products may be in the region of 50 tonnes per year.

[233] Available from a search at https://datacvr.virk.dk/data/

Appendix 4. Raw material requirements for bio-based polymers

Appendix 4.1 Land Use

TABLE 16. Land use required to produce each tonne of polymer[234]

	Land use requirements dependent on feedstock, hectare per tonne of polymer				
Polymer	**Sugar cane**	**Sugar beet**	**Corn**	**Potato**	**Wheat**
PBAT	No information	No information	No information	No information	No information
PBS (100% bio-based)	0.09	0.09	0.21	0.24	0.56
PBS (100% fossil-based)	0.18	0.19	0.42	0.49	1.13
PLA	0.16	0.18	0.37	0.44	1.04
PHA[235]	0.30	0.31	0.69	0.81	1.88
Starch blends	No information	No information	No information	No information	No information
PTT[236]	0.30	0.31	0.69	0.81	1.89
Bio-PA[237]	0.34	0.37	0.77	0.92	2.18
Bio-PET[238]	0.08	0.08	0.18	0.21	0.49
Bio-PE	0.46	0.47	1.06	1.24	2.88

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[234] Institute for Bioplastics and Biocomposites *Biopolymers facts and statistics 2017*, https://www.ifbb-hannover.de/files/IfBB/downloads/faltblaetter_broschueren/Biopolymers-Facts-Statistics_2017.pdf

[235] Assuming that all PHAs have the same land use requirement as PHB

[236] Assuming that all is 100% bio-based

[237] Assuming that all is PA-6

[238] For bio-PET with 32% bio-based content. 100% bio-based would be roughly three times more land intensive

Appendix 5. Municipal Plastic Waste Collections

TABLE 17. Summary of Municipal Plastic Waste Collections[239]

		Flats (municipalities)		Houses (municipalities)	
	Co-collection	**No.**	**% of all**	**No.**	**% of all**
Kerbside Collection	Rigid plastic/metal/glass only	14	14%	14	14%
	Rigid plastic/metal/glass with paper/card/plastic films	7	7%	8	8%
	Rigid plastic/metal	5	5%	5	5%
	All plastic/metal	7	7%	7	7%
	Rigid plastic/glass with card/plastic films	1	1%	0	0%
	Single-stream				
	Rigid plastics only	3	3%	4	4%
	Mixed rigids and films	20	20%	20	20%
	Separate rigids and films	7	7%	6	6%
	Sub-total: kerbside collection	64	65%	64	65%
Local bring sites (bring banks)	Rigid plastics only	4	4%	3	3%
	Mixed rigids and films	4	4%	4	4%
	Separate rigids and films	1	1%	1	1%
	Rigid plastic/metal/glass only	1	1%	1	1%
	Sub-total: kerbside collection and local bring sites	74	76%	73	74%
Only HWRC[240]	Rigid plastics only	4	4%	4	4%
	Plastic films only	1	1%	1	1%
	All plastic	1	1%	2	2%
	Rigid plastics and plastic films separate	18	18%	18	18%
	Total: any kerbside collection, local bring site or HWRC	98	100%	98	100%

[239] https://genanvend.mst.dk/projekter/projektbibliotek/2015/kortlaegning-af-kommunale-affaldsordninger-for-husholdningsaffald-1/

[240] Household Waste and Recycling Centre

Appendix 6. Interviewees

Name of organisation	Type of organisation
PlanetGreen	Producer / Importer
Coop	Retail
Salling Group	Retail
Dansk Plast Industri	Trade association (Producers / Importers)
Plastic Change	NGO
Biovækst	Waste management – pre-treatment and biogas facility
Nature Energy	Waste management – biogas facility
Solrød Biogas	Waste management – biogas facility
Ragnsells	Waste management – pre-treatment
Affald Plus	Waste management – municipal waste company
Dansk Affaldsminimering	Waste management – plastic recycler
Københavns Kommune	Municipality
Vejle Kommune	Municipality
Biobag Denmark	Producer / Importer
Greenway-Denmark	Producer / Importer

