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Bio-based and biodegradable plastics – Facts and Figures

Focus on food packaging in the Netherlands

Martien van den Oever, Karin Molenveld, Maarten van der Zee, Harriëtte Bos

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Preface

For over 25 years Wageningen Food & Biobased Research (WFBR) is involved in research and development of bio-based materials and products. Examples of materials and products developed include bioplastics for packaging, casings for consumer electronics, textiles and parts for the automotive industry. A unique aspect of the work of WFBR is our broad and detailed knowledge of the full production chain, from the biomass to bio-based materials, and of collection and recycling of plastics. Next to our technological knowledge, we also focus on sustainability, logistics, economics, normalisation and end-of-life options. We take part in a number of normalisation committees. Also we have done several studies on plastics collection and recycling. In recent years, we have contributed to a wide range of projects for both industry and governments.

For that reason WFBR has been asked by RVO.nl to collect facts and figures on technical, economical and sustainability aspects of bio-based and biodegradable plastic food packaging and present them in a scientific overview report. This report builds on previous publications such as Biobased Plastics 2012 and the Catalogue Biobased Packaging and addresses unclear and contradictory information present in society regarding bio-based and/or biodegradable plastics. On request of the Dutch Ministry of Economic Affairs, the target audience of this report is the Dutch retail sector and consumers.
Parallel to this report, the Ministry of Infrastructure & the Environment (I&M) has commissioned CE Delft to prepare a report on the conditions under which bio-based and/or biodegradable plastics are compatible with the circular economy. The focus of the CE Delft report is on greenhouse gas (GHG) balance and the use of (natural) resources throughout the life cycle.

Reader's Guide

Throughout the report, typical questions from consumers and also from retailers and other professionals related to bio-based and biodegradable plastics have been highlighted in text boxes. In the subsequent text facts and figures are presented to address these questions.

Several relevant aspects regarding bio-based and biodegradable plastics are defined in the first chapter. In chapter 2, the appearance and recognition of these plastics are addressed. Next, figures for the availability and costs of bio-based and biodegradable plastics are presented in chapter 3. Their application and suitability for packaging of food is discussed in chapter 4, while end-of-life options for bio-based and/or biodegradable plastic products with focus on post-consumer food packaging are reviewed in chapter 5.
Finally, several sustainability issues of bio-based plastics are addressed in chapter 6, like its impact compared to fossil-based plastics, the food versus bio-based plastics discussion, the use of genetically modified organisms for bio-based plastic production and disposal in the environment.

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Disclaimer
Facts and figures have been collected from various reputable sources. Some of the figures are more recent than others. We assume to the best of our knowledge that the information presented gives a truthful representation of the present situation, but we cannot take any responsibility for the accuracy of information provided.

Bio-based and biodegradable plastics are a large family of materials with widely varying properties. As with conventional plastics, the end-of-life options depend entirely on the application, the way the product is disposed of by its user, and the available infrastructure in the region where the product is being disposed of.

Abstract

This report presents an overview of facts and figures regarding bio-based and/or biodegradable plastics, in particular for packaging applications.

Often, the term bioplastic is used by the public. However, the term 'bioplastic' refers to either the bio-based origin of a plastic or the biodegradable character of a plastic. These two aspects of a plastic are not synonymous, and therefore the term 'bioplastic' is confusing. In this report a clear distinction is made between bio-based and biodegradable plastics.

Appearance and recognition
Just like fossil based plastics, bio-based and/or biodegradable plastics are available in many grades with a wide variety of properties. The suitability of bio-based and/or biodegradable plastics for particular applications depends on these properties. Also the most suitable end-of-life option depends on its properties. However, bio-based plastic products often have a very similar appearance compared to conventional fossil-based plastic products. As a consequence, they cannot be easily distinguished by consumers. The same is valid for biodegradable versus non-biodegradable products. Logo's and labels can be used to make clear to the consumer (and retailer) whether a plastic is bio-based and/or compostable, and how to dispose of the plastic after use. Some qualifications like 'biodegradable' are not unambiguously defined. Consequently, logo's and labels will need to be linked to a normalisation and certification system. Moreover, even when a plastic is biodegradable, this does by no means imply that the material degrades in the environment in a short period of time.

Availability and costs
In 2015, the production capacities for bio-based and biodegradable plastics account for nearly 1% of total global plastics production. The markets for some bio-based and/or biodegradable plastics are expected to grow significantly during the coming years (Bio-PET, PBS and PLA), others are expected to consolidate (CA and Bio-PA). Overall, it is expected that by 2020 the share of bio-based and biodegradable plastics will increase to 2.5% of fossil plastics production. For most of the bio-based and biodegradable plastics there are several suppliers and most plastics are readily available. In general, bio-based and biodegradable plastics are more expensive than fossil-based plastics on a weight basis. However, specific material properties can allow costs reductions in the use or end-of-life phase. There are several examples of bio-based and/or biodegradable plastic products being cost competitive already today. Further, the price of fossil-based plastics is depending on oil prices and fluctuates with oil prices while in general the prices of bio-based plastics depend on biomass prices that are more stable. When the economy-of-scale of production, conversion into products and logistics becomes more favourable it is expected that the prices of bio-based plastics will come down.

Bio-based and biodegradable plastics is food packaging

The main applications of bio-based and biodegradable plastics are currently in (food) packaging, food service ware, (shopping) bags, fibres/nonwovens and agricultural applications. Bio-based drop-in plastics such as bio-PE and bio-PET are identical to fossil-based counterparts and can be used in exactly the same applications. The three most commonly used bio-based plastics with unique properties are PLA, Starch based plastics and Cellophane. Like for fossil-based plastics, careful selection of a bio-based and/or biodegradable packaging material is necessary to ensure that a packed product has the required shelf life. Some characteristics of a plastic can be a disadvantage in one application, and an advantage in another; f.i. the low water vapour barrier of the bio-based plastic PLA is a disadvantage for a water bottle but an advantage in (breathable) packaging of vegetables and fruit. Further, bio-based and/or biodegradable plastics have to comply with the same regulations with respect to food safety as fossil-based plastics, and many bio-based plastics have certificates to prove that they can be used in food-contact applications.

End-of-life options

The most suitable end-of-life solution depends on the type of bio-based and biodegradable plastic, the volume on the market, the application and the available collection and processing infrastructure. With the exception of the PET bottle recyclates, all post-consumer fossil plastic recyclates are not 100% pure and cannot be used in food packaging products due to food-safety regulations. Although it is technically possible to recognise all plastic materials with NIR (except for black plastic), a 100% sorting efficiency is difficult to achieve in practice. Since all post-consumer plastic recyclates are blends, the effects of the (very small) quantities of bio-based and/or biodegradable plastics are currently not measurable. And as film products are not sorted for material type, the composition of film recyclates is a reflection of the consumption pattern of the region. The influence of bio-based packaging on the quality of recyclates should therefore be measured in these mixtures. A study at WFBR has shown that mixing up to 10% of a starch based film and up to 10% of a PLA film in a sorted plastic film mixture has no significant negative effect on mechanical properties.

Apart from the end-of-life options suitable for conventional plastics, certified biodegradable plastic products can also be (industrially and home) composted, digested or biodegraded on agricultural land. Industrial composting, which is considered as a form of organic recovery or recycling, is a cost effective way of processing municipal organic kitchen and garden waste. Today, a significant amount of kitchen waste ends up in the grey bin (for residual waste) and is incinerated. However, since kitchen waste is often rather wet, incineration can be less energy efficient compared to composting. Therefore, a particular benefit of biodegradable plastic packaging and (garbage) bags is that they may help to collect a larger share of the municipal kitchen waste and convert waste from the grey bin into the green bin. Unclear communication, however, may result in people using non-compostable bags for this purpose, thus increasing the amount of this plastic in the organic waste stream. Today, about 1% of the municipal kitchen

waste stream is non-biodegradable plastic. Some of the Dutch waste processors are still hesitating to accept, next to the compostable plastic bags containing biowaste, other types of biodegradable plastic (packaging) because they fear potential unwanted introduction of more non-biodegradable plastics (as a result of consumers not understanding the difference). The Dutch association of waste processors and Holland Bioplastics are working on a covenant on the acceptance of compostable plastics in the green bin.
Biodegradable plastic packaging which is not mechanically recycled and which does not add benefits in the composting route can be incinerated, thus allowing energy recovery.

Collection and sorting, which starts at consumers and their behaviour, largely determine the (energy) efficiency of waste management systems. To facilitate consumers to choose the right route of disposal for packaging waste, pictograms can be used to indicate the preferred disposal route. Related to this, for compostable packaging products that are certified according to EN13432 a new pictogram that shows the product can be disposed in the GFT waste bin has been introduced in the Netherlands recently.

Sustainability issues

The land needed to grow the feedstock for the presently produced bio-based plastics world-wide amounts about 0.02% of the arable area. If we would base *all* present world-wide fossil plastics production on biomass as feedstock instead, the demand for feedstock would be in the order of 5% of the total amount of biomass produced and harvested each year by mankind. But such scenarios are not likely to happen since it is expected that the industry will develop technologies that can use alternative feedstocks from waste and side streams of agriculture and food production, for example non-edible lignocellulosic feedstocks for chemical building blocks. Recent research shows that a sustainable co-production of biofuels (and bio-based plastics) and food is possible and that biofuels production may serve as a stabilizer for food prices, providing farmers with more secure markets and thereby leading to more sustainable production. A further relation between food and bio-based plastics is that some of these plastics like PLA have barrier properties which can help food to stay fresh longer and to extend the sell by date.

The environmental impact of bio-based plastics and fossil-based plastics are in different impact categories. Substitution of fossil-based plastics by bio-based plastics generally leads to lower non-renewable energy use (NREU) and greenhouse gas (GHG) emission. The GHG emission reduction, however, may be negatively influenced by direct and/or indirect land-use change. The GHG emission reduction that is reached by bio-based plastics is generally significantly larger than that by biofuels. For the categories related to agriculture, such as eutrophication and acidification, bio-based plastics generally have a higher impact than fossil plastics. Because there are large differences in impact both in the family of bio-based plastics as well as in the family of fossil plastics no absolute rule can be given.

Genetically modified (micro)organisms (GMOs) are not necessary for the production of many bio-based plastics. Biomass feedstock in general is non-GMO, although in some countries GMO plants are more common. For example in the US a large share of corn is GMO. A mix of this corn and non-GMO corn is used to produce PLA. PLA does not need the GMO corn. Some monomers like succinic acid and 1,3-Propanediol and a polymer like PHA can be produced via fermentation with GMO strains. However, the fermentation is usually performed in closed systems, so the GM organisms can be controlled (white biotechnology). The conversion of woody biomass to fermentable sugars for the production of second-generation polymers is also often performed using GMO strains (in closed systems).

Biodegradable plastics are not a solution to the problem of litter and the 'plastic soup'. On the other hand, biodegradability can be a useful characteristic for specific marine and soil related applications like fishing lines and mulch films. When lost at sea or when only partly recovered from the land, marine or soil biodegradable plastics would at least result in a lower risk of harmful consequences than if they fail to break down at all. As a certified claim like OK biodegradable MARINE or OK biodegradable SOIL could stimulate consumers to leave a certified product behind in the environment, a clear distinction should be made between certification of the claim and authorization to communicate about this certification.

Samenvatting

Dit rapport geeft een overzicht van feiten met betrekking tot bio-based en/of biologisch afbreekbare kunststoffen, in het bijzonder voor verpakkingstoepassingen.

Vaak wordt de term bioplastic gebruikt. De term 'bioplastic' verwijst naar ofwel de bio-oorsprong van een plastic of het biologisch afbreekbare karakter van een kunststof. Deze twee aspecten van een kunststof zijn niet synoniem, en daarom is de term bioplastic verwarrend. In dit rapport wordt een duidelijk onderscheid gemaakt tussen bio-based en biologisch afbreekbare plastics.

Uiterlijk en herkenning

Net als fossiele plastics, zijn bio-based en/of biologisch afbreekbare plastics verkrijgbaar in vele soorten met een breed scala aan eigenschappen. De geschiktheid van bio-based en/of bioafbreekbare plastics voor bepaalde toepassingen is afhankelijk van deze eigenschappen. Ook de meest geschikte end-of-life optie is afhankelijk van de eigenschappen. Echter, bio-based plastic producten hebben vaak een zeer vergelijkbaar uiterlijk als conventionele fossiele kunststof producten. Als gevolg daarvan is het voor de consument niet gemakkelijk ze te onderscheiden. Hetzelfde geldt voor biologisch afbreekbaar versus niet-biologisch afbreekbare producten. Logo's en labels kunnen worden gebruikt om voor de consument (en retailer) duidelijk te maken of een plastic bio-based en/of composteerbaar is. En, soms nog belangrijker, in welke container het plastic weg te gooien na gebruik.

Sommige kwalificaties zoals 'biologisch afbreekbaar' zijn niet eenduidig gedefinieerd. Daarom is het belangrijk dat logo's en labels gekoppeld zijn aan een normalisatie en certificatie-systeem. En zelfs wanneer een plastic bioafbreekbaar is, dan betekent dit nog niet dat het materiaal in het milieu afbreekt in een korte tijd.

Beschikbaarheid en kosten

In 2015 was de productiecapaciteit voor bio-based en/of bioafbreekbare plastics goed voor ongeveer 1% van de totale wereldwijde kunststofproductie. De markten voor sommige bio-based en/of biologisch afbreekbare plastics zullen naar verwachting aanzienlijk groeien in de komende jaren (Bio-PET, PBS en PLA), anderen zullen naar verwachting consolideren (CA en Bio-PA). Globale verwachting is dat het aandeel van bio-based en biologisch afbreekbare plastics in 2020 zal toenemen tot 2,5% van de fossiele kunststofproductie.

Voor de meeste bio-based en/of bioafbreekbare plastics zijn er meerdere leveranciers en de meeste kunststoffen zijn beschikbaar. Over het algemeen zijn bio-based en bioafbreekbare plastics op gewichtsbasis duurder dan fossiele kunststof. Specifieke materiaaleigenschappen kunnen echter een materiaalbesparing of kostenbesparingen mogelijk maken tijdens het gebruik of aan het einde van de levensduur. Vandaag de dag zijn er inmiddels verschillende voorbeelden van concurrerende bio-based en/of biologisch afbreekbaar plastic producten. Verder is de prijs

van fossiele plastics afhankelijk van olieprijzen en fluctueren deze met de olieprijzen mee terwijl in het algemeen de prijs van bio-based plastics afhankelijk is van biomassaprijzen die stabieler zijn. Met verdere schaalvergroting is de verwachting dat de prijzen van bio-based plastics zullen dalen.

Bio-based en bioafbreekbare plastics is voedselverpakkingen
De voornaamste toepassingen van bio-based en bioafbreekbare plastics zijn in (voedsel)verpakkingen, wegwerp servies en bestek, (winkel)tassen, vezels/non-wovens en landbouwtoepassingen. Bio-based drop-in kunststoffen zoals bio-PE en bio-PET zijn identiek aan fossiele tegenhangers en kunnen worden gebruikt in dezelfde toepassingen. De drie meest gebruikte bio-based plastics met unieke eigenschappen zijn PLA, zetmeel gebaseerde kunststoffen en Cellofaan. Zoals voor fossiele kunststoffen is een zorgvuldige selectie van bio-based en/of biologisch afbreekbaar verpakkingsmateriaal nodig om ervoor te zorgen dat een verpakt product de vereiste houdbaarheid heeft. Sommige kenmerken van een kunststof kunnen nadelig zijn in de ene applicatie en een voordeel zijn in een andere; de lage waterdampbarrière van bio-based PLA kunststof is een nadeel voor een waterfles maar een voordeel voor een (ademende) verpakking van groente en fruit. Verder moeten bio-based en/of biologisch afbreekbare plastics voldoen aan dezelfde regels met betrekking tot de voedselveiligheid als fossiele plastics, en vele bio-based plastics hebben certificaten om te bewijzen dat ze kunnen worden gebruikt in contact met voedingsmiddelen.