Appendix 7. Biodegradation Studies and Institutions

Organisation(s) involved	Organisation type	Key words	Study title	Study description
Danmarks Tekniske Universitet (DTU)	University	bioplastic degradability; commercialisation; environment; waste management; organic waste; microorganism recycling	Re-cycling and up-cycling of bioplastic	Research looking at various elements of bio-based plastics including biodegradability. Focus is more on the content of bio-based plastics, identifying microorganisms which can degrade bio-based plastic.
University of Stuttgart	University	biodegradability; plastic; environment; microbes; pollution	BMBF-Project ENSURE - Plastics in the Environment	Researching the effect of plastic pollution in the environment and how plastic degrades in different marine environments. Looking at how these degraded products affect the marine environment. The development of plastics with optimised biodegradability and microbe biodegradability
UCL	University	biodegradability; LCA; circular economy analysis; polymer biodegradability; biopolymer circular economy	Institute of making - Designing out plastic waste	Funded by UKRI, Looking at different options for a biopolymer circular economy. This includes biodegradable plastics but also enzyme catalysed recycling.
University of Bath	University	biodegradable; plastic; microbeads; designing biodegradable plastics	Department of Chemistry - Materials	Ongoing studies into biodegradable plastics, recently focused on commercialising a biodegradable plastic microbead
Aston University	University	polyesters; material; development; biodegradability	Biodegradable polymers	Improving the properties of biodegradable polyesters so they are more useful.
Goethe University Frankfurt; Institute for Social-Economic Research; Max Planck Institute for Polymer Research	University	biodegradable; polymers; food packaging; characterisation of properties	PlastX	A joint research project researching problem plastics in general with a sub group focusing on biodegradable polymers for food packaging
University of Houston	University	biodegradable; biobased polymers; properties; structure; function; polyacrlates; thio-ebe elastomers; polystyrene	The Robertson Research Group - Department of Chemical and Biomolecular engineering	Research group looking into specific biodegradable plastic polymers and comparing their structural properties with traditional, fossil fuel derived plastics.
Cornell University	University	poly(hydroxyalkanoates; polyesters; polycarbonates; biodegradable; plastic; synthesis; development; CO2 feedstock	The Coates Research Group	Research looking into the synthesis and technical properties of several biodegradable polymers

Organisation(s) involved	Organisation type	Key words	Study title	Study description
RUC	University	marine; plastic pollution; animals	Environmental dynamics	Studies into plastic pollution and it's effect in the marine environment.
KU	University	new bio-based plastic; PLA research; LCA; biodegradable plastics; development	Centre for Sustainable Catalysis and Engineering; Toward better biodegradable plastics via innovative mono- and dilactone chemistry	No description of actual research other than title found
Aalto University	University	lignocellulose; cellulose; biodegradable; new polymers;	Biopolymer Chemistry and Engineering (bio2)	Research into the alternatives to cellulose from bio-based biodegradable products. Have found no evidence of research into biodegradability
Wageningen University & research	University	bio-based plastic; biodegradable plastics; production; market analysis; composting	Biobased products and markets	Several ongoing, product specific biodegradable products ongoing e.g. one is looking at the biodegradability of plant pot alternatives
Polymer processing and flow research group	University	PLA; properties; biodegradable; plastic; food safety; bacteria;	P-PROF	Research into the mechanical properties of polylactic acid, including property modifiers and anti-bacterial performance
Hochschule Hannover	University	development of bioplastics; biodegradable bio- based plastic development	Bio-plastics research 'cluster group'	Not clear if there are currently any projects underway looking into biodegradability of plastics
Johannes Gutenberg Universitat mainz	University	polyesters; properties; applications; PLA; new polymers; development	Polyesters / Biodegradable materials	Unclear whether research group is still active. Looking into the properties of polyesters especially and the development of new polymers with better properties
Lund University	University	LCA; Consumer behaviour; industrial biotechnology; enzyme recycling; design plastics	STEPS (Sustainable Plastics and Transition Pathways)	Mistra financed programme. Reviewing the use of feedstocks, designing plastics for biodegradation. Mainly focusing on polyesters.
Aarhus University	University	bio-refining; conversion; recirculation; anaerobic digestion; bio-based materials; biogas;	Aarhus University Centre for Circular Bioeconomy	Research lab looking into the impacts of bio-mas production for use as plastics and the end of life of bio-based plastics, mostly through anaerobic digestion. Circular Biomass Cascade to 100%: https://research.hanze.nl/en/projects/circular-biomass-cascade-to-100
University of Applied Science and Arts	University	optimising production; material flow management	Centre for resource efficiency	No specific research on biodegradable plastics