End-of-life opties
De meest geschikte end-of-life route is afhankelijk van het type bio-based en bioafbreekbaar plastic, marktvolumes, de toepassing waarin het werd gebruikt en de beschikbare infrastructuur voor inzameling en verwerking. Met uitzondering van gerecycleerd PET-fles materiaal, zijn gerecycleerde *post-consumer* plastic materialen niet 100% zuiver en kunnen niet gebruikt worden in levensmiddelenverpakkingen als gevolg van voedselveiligheidsvoorschriften. Hoewel het technisch mogelijk is om alle kunststoffen met NIR te herkennen (behalve zwart plastic), is een 100% sorteerefficiëntie in de praktijk moeilijk te realiseren. Aangezien alle *post-consumer* kunststoffen blends zijn, is het specifieke effect van de (zeer kleine) hoeveelheden bio-based en/of biologisch afbreekbare kunststoffen momenteel niet meetbaar. En als filmproducten niet worden gesorteerd naar materiaalsoort, dan weerspiegelt de samenstelling van de film recyclaten het consumptiepatroon van de regio. De invloed van bio-based verpakkingen op de kwaliteit van de recyclaten moet derhalve worden gemeten in deze mengsels. Een studie door WFBR heeft aangetoond dat het bijmengen van tot 10% zetmeel gebaseerde film of PLA-folie in een gesorteerd kunststoffoliemengsel geen significant negatief effect heeft op de mechanische eigenschappen.

Afgezien van de end-of-life opties die geschikt voor conventionele kunststoffen, kunnen gecertificeerde biologisch afbreekbare plastic producten ook worden gecomposteerd, vergist of

biologisch afgebroken op landbouwgrond. Industrieel composteren, dat wordt beschouwd als een vorm van organische recycling, is een kosteneffectieve verwerking van organisch huishoudelijk GFT-afval. Vandaag de dag komt een aanzienlijke hoeveelheid huishoudelijk afval in de grijze bak (voor restafval) terecht en wordt verbrand terwijl het keuken afval relatief nat is waardoor verbranding minder energie-efficiënt is in vergelijking met compostering. Daarom is een bijzonder voordeel van biologisch afbreekbaar plastic verpakkingen en (vuilnis)zakken dat ze kunnen helpen om een groter deel van huishoudelijk groeten- en fruitafval te verzamelen ten behoeve van compostering. Onduidelijke communicatie kan er echter voor zorgen dat mensen niet-composteerbare zakken daarvoor gaan gebruiken, waardoor de hoeveelheid van dit plastic in de organische afvalstroom toeneemt. Momenteel bestaat ongeveer 1% van de huishoudelijke GFT afvalstroom uit niet-biologisch afbreekbaar plastic. Nederlandse afvalverwerkers aarzelen nog met het aanvaarden van biologisch afbreekbare plastic verpakkingen anders dan de composteerbare plastic zakken met bioafval omdat zij bang zijn voor insleep van meer niet-bioafbreekbare plastics (omdat de consument het verschil tussen composteerbaar en niet-composteerbaar plastic niet kent). De Vereniging Afvalbedrijven en Holland Bioplastics zijn in gesprek over een convenant over de acceptatie van composteerbare plastics in de GFT-afvalstroom.
Bioafbreekbare plastic verpakkingen die niet mechanisch worden gerecycled en die geen voordelen geven in het composteringsproces kunnen verbrand worden met energieterugwinning.

Inzameling en sortering van plastic begint bij consumentengedrag en bepaalt voor een groot deel de (energie) efficiency van de afvalsystemen. Om consumenten te helpen bij het kiezen van de juiste afvalroute voor verpakkingen kunnen pictogrammen worden gebruikt om de voorkeursroute aan te geven. In verband hiermee is in Nederland onlangs een nieuw pictogram ingevoerd dat aangebracht kan worden op composteerbare verpakkingen die zijn gecertificeerd volgens EN13432 en dat aangeeft dat de verpakking in de GFT container mag.

<u>Duurzaamheidsvraagstukken</u>
Het land dat nodig is voor het verbouwen van de grondstoffen voor de momenteel geproduceerde bio-based plastics bedraagt wereldwijd ongeveer 0,02% van het bouwland gebied. Indien de totale huidige wereldwijde fossiele kunststofproductie gebaseerd zou worden op biomassa zou de vraag naar deze grondstoffen in de orde van 5% van de totale jaarlijks geoogste hoeveelheid biomassa zijn. Maar een dergelijk scenario is onwaarschijnlijk omdat de verwachting is dat de industrie technologieën zal ontwikkelen die alternatieve grondstoffen uit afval en reststromen van de landbouw en voedselproductie kunnen gebruiken, zoals bijvoorbeeld niet-eetbare lignocellulose grondstoffen voor chemische bouwstenen. Recent onderzoek laat zien dat een duurzame co-productie van biobrandstoffen (en bio-based plastics) en voedsel mogelijk is en dat de productie van biobrandstoffen kan dienen als stabilisator voor de voedselprijzen. Een verdere relatie tussen voeding en bio-based plastics is dat sommige van deze kunststoffen, zoals

PLA, barrière-eigenschappen hebben die kunnen helpen voedsel langer vers te houden en daarmee de houdbaarheidsdatum verlengen.

De milieu-impact van bio-based plastics en fossiele brandstoffen gebaseerde kunststoffen vindt plaats in verschillende impactcategorieën. Substitutie van fossiele plastics door bio-based plastics leidt in het algemeen tot lager gebruik van niet-hernieuwbare energiebronnen (NREU) en broeikasgassen (BKG). De reductie in uitstoot van broeikasgassen kan echter negatief beïnvloed worden door directe en/of indirecte veranderingen in landgebruik. De broeikasgasemissie reductie die wordt bereikt met bio-based plastics is in het algemeen aanzienlijk groter dan die van biobrandstoffen. Voor de categorieën met betrekking tot de landbouw, zoals eutrofiëring en verzuring, hebben bio-based plastics over het algemeen een grotere impact dan fossiele kunststoffen. Omdat er grote verschillen in effecten zijn, zowel in de familie van bio-based plastics als in de familie van fossiele kunststoffen, kan geen absolute regel gegeven worden.

Genetisch gemodificeerde (micro-) organismen (GMO's) zijn niet nodig voor de productie van veel bio-based plastics. Biomassa is meestal niet-GMO, hoewel in sommige landen meer GMO gewassen geteeld worden. In de VS is bijvoorbeeld een betrekkelijk groot aandeel maïs GMO. Een mix van GMO en niet-GMO maïs wordt gebruikt om PLA te produceren. Voor de productie van PLA is echter geen GMO maïs vereist. Sommige monomeren zoals barnsteenzuur en 1,3-propaandiol en een polymeer als PHA kan worden geproduceerd via fermentatie met GMO stammen. Echter, de fermentatie wordt meestal uitgevoerd in gesloten systemen, zodat de GM-organismen onder controle gehouden kunnen worden (witte biotechnologie). De omzetting van houtachtige biomassa naar suikers voor de productie van tweede generatie polymeren wordt vaak uitgevoerd met behulp GMO stammen (in gesloten systemen).

Biologisch afbreekbare kunststoffen zijn geen oplossing voor het probleem van zwerfafval en de ‘plastic soep’. Aan de andere kant kan de biologische afbreekbaarheid een nuttige eigenschap zijn voor specifieke marine- en bodem-gerelateerde toepassingen zoals vislijnen en mulch films. Wanneer ze op zee verloren gaan of wanneer ze slechts gedeeltelijk van het land ingezameld kunnen worden, zullen Marine en Soil biologisch afbreekbare plastics tenminste resulteren in een lager risico op schadelijke gevolgen dan wanneer ze niet af te breken. Aangezien een gecertificeerde claim zoals OK biodegradable MARINE of OK biodegradable SOIL consumenten gemakkelijk kan stimuleren om een gecertificeerd product in het milieu achter te laten, moet een duidelijk onderscheid worden gemaakt tussen de certificering van de claim en toestemming te communiceren over deze certificering.

Content

1 Introduction and definitions

1.1 Introduction

The term bioplastic refers to either the bio-based origin of a plastic or to the biodegradable character of a plastic. Bio-based and biodegradable are not synonymous (see Figure 1) and therefore the term bioplastic is confusing. It is more clear to specify which of the two aspects, or whether eventually both, are applicable. Like fossil-based plastics, bio-based plastics are available in many grades with a wide variety of properties (Molenveld, 2015). Therefore, this report makes a clear distinction in between bio-based and biodegradable plastics and the properties, possibilities and limitations of bio-based and biodegradable plastics will be discussed per type and class of plastic.

This report starts with an introduction on the most important definitions related to bio-based and biodegradable plastics since using clear definitions helps to reduce and prevent misconceptions and it will enable discussions on facts and figures of bio-based and biodegradable plastics.

	Petrochemical	Partly bio-based	Bio-based
Non-biodegradable	PE, PP, PET, PS, PVC	Bio-PET, PTT	Bio-PE
Biodegradable	PBAT, PBS(A), PCL	Starch blends	PLA, PHA, Cellophane

Figure 1. Diagram indicating positioning of bio-based versus petrochemical plastics and biodegradable versus non-biodegradable plastics.

1.2 Bio-based

'Bio-based' is defined in European standard EN 16575 as 'derived from biomass'. Therefore, a bio-based product is a product wholly or partly derived from biomass. Biomass is material of biological origin, excluding material embedded in geological formations and/or fossilized (EN 16575, 2014). Examples are paper and wood, but also plastics such as PLA whose building blocks are produced from sugars. The bio-based carbon content in a material can be measured according to e.g. ISO 16620-4 or EN 16640. The bio-based content of a material can be determined with EN 16785-1 (see Appendix B for more information).

1.3 Renewable

Consumed feedstock may be called renewable when it is collected from resources which are naturally replenished on a human timescale (Ellabban, 2014), in contrast to fossil oil which takes millions of years to be formed. Bio-based feedstock can be called renewable as long as new crop cultivation balances harvesting. For instance, peat is not considered renewable due to slow regeneration rate, and tropical hardwood only is renewable when well managed (UN, 1982). Consequently, bio-based is not intrinsically 'renewable'.

1.4 Petrochemical / fossil

Petrochemical or fossil plastics are made of fossil feedstocks like petroleum and natural gas (EIA, 2016) which has taken millions of years to be formed. Nowadays, about 7% of all petroleum is converted into plastics (European Bioplastics, 2015; IEA, 2016). Examples of fossil-based plastics are polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS) and others. Whereas presently these materials are predominantly made from fossil feedstock, they could also be produced from biomass, and would then be bio-based.

1.5 Biodegradable

Biodegradable materials are materials that can be broken down by microorganisms (bacteria or fungi) into water, naturally occurring gases like carbon dioxide (CO_2) and methane (CH_4) and biomass (e.g. growth of the microorganism population). Biodegradability depends strongly on the environmental conditions: temperature, presence of microorganisms, presence of oxygen and water. So both the biodegradability and the degradation rate of a biodegradable plastic product may be different in the soil, on the soil, in humid or dry climate, in surface water, in marine water, or in human made systems like home composting, industrial composting or anaerobic digestion. (Van der Zee, 1997; OWS, 2013).

1.6 Compostable

Compostable materials are materials that break down at composting conditions. <u>Industrial composting</u> conditions require elevated temperature (55-60°C) combined with a high relative humidity and the presence of oxygen, and they are in fact the most optimal compared to other everyday biodegradation conditions: in soil, surface water and marine water. Compliance with EN 13432 is considered a good measure for industrial compostability of packaging materials, a.o. biodegradable plastics. According to the EN13432 standard, plastic packaging can only be called compostable if it is demonstrated that:

- The packaging material and its relevant organic components (>1 wt.%) are naturally biodegradable;
- Disintegration of the packaging material takes place in a composting process for organic waste within a certain time;
- The packaging material has no negative effect on the composting process;
- The quality of the compost is not negatively influenced by the packaging material.

At <u>home composting</u> conditions, temperature is lower and less constant compared to industrial composting conditions due to the smaller amount of compostable material. As a result of the lower temperature, the degradation rate of a material is (much) slower compared to industrial composting, depending on the type of material. Vinçotte has its own test standard for certification of home compostable materials. An EN standard is currently being developed (De Wilde et al, 2016).

1.7 Recycling

Material recycling is defined in European standard EN 13430 and EN 16848 (adapted from ISO 18604) as the reprocessing of a used product material into a new product. An example is plastic which after use can be collected, sorted and reprocessed into new products (see section 5.1). This type of recycling is called mechanical recycling. Another option is chemical recycling where materials are broken down to monomers which can be used again for the production of polymer. An example is the Loopla process developed by Galactic were PLA is hydrolysed to lactic acid (Looplife, 2016).

Within the EU Directive 94/62/EC of 20 December 1994, composting and anaerobic digestion (biogasification) are considered a specific form of material recycling, which is sometimes referred to as 'organic recycling' (EU, 1994). In the Dutch National Waste Management Plan 2017 – 2029 (LAP3), conversion of organic material into compost is even considered as equivalent to material recycling (LAP3, 2017). Energy recovery and the use of the product as a fuel is not considered recycling, although it may be a good option for specific plastic waste streams (also see section 5.3).

Reuse means that the packaging product is used again. In the past in the Netherlands large PET bottles were reused. Nowadays, these refund PET bottles are mechanically recycled. Some glass refund bottles are still on the market.

1.8 Durability and Sustainability

In Dutch, the term *'duurzaamheid'* is used for both durability as well as sustainability. As durability and sustainability have very different meanings, it needs to be considered that the Dutch word *duurzaamheid* may cause confusion.

Durability refers to the ability of a material to offer its performance for a long period without significant deterioration by resisting the effects of use and ageing. The durability of a plastic does not depend on the origin of the feedstock, but on the type of chemical structure of the polymer and on the conditions the plastic is subjected to. Bio-PE and bio-PET have the same durability as fossil-based PE and PET.
Sometimes, plastic materials are referred to as durable, as opposite to biodegradable. However, it may be noted that f.i. PLA can be durable at indoor conditions (life span of 10 – 20 years) and biodegradable at industrial composting conditions.

"Sustainability is defined as a requirement of our generation to manage the resource base such that the average quality of life that we ensure ourselves can potentially be shared by all future generations. ... Development is sustainable if it involves a non-decreasing average quality of life" (Asheim, 1994).

2 Appearance and recognition

> *"How can I see the product is made of bio-based and/or biodegradable plastic?"*

Mainstream consumers often do not know that different types of plastic are on the market. And even when they are aware: Due to their similar appearance bio-based and/or biodegradable plastic products often cannot be easily distinguished from conventional fossil-based (non-biodegradable) plastic products. The bio-based and/or compostable characteristics of a plastic, however, can be measured. Logo's and labels can be used to make clear to the consumer whether a plastic is bio-based and/or compostable, and even more important, how to dispose of the plastic after use. Such logo's and/or labels will need to be linked to a certification system.

The qualification 'biodegradable' is an isolated claim and not unambiguously defined. Consequently, the term may cause confusion about the proper way for disposal of the plastic by the consumer. Moreover, even when a plastic is biodegradable, this does by no means imply that the material degrades in the environment in a short period of time. Therefore, correct claims are linked to regulations specifying biodegradation conditions and time.

'Industrial Compostable' is a regulated term, see section 1.6. Products which meet EN 13432 may carry the seedling logo and may be disposed of in the green bin (Figure 2; Also see sections 5.2 and 5.4). There are two organisations in Europe that provide certifications and corresponding labels based on this standard: DIN Certco and Vinçotte. Certified products are listed on their respective websites [1]. Identifiers connected to the seedling logo refer to the certificate number and identifies the certified product and the producer. The initial 2 characters of the identifiers relate to the type of product:

- 7P and 9G = Product from compostable material for industrial composting
- 7H and 9L = Semi-finished products from compostable material for industrial composting
- 7W and 9K = Compostable material for industrial composting
- 7Z = Compostable additive
- 9P = Product from compostable material for home and garden composting
- 9R = Compostable material for home and garden composting

In line with other labels for end-of-life disposal, like Plastic Heroes for recycling of plastics, a new label to indicate that a plastic may be disposed of in the GFT bin has been developed (Figure 3). The label consists of 3 parts: at the top it is indicated what the label refers to, either the packaging or part of the packaging, in the middle an icon indicates the preferred disposal route, and at the bottom the preferred disposal route is presented in words.