Organisation(s) involved	Organisation type	Key words	Study title	Study description
Norwegian University of Life Sciences (NMBU)	University	biofuel; bio4fuels; fuel; energy; biomass; organic residue	Faculty of Environmental Sciences and Natural Resource Management	Studies focus on biofuels, no specific research into plastics or biodegradable plastics
Royal Institute of Technology Stockholm	University	bioenergy; biomass harvesting	the Department of Chemical Engineering and the Department of Biotechnology and Food Science	No ongoing research project directly relevant to the biodegradation of plastics. Ongoing research into biomass harvesting for bioenergy. In a research group with Aalto University who do the research into biodegradable plastics.
Belgium Organic Waste Systems (OWS)	Private company - Registered standard testing laboratory	biodegradability; compostability; ecotoxicity; product development; screening tests; certification tests; ISO 17088; ISO 18606; EN 14995; EN 13432; ASTM D6400; ASTM D6868; AS 4736; TUV Austria; DIN CERTCO; BPI; JBPA; ABA (seedling)	Biodegradability, Compostability & Ecotoxicity (BCE)	Private company associated with the University of Gent. A research lab and company, researching anaerobic digestion, biodegradability, compostability and waste management. Testing facility testing industrial compostability, home compostability, degradation in other environments and abiotic degradation of oxo-degradable plastics
ARCHA	Private company - Registered standard testing laboratory	plastic; testing; biodegradability; standards; TUV Austria	Testing facility offering a variety of certifications	List of accredited tests: http://www.archa.it/Cms-Data/pdf/elenco%20prove%20ARCHA%20v16.PDF
ITENE	Private company - Registered standard testing laboratory	plastic; testing; biodegradability; standards; disintegration; ISO 16929; TUV Austria	Biodegradability, disintegration an ecotoxicity facility	Running a pilot plant disintegration of plastic materials study under defined composting conditions in a pilot-scale test according to 16929
innovhub	Private company - Registered standard testing laboratory	plastic; testing; biodegradability; standards; TUV Austria	Compostability and biodegradability testing	Certified TUV Austria testing laboratory
BetaAnalytic	Private company - Registered	plastic; testing; TUV Austria; biobased	Biobased plastic testing	Certified TUV Austria testing laboratory

Organisation(s) involved	Organisation type	Key words	Study title	Study description
	standard testing laboratory			
Aimplas	Private company - Registered standard testing laboratory	biodegradation; disintegration; plastic; testing; aerobic degradability; anaerobic biodegradability; degree of disintegration	Biodegradability and disintegration testing facility	Certified TUV Austria testing laboratory
TÜV Austria	Private company	OK compost; OK biobased; NEN biobased; seedling logo; testing; products;	Testing of products to standards	https://www.tuv.at/en/news/news-article/news-single/on-course-for-expansion-bioplastics-certification-now-part-of-tuev-austria-group/
Danish Technological Institute	Private company	biobased; LCA; greener materials; fiberboards;	Biobased society business area	Research into biobased products as a whole. Focus on bioplastic, biogas and biomass products. No explicit research into biodegradable plastics
Institute for Bioplastics and Biocomposites	Private company	bioplastics; biocomposites; market; product optimisation; bioplastic material development;	IfBB (Institute for Bioplastics and Biocomposites)	Sustainable strategies for recycling products and waste materials from biobased plastics. Focus is on developing new bio-based plastics and to review recycling scenarios. No current research directly related to biodegradable plastics
Force Technology	Private company - Standard testing laboratory	testing; plastics consultancy; weather condition test; climate chamber; UV; weather-o-meter		Weather condition test (accelerated ageing) in climate chamber (UV, Weather-o-Meter)
Østfoldforskning	Private company	Environmental product declarations; LCA; food waste; packaging LCA; value-chain; waste logistics	Food and Packaging	Research into the relationship between packaging and food waste from an LCA perspective.
Danish Materials Network	Private company	material group; knowledge hub	No research conducted, the follow on from PastNet	The report reviews various types of bioplastics, their technical characteristics, their distribution in the Danish market in relation to disposable articles, relevant legislation and an assessment of the environmental advantages and disadvantages of using bioplastics as an alternative to conventional crude oil plastics. https://www.dmn-net.com/da/dansk-materiale-netvaerk/projekter/afsluttede-projekter/engangsartikler-i-bioplast
Plymouth University	University	Marine; litter; degradation; environment; sea; soil; open-air	International Marine Litter Research Unit Publication	Research unit focusing on marine litter and plastic degradation in the natural environment. Publications: Napper, I. E. & Thompson, R. C. (2019) Environmental Deterioration of Biodegradable, Oxo-biodegradable, Compostable, and Conventional Plastic Carrier