[1] *DIN Certco:* *http://www.dincertco.tuv.com/search/companies_with_product?locale=de&title_id=85*
Vinçotte: *http://www.okcompost.be/en/certified-products/*

Figure 2. Examples of labels showing that products are compostable according to EN13432: OK Compost by Vinçotte (left); Seedling logo and DIN Geprüft logo by DIN Certco (middle and right).

Figure 3. Example of label for end-of-life disposal in the GFT bin (KIDV, 2016).

For clear communication regarding the bio-based <u>carbon</u> content, claims must be supported by a standard test method which specifies the calculation method for determining the bio-based <u>carbon</u> content in plastic materials, e.g. the EU standard EN 16640 (2015) or ASTM D6866. These methods are based on measuring the biogenic carbon content, using ^{14}C content measurement (see Appendix B). How the measured amount of biogenic carbon is expressed as a percentage in the product, however, varies between different methods and certification schemes. The EN 16640 standard expresses the carbon as a percentage of total carbon, the ASTM D6866 standard as a percentage of total organic carbon. The ISO 16620-4 (2016) method expresses the bio-based carbon as percentage of polymeric carbon. Materials certified as bio-based, based on these standards, may bear the labels as indicated in Figure 4. The DIN Certco label is based on the EN standard, the Vinçotte and USDA label are based on the ASTM standard. It may be noted that despite these institutes measure the bio-based carbon content, they label it as the bio-based content. This can be confusing since the bio-based carbon content is something different from the bio-based content, which is discussed in the next paragraph.

Figure 4. Examples of labels of Din Certco, Vinçotte and the USDA, to indicate that a material has bio-based content.

Substantiations of <u>bio-based content</u> claims must be supported by the EN16785-1 test method, which specifies the calculation method for determining the bio-based content in plastic materials. The method is based on the ^{14}C method, elemental (O, H and N) analysis, and producer declarations. A certification scheme, NCS 16785 (2016)[2], has recently been launched by NEN. The label which shall be used on the certified product is indicated in Figure 5.

Figure 5. Example of label for bio-based content of a product, indicating the content, the product it refers to and a unique registration number (NCS 16785, 2016).

Vinçotte also publishes a list of deceptive use or misuse of the labels (Vinçotte, 2016a).

Unfortunately, there are so many labels that these may merely confuse, rather than inform, consumers. European standards are currently being developed to provide guidance in how to communicate the aspects of bio-based products in business to business relations (B2B) and to the consumers (B2C):

- EN 16848:2016 Bio-based products - Requirements for Business to Business communication of characteristics using a Data Sheet
- EN 16935:2017. Bio-based products - B2C reporting and communication - Requirements for claims

When other environmental benefits are claimed for a product or material, accountability is of major importance in order to prevent green washing and falsified claims. More info can be found at European Bioplastics (2014).

[2] *http://www.biobasedcontent.eu/en/certification-documents/*

3 Availability and cost

3.1 Availability

Production data for bio-based and biodegradable plastics are available to a limited extent only. Production *capacity* data are more readily accessible. The Institute for Bioplastics and Biocomposites in Hannover and the Nova Institute together with European Bioplastics have published production capacity data for 2015/2016 (IfBB, 2016; EuBP, 2016). The averages of the data per type of plastic are presented in Figure 6. Although it is difficult to retrieve accurate numbers for production capacities, it is assumed that these data provide a good indication of the range.

The study by IfBB also provides projected production capacity for 2020 (Figure 6). These data can basically be seen as a general thermometer for intentions of producers to increase their production capacities. The markets for Bio-PET, PBAT/PBS/PCL and PLA are expected to grow, whereas others like CA, Bio-PE, Starch and Bio-PA are expected to consolidate, or the present production capacity for these materials may leave sufficient space for increased demand.

Like for the bio-based and biodegradable plastics, also for fossil plastics it is difficult to find accurate global production data per type of plastic. Global production data for fossil are taken from Wikipedia (Wiki, 2016) and Plastics Europe (2015). From these data it appears that the production capacities for bio-based and biodegradable plastics only account for slightly less than 1% of total global plastics production (Figure 7). This bio-based and biodegradable plastics share found is in the same range as presented in market studies issued by Nova Institute (Nova, 2013; Nova 2015).

At a steady growth of the fossil plastic production as foreseen by PlasticsEurope and the Ellen MacArthur Foundation, and assuming the projected bio-based and biodegradable plastic production capacity as presented by IfBB in 2020, bio-based and biodegradable plastics would account for 9.410/370.000 = 2.5% of fossil plastics production (PlasticsEurope, 2015; EMF, 2016). This means that bio-based and biodegradable plastic are increasing their share.

For most of the bio-based and biodegradable plastics there are several suppliers (Table 1) and in general, bio-based and biodegradable plastics are readily available but this may vary for specific types. Table 1 includes an indication on availability as based on WFBR experience.

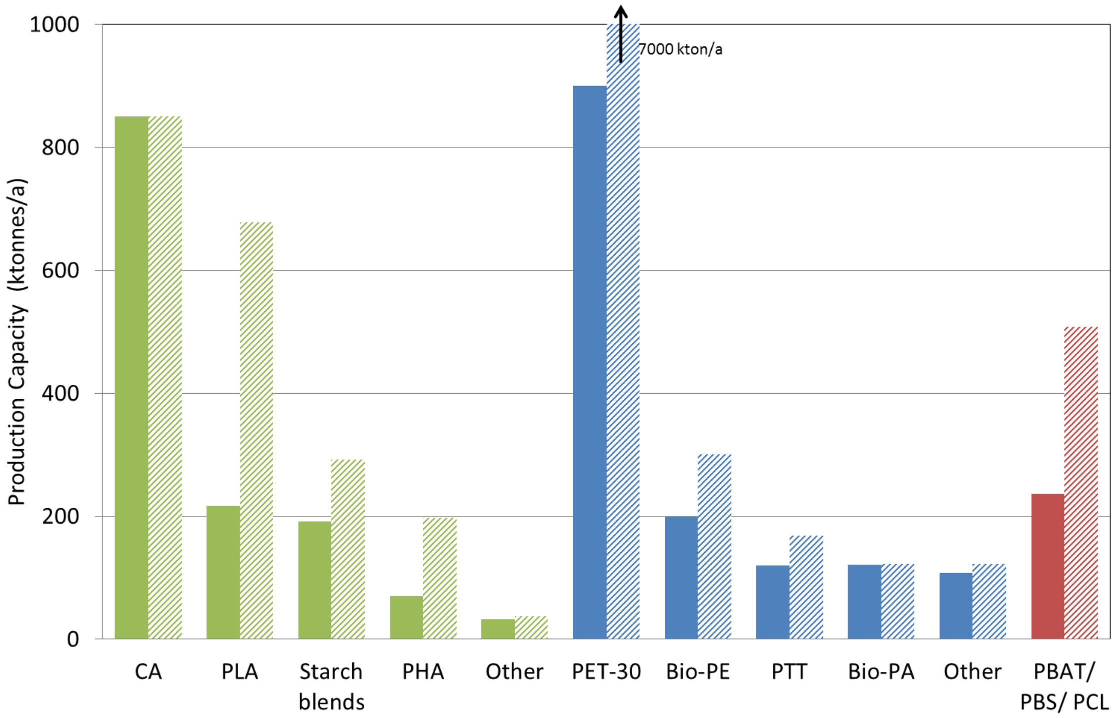

Figure 6. Global production capacity data[3] in 2015/2016 (solid bars) and announced production capacities for 2020 (shaded bars) of bio-based biodegradable polymers (Green), bio-based non-biodegradable (drop in) polymers (Blue) and fossil-based biodegradable polymers (Red) (IfBB, 2016; EuBP, 2016).