Organisation(s) involved	Organisation type	Key words	Study title	Study description
				Bags in the Sea, Soil, and Open-Air Over a 3-Year Period Environmental Science and Technology, in press.
Hydra marine sciences	Private company	Marine; litter; degradation; environment; sea; soil; open-air	Performance of biodegradable plastics in the marine environment	Laboratory tests of biodegradable plastics in imitated seafloor conditions

Appendix 8. Bio-based Plastics – Ethical Certification Standards

Scheme name	Scheme running organisation	Scope	Aimed at	Typical certified organisations	Criteria key words	Description
International Sustainability & Carbon Certification (ISCC Plus)	ISCC	Biomass production	Bio-based plastic producers buying feedstock. Recognized by SAI, Unilever, CocaCola and Fefac.	Farm/plantation; logistic centre; polymerisation plant; trader; treatment plant for waste and residues	deforestation (compensation for new planting is not allowed); declaration of supply chain; GHG emissions calculations; mass balance	Different guidance depending on feedstock, for example, shea nuts and short rotation coppice and a bespoke audit time period, for shea nuts and short rotation coppice Third party auditors review information provided by the company's internal audit team Voluntary certification for non-regulated markets. The certification can be expanded to specific market area add owns: increasing biodiversity; phasing out hazardous chemicals; reduce the consumption of water fuels and electricity; reducing GHG emissions; producing non GMO

Scheme name	Scheme running organisation	Scope	Aimed at	Typical certified organisations	Criteria key words	Description
Initiative on Sustainable Supply of Raw Materials (INRO)	INRO	Biomass production	Bio-based plastic producers buying feedstock.	N/A	Conservation; protection of areas with high carbon stock; soil protection; water protection; fertilisers; pesticides; waste management; GHG emissions; social; economic	Not yet launched, last documents dated 2013, so may have been scrapped Currently liaising with different stakeholders including packaging sector, associations, German ministries. Aim to become Europe wide and then worldwide. Economic, social and environmental criteria.
Bonsucro EU	Bon surcro	Sugarcane production	Bio-based plastic producers buying feedstock.	Producers e.g. small hold farmers, farms; sugarcane mills. 25% of all sugar cane companies are members	law; labour; efficiency; biodiversity; improve	Two standards, a production standard and a chain of custody standard Internal audit and gap analysis; contract an audit body to undertake the assessment
RTRS	RTRS	Soy production and supply chain	Bio-based plastic producers buying feedstock.	Producers; manufacturers (traceability)	legal; labour; community; environment; agriculture	Two standards, a production standard and a chain of custody standard
RSB	RSB bioproduct standard	Biomass production and supply chain	Bio-based plastic producers buying feedstock.	Producers	traceability; risk management; traceability; displacement effects; ghg; advanced fuels	Certification takes into account the feedstock, product, operator size
Scottish quality crops	SQC	Biomass production	Bio-based plastic producers buying feedstock.	Producers	fertilisers; crop protection products; production; harvesting; storage; haulage	Farming certification standard, began with only cereal producers but now covers all products. All non-conformance against the standard must be rectified More compliance against standards as opposed to going above and beyond

Scheme name	Scheme running organisation	Scope	Aimed at	Typical certified organisations	Criteria key words	Description
REDcert	REDcert2	biomass for material purposes	Consumers	Bio-based plastic producers	GHG emissions; waste and residues; cultivation	All phases of bio-based plastic production from farmer to supplier and trade.
PSPO RED	RSPO	Palm oil	Bio-based plastic producers buying feedstock.	Palm oil producers; supply chain	GHG emissions; land use; land use change; label of sampling; supply chain	Certification focusing on complying the requirements in the RED directive and ensuring traceability through supply chains.
PSPO next	RSPO	Palm oil	Bio-based plastic producers buying feedstock.	Palm oil producers; supply chain	use of fire; peat; GHG; human rights; transparency	Certification based on RSPO RED buy offering an improved standard level.
Better biomass	Better biomass	Biomass production	Bio-based plastic producers buying feedstock.	Producers; supply chain	Need to buy standard to see criteria	Several schemes: sustainability of biomass and chain of custody
UEBT Ethical biotrade standard	Union for Ethical Biotrade	All 'natural ingrediencies' mostly used for food and cosmetic sectors	Bio-based plastic producers buying feedstock.	Producers; supply chain	conservation; biodiversity; sustainability; socio-economic; legislation; traceability; supply chain	Two certification schemes: ethical sourcing system certification and natural ingredient certification. Ethical sourcing system certification assess a company's commitments, due diligence in relation to supply chains and traceability of feedstocks.
Nordic swan ecolabel	Nordic ecolabel	Sanitary products	Consumers	Bio-based plastic producers. 25,000 products currently certified over 60 product groups	Material certification; sustainability; process; air quality	One certification label with different criteria for separate products. The 'Sanitary product' criteria includes consideration for the % of the material, if plastic, which is biobased. Does not consider biodegradable plastics within the criteria.

Scheme name	Scheme running organisation	Scope	Aimed at	Typical certified organisations	Criteria key words	Description
SSAP red	U.S. Soybean Sustainability Asssurance Protocol	Soy bean	Bio-based plastic producers buying feedstock	Producers; supply chain	mass balance supply chains; biodiversity; high carbon stock; production practices; health; labour; welfare; GHG	Several schemes, one for producers and several for different chains in the supply chain to certify that they can sell on soy beans with the certification. Operate a mass balance sustainability approach.

Bio-based and Biodegradable Plastics in Denmark - Market, Applications, Waste Management and Implications in the Open Environment

There is currently considerable interest in bioplastics from consumers and industry and business, but there is still great uncertainty about the subject and several misconceptions exist. With the National Plastic Action Plan developed by the former Danish Government in December 2018 and the subsequent political agreement of 30th January 2019, Denmark has a consolidated plan of action for plastics. The plan focuses on less plastic in nature, smarter production and consumption, more cooperation in the value chain, better waste management, a stronger scientific evidence base and increased recycling—plan initiative no. 23 requires the building up of knowledge around the advantages and disadvantages of bio-based plastics.

The Danish Environmental Protection Agency (Miljøstyrelsen) on the basis of the above need to build knowledge of biobased and biodegradable plastics as an alternative to conventional plastics based on fossil resources, including supply and market mapping and possible waste management scenarios. To this end the following requirements were investigated during the course of this report:

- Literature review of biodegradable plastics and how they behave under different conditions and outline of ongoing studies
- Description of current standards and regulations, and recommendations for possible future standards and regulations for Denmark
- Description and analysis of the national and global levels of feedstock and material along with current and future applications of biobased and biodegradable plastics
- Description and analysis of scenarios for waste products of bio-based and biodegradable plastics, including options for recycling, composting and other biological treatment in relation to Danish conditions
- Analysis of other countries waste management of bio-based and biodegradable plastics

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