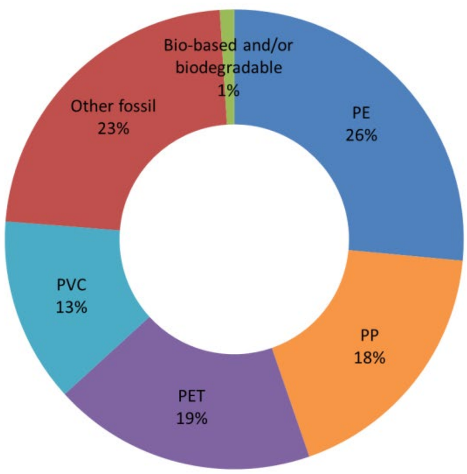

Figure 7. Global bio-based and biodegradable production capacity data in 2015 and fossil plastic production data at different years in the period 2007-2016: Shares of 302.000 ktonne in total (IfBB, 2016; EuBP, 2016; Wiki, 2016; PlasticsEurope, 2015).

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[3] *Starch blend value indicates starch fraction only, based on IfBB data.*

Table 1. Availability of bio-based and biodegradable plastics as experienced by WFBR and global number of producers per type of bio-based and biodegradable plastic (Nova Institute, 2015).

Polymer type	# producers 2013	Availability 2016	Comments
CA	17	Good	Has been on the market for a long time, limited applications in food packaging
Bio-PA	9	Good	Increasing number of producers and grades. Limited applications in food packaging.
Bio-PE	1	Sufficient	In Europe bio-PE produced by Braskem is currently distributed by FKuR, Resinex, Mibepa and Polydist for specific regions.
Bio-PET	5	No experience	FKuR markets bio-PET in Europe
PBAT	4	Sufficient	With previous capacity expansions, available volumes seem sufficient. Food contact approved.
PBS	10	Sufficient	Increasing, but since most PBS is produced in Asia it is sometimes difficult to acquire. Some grades are food contact approved and some grades are 50% bio-based.
PHA	14	Poor	Small enterprises
PLA	28	Good	Has been on the market for a long time and in a broad variety of grades. Increasing production capacity and new producers expected. Food contact approved.
Starch blends	15	Sufficient	Various suppliers, broad range of grades and technologies. Not all grades are food contact approved.

3.2 Costs

"Are bio-based and biodegradable plastics cost competitive today?"

In general, bio-based and biodegradable plastics are more expensive then fossil-based plastics on weight basis (Table 2 and Table 3). Also, most bio-based plastics have a higher density that contributes to this higher price. However, there are exceptions when prices are compared on a product level. Redesign and specific material properties can allow material savings, e.g. due to the higher stiffness of PLA compared to PS, PLA products can be down-gauged in thickness (e.g. Danone dairy cup). For instance, a traditional HIPS based cup of 0.89 mm wall thickness could be down-gauged using impact modified PLA to 0.66 mm thickness

(Schut, 2016). In agriculture, labour cost can be reduced, e.g. by replacing PE mulch film by soil biodegradable plastic mulch film. Moreover, it may be mentioned that PE mulch films are produced a factor 2 thicker than required for the actual purpose of covering the soil, just in order to allow removal of the film after use. In the higher market segments (engineering plastics) there are various examples were bio-based engineering plastics are competitive as compared to fossil-based engineering plastics. Replacing high heat ABS by Durabio (bio-based PC) in a dash board part of a Renault Clio results in a saving of 0,40 €/part (Roma, 2016).
The price of fossil-based plastics is depending on oil prices and fluctuates with oil prices (Figure 8). In general the prices of bio-based plastics are more stable. If oil prices are high a commodity plastic like PS is more expensive than PLA (Figure 9). However, even today with low oil prices, PLA prices in the US are very close to market prices of general purpose PS and PET (Vink, 2016). It is expected that the prices of bio-based plastics will drop in the near future when the economy of scale of production, conversion into products and logistics becomes more favourable. A good example is bio-PBS. Since succinic acid can be produced more efficiently from biomass than from fossil feedstock it is expected that with an increasing production volume the price of bio-PBS will drop from 4 to 2.5€/kg. Drop-in plastics like bio-PE are marketed at a premium price although producer Braskem claims that the production is competitive.

Table 2. Price level for bio-based and/or biodegradable plastics in 2016 based on WFBR experience.

Plastic	Price level 2016 (€/kg)	Density (kg/m^3)
CA	5	1200 – 1300
Bio-PA	+ 10 – 20%	1040 – 1190
Bio-PE	+ 20 – 40%	910 – 970
Bio-PET	No information	1370 – 1390
Bio-PP [4]	+ 80 – 100%	900 – 920
PP (certified bio) [5]	+ 40 – 50%	900 – 920
PBAT	3.5	1250
Bio-PBS	4	1260
PHA	5	1200 – 1250
PLA	2	1250
PTT	4	1320
Starch blends	2 – 4	1250 – 1350

[4] *FKuR markets bio-PP (Terralene) with a bio-based content of about 30%. This material is a blend of conventional PP with bio-based HDPE.*
[5] *Some PE and PP materials are marketed as certified bio-based (via mass balance methods, see Appendix B), which is at odds with the definition of bio-based since it is not possible to measure the bio-based content in such plastics.*

Table 3. Price level of fossil-based plastics in 2016 (Vraag en aanbod, 2016).

Plastic	**Price level 2016 (€/tonne)**	**Density (kg/m^3)**
LDPE	1250 – 1450	910 – 940
HDPE	1200 – 1500	930 – 970
HIPS	1350 - 1525	1080
PET	850 – 1050	1370 – 1390
PP	1000 – 1200	900 – 920
PS	1250 – 1430	1040
PVC	800 – 930	1100 – 1450

Figure 8. Comparison daily crude oil prices with the daily prices of HDPE and LLDPE by PetroChemWire (copied from Langan, 2011).

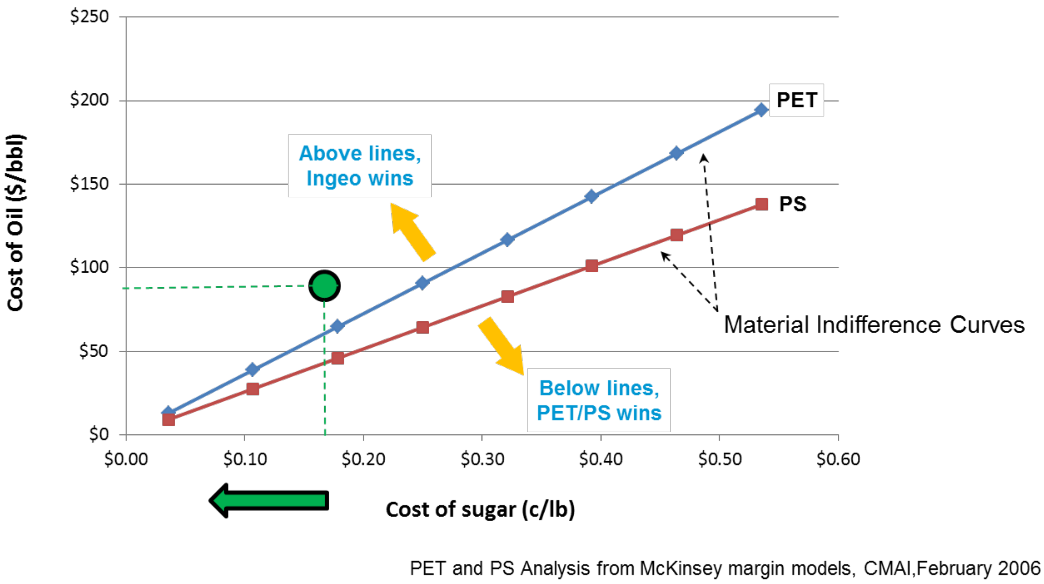

Figure 9. Comparison of PLA price versus PS and PET prices at given crude oil and sugar feedstock prices (copied from Verbruggen, 2013).

4 Packaging of food

4.1 Introduction

The main applications of bio-based and biodegradable plastics are currently in (food) packaging, food service ware, (shopping) bags, fibres/nonwovens and agricultural applications. This can be explained by the history of many bio-based and biodegradable plastics. These materials were developed to reduce plastic waste and are biodegradable or rather compostable. Target applications were in products with a relatively short functional life (packaging and disposables) and in applications where biodegradability was beneficial (agriculture). The more recently developed bio-based non-biodegradable plastics (bio-PE and bio-PET) are also mainly used in food packaging. The increasing awareness of the environmental impact of packaging products and a willingness to replace packaging materials by alternatives with e.g. a lower carbon footprint or made from renewable resources are the main driver for development and the use of these materials.

This chapter focusses on the suitability of bio-based and biodegradable plastics for food packaging and issues and questions from consumers, retail, packaging companies and food producers. Examples of existing questions are:

- How do bio-based and biodegradable plastics influence the shelve life of food products?
- How safe are bio-based and biodegradable plastics?

The "Bio-based packaging catalogue" (Molenveld and Van den Oever, 2015) answers many of these questions by giving background information regarding bio-based plastics but also by showcasing existing examples of bio-based packaging products. The catalogue also shows that bio-based and biodegradable plastics are a large family of materials with widely varying properties, as are fossil-based plastics.

To efficiently and clearly discuss the suitability of using bio-based plastics as food packaging material, in this chapter most attention will be given to the 3 most commonly used bio-based plastics with unique properties. After this also attention will be given to drop-in plastics and new developments. An overview table in section 4.8 summarises this chapter giving information on application fields, fossil counterparts, packaging types and some specific comments.

4.2 Polylactic acid (PLA)

Polylactic acid (PLA) is a 100% bio-based plastic that is widely used in packaging applications. Since most PLA grades are readily industrially compostable for thicknesses of up to 2 – 3.2 mm (depending on the grade), PLA is very suitable for the manufacture of compostable packaging products. Specific benefits of PLA in packaging applications are its transparency, gloss, stiffness, printability, processability and excellent aroma barrier. PLA is a rigid material with (mechanical) properties that are comparable with Polystyrene (PS) and Polyethylene Terephthalate. PLA is approved for direct contact with food (NatureWorks, 2016a) and is applied in a range of packaging products (NatureWorks, 2016b). PLA is frequently used in combination with other bio-based and or biodegradable polymers to improve stiffness and strength and to reduce costs.

4.2.1 PLA film

PLA films are highly transparent and are used in packaging materials as a homo material (a.o. biaxially oriented PLA (BOPLA) films for packaging of products) and as laminates (barrier films). PLA films are not flexible like LDPE films, but rather stiff (comparable to PET and cellophane films) and can be sensitive to tearing.
In packaging of (cut) vegetables and fruit, BOPLA films can replace biaxially oriented PP (BOPP) films. In this application the BOPP films are perforated to increase the water permeation to the required level. The higher water vapour permeability of BOPLA is an advantage. Additionally the PLA films can be industrially composted with the fruit and vegetable waste.

Without additional barrier materials PLA is not suitable for the packaging of water sensitive products that will be stored over longer periods. Examples are products like cookies (long shelve life) or bread that is put in the freezer. These products need a high water vapour barrier and are usually packed in PE film. Plastics with a lower water vapour barrier like PLA (but also PET) are not suitable in these applications. Fresh bread that is still warm from the oven however will benefit from the low vapour barrier of PLA.
When PLA films are used in laminates with barrier materials or when SiOx or AlOx technologies are used it is possible to construct materials with good barrier properties for a wide range of applications (including crisps and coffee) while still maintaining compostability. As an example, NatureWorks and Metalvuoto announced a new generation of high barrier PLA based flexible substrates designed to keep processed foods fresh on store shelves. While PLA film has been used for years in fresh food packaging, this is the first application for longer shelf life foods that are increasingly packaged in flat, stand up, or squared bottom pouches (NatureWorks, 2016c).

4.2.2 PLA trays and other thermoformed products

PLA trays are highly comparable to polystyrene (PS) trays and can be used to pack fruits like strawberries, and vegetables like mushrooms. In this application barrier properties are not important. PLA thermoformed cups are also very suitable to replace PS in dairy product cups. The high stiffness of PLA allows a reduction in wall thickness of the products and the packaging can be composted with its (remaining) content. For further weight reduction, also foamed PLA trays and cups can be used.

4.2.3 PLA bottles

Bottle applications are not actively promoted by PLA producers. Still, PLA can be used for the production of bottles that have a very similar look and feel as PET bottles. The barrier properties of PLA (higher water permeability) are not sufficient to replace PET in long shelf life applications. Today, PLA is only used in small (< 1 litre) water bottles (Italy). In the US it has

been used for bottles for short shelve life (cooled) juices. PLA is not suitable for packaging of soda without adding a proper barrier layer (multilayer, SiOx).
The company KHS has reported that when using SiOx technology it is possible to produce PLA bottles with excellent barrier properties (Klages, 2013). The SiOx technology is rather expensive and has not been implemented for PLA bottles. Alternatively, PLA based barrier bottles can be produced using Polyglycolic acid (PGA) (Kuredux, 2011). The advantage of PGA is that the material is biodegradable but can also be removed during mechanical recycling using alkaline washing.

4.2.4 Other packaging products
An innovative PLA product are teabags. These are based on PLA non-wovens and can be industrially composted together with the tea waste. The material replaces paper based teabags that commonly contain about 20-30% PP fibre to allow heat sealing. Despite ending up in home and in industrial composting systems, current PP containing tea bags are not compostable. Similarly, various companies market compostable coffee capsules. Most of these compostable capsules are based on PLA.
An EPS resembling expandable bead foam based on PLA (EPLA), is used in various packaging products (included ice packaging). EPLA foam is certified industrially compostable and is allowed for direct contact with food.

PLA is widely used in food service ware (cups, plates and cutlery) and products vary from transparent cups for cold drinks to paper cups coated with PLA, various plates and cutlery types. In this applications PLA replaces PS, PP en PET (cups and cutlery) and PE (coating for paperboard). The advantage here is that mixed food / food service ware waste stream can be industrially composted without separation of components.

4.3 (Biodegradable) Starch based plastics
Starch based plastics are complex blends of starch with compostable polyesters (such as PLA, PBAT, PBS, PCL and PHAs) and additives like plasticisers and compatibilisers. Blending of starch with polyesters is necessary to improve water resistance, processing properties and mechanical properties. Commonly the starch content of starch based plastics is lower than 50% and the overall bio-based content of these materials depends on the nature of the other components. Starch based plastics are used in applications where biodegradability is an advantage like agricultural products (mulching films), service ware, garbage bags for green waste and carrier bags. The advantage is that these products can be composted together with the organic waste. Starch blends are generally compostable and various materials (depending on the other blend components) are also biodegradable in soil, anaerobic digestion installations, fresh water or marine environment. Not all starch blends are allowed for food contact applications and this depends on the presence of blend components that can potentially migrate out of the starch blend.

4.3.1 *Starch based films*

Starch based films can be translucent (not transparent) and are used in packaging materials as a mono layer and as laminates (for example barrier films in combination with cellulose). They are used in applications were transparency is not required. Starch films can be highly flexible when they contain flexible polyesters like PBAT. These materials are suitable for packaging of products like potatoes and carrots and also for grocery bags (Amcor, 2016; Novamont, 2016). In these applications the starch based films replace (perforated) PE and barrier properties are not important. New is the starch based candy wrapping of Mars that replaces BOPP (Biaxially oriented Polypropylene). In this application starch based films are combined with PLA films as an outer layer. Starch based films are frequently used in cellophane based barrier laminates to allow heat sealing. These types of laminates are used in pouches for products like cereals and cookies.

4.3.2 *Starch based trays and other thermoformed products*

Starch based trays (rigid or foamed) can be used to pack fruits and vegetables. Starch based trays are not transparent. Barrier properties are not important in this application so functionality is based on the mechanical properties and the end-of-life options. Since materials for thermoformed products need to be rigid, PLA can be used in the blend composition, whereas in films highly flexible fossil-based biodegradable polyesters are used. Since PLA is 100% bio-based in this application the overall bio-content of starch blends is higher than in films.
A specific type of foamed starch tray is Paperfoam™. Paperfoam is mainly used in packaging applications were product protection is important, for example in egg boxes but also in packaging of electronic devices. Paperfoam is certified compostable and is also allowed in paper recycling.

4.3.3 *Other packaging products*

Starch based materials are frequently used in loose fill foams for transport packaging.
Another application is in service ware (cups, plates and cutlery).

4.4 Cellophane

4.4.1 *Cellophane films*

Cellophane films are highly transparent, rather stiff and have been on the market for decades although their market share is small. Cellophane films can be coloured and are well known as candy wrappings. In this applications the dead fold [6] of cellophane films is a big advantage. Other applications include luxury films for flower wrappings and the glossy transparent films that cover tea boxes. Cellophane films cannot melt and this implies that the films have an excellent dimensional stability. This is used in the manufacture of laminates. The biodegradable (barrier) films are available in a wide range of grades, and a.o. they can be used to pack products ranging from cheese to coffee and chocolate.

[6] *Dead fold means that a plastic retains its twist after twisting.*

4.4.2 Other products based on cellulose

(Regenerated) cellulose, like cellophane is not a thermoplastic and only available as film or fibre (viscose). When extensively modified, cellulose can become thermoplastic. An example is cellulose acetate. This material is rather expensive and rarely used in packaging applications.

4.5 Biodegradable (and bio-based) polyesters

A variety of biodegradable polyesters has been developed in the eighties of the previous century. These biodegradable polyesters are predominantly based on fossil fuels. These materials are mainly used in combination with bio-based polymers like starch and PLA. The most frequently used biodegradable polyesters are PBAT, PCL and PBS(A). Partly bio-based PBS is commercially available.

4.5.1 Flexible films based on biodegradable polyesters

A large product group containing biodegradable polyesters are flexible films. Applications range from shopping bags, food packaging films, waste bags to mulching films. The predominantly fossil-based biodegradable polyesters are often combined with bio-based materials. Examples are:

- Starch based flexible films containing polyesters like PBAT to improve processability, water resistance and tear strength. The content of biodegradable polyesters is commonly 50% or more.
- PLA based flexible films containing polyesters like PBAT, PBS and PCL to reduce stiffness and improve tear strength. Again the content of biodegradable polyester is usually high (> 50%).

4.5.2 Trays and other thermoformed products

Biodegradable polyesters are used as a blend component in trays and thermoformed products, most commonly in combination with PLA. These products are non-transparent and the amount of biodegradable polyester used is considerably lower than in films.

4.5.3 Other packaging products

Biodegradable polyesters and blends are also used in coated paperboard for the production of plates, cups and other compostable paper-based packaging products. Moreover they can be found in other disposables like cutlery, straws, lids for coffee cups etc. For the packaging of vegetables and fruits compostable nets are available on the market. Coffee capsules are based on/or contain biodegradable polyesters for example in combination with PLA. New on the market is PLA/PBAT based particle foam for protective (heat and impact) packaging of various products.

4.6 Drop-in bio-based materials

At present drop-in bio-based materials are the fastest growing group of bio-based materials. The main materials used in packaging are bio-PE and bio-PET (bio-based content 30%). Since drop-in bio-based plastics are chemically identical to their fossil counterpart they can be used in exactly the same applications. Obviously, bottles are an important application for bio-PET and flexible films for bio-LDPE.

4.7 Developments

An important new bio-based material for packaging applications is PEF (polyethylene furanoate). The properties of PEF are highly similar to PET but the barrier properties of PEF are more favourable. Applications that are envisaged are in bottles and (barrier)films. Avantium and BASF established a joint venture and plan to construct a pilot plant for the production of PEF in Antwerp. Other companies active in the production of PEF are Dupont in cooperation with ADM and Corbion.

Another material group that is not yet commercially applied in (food) packaging applications are PHA's (polyhydroxy alkanoates). Although the properties of the material are promising (hydrophobic, high maximum usage temperature, versatility of properties) this material is not yet a commercial success due to price. At present various routes are explored to lower the price of PHA's including production from waste streams and up-scaling of biotechnological production.

4.8 Overview

'Which type of bio-based and/or biodegradable plastics are available for which application?"

There is a wide range of plastics and this is true for both fossil-based plastics and for bio-based plastics. A careful selection of the appropriate packaging material is always necessary. Issues with poor performance of bio-based plastics in general can often be related back to the wrong material selection.
The following tables can be used to select bio-based materials (Table 4 and Table 5).

Table 4. Overview table of suitable fossil and bio-based plastics for different property requirements.

Properties	Fossil plastic	Bio-based plastic
Flexibility and water barrier	PE	Bio-PE
Flexibility	PE	Starch based blends, Biodegradable polyesters
Transparency, stiffness, barrier properties	PET laminate or multilayer oxygen scavenger	PLA provided with SiOx barrier
Transparency, stiffness	PS, PET, PP	PLA
Stiffness	PS, PET	PLA, starch blend, Paperfoam

Table 5. Overview table of suitability of bio-based plastics for different types of applications.

	Film	**Rigids (Trays/Cups)**	**Bottles**	**Other**
PLA	e.g. (cut) vegetables & fruits, flower wraps, bread bags, shrink films. Not for long shelve life products, unless barrier laminates are used.	Salads, vegetables, fruits, dairy products, bakery, drinking cups, meat. Avoid storage of empty trays and cups at high temperatures.	Not a preferred material. Used in small water bottles and chilled, short shelf life juices and dairy products, and wine bottle capsules. Needs barrier materials for further applications.	Compostable teabags and coffee capsules. Coated paperboard (coffee cups) and other service ware. Foamed trays and boxes.
Starch blends	Food waste bags, translucent grocery bags. Vegetables and fruits. Mulch films.	Vegetables and fruits. Coffee capsules	N.a.	Loose fill foams. Service ware. Labels.
Cellulose based	Cellophane, candy wrapping	N.a.	N.a.	Some cellulose acetate in cutlery
Biodegradable polyesters	Grocery bags. Vegetables and fruits. Frozen produce.	Vegetables and fruits (non- transparent)	N.a.	Biodegradable nets. Coated paperboard. Particle foam. Coffee capsules.
Drop-in bio-PE	Shopping bags. Various packaging films.	Trays	Bottles for dairy products, shampoo and detergents	Coated paperboard for packaging of dairy products. Caps and closures.
Drop-in bio-PET	N.a. (yet)	N.a. (yet)	Various bottles for soda and water	N.a. (yet)

> *"Is shelf life of food in bio-based and/or biodegradable plastics shorter than with fossil-based plastics?"*

To ensure that a packed product has the required shelf life, a careful selection of packaging material is necessary. This holds true for fossil-based plastics as well as bio-based plastics. The oxygen barrier of various bio-based polymers is highly comparable to commodity plastics. If high oxygen barriers are needed it is necessary to apply specific barrier layers (EVOH, oxygen scavengers, SiOx, AlOx) just like for fossil-based barrier laminates. Except for bio-based polymers like bio-PE, in most cases the water vapour barrier of bio-based plastics is poor. In specific fresh products this is an advantage like for breathable vegetables and fruit (longer shelve life) and for fresh bakery products (just after baking, water vapour should escape in order to avoid the bread becoming wet), and PLA can be used for this application. For bakery products which are stored for longer periods, films with good water vapour barrier should be used (also see section 4.2.1). Figure 10 shows the barrier properties of various plastics. These are not absolute values but can (to some extent) depend on manufacturing processes (orientation) and specific grades. It can be seen that barrier properties differ from plastic to plastic. Whereas PE has an excellent water barrier (WVTR <1) its oxygen barrier is poor (OTR >1000). EVOH has an excellent oxygen barrier but only at low relative humidity (RH), the same is true for starch. To profit from the oxygen barrier of these materials they should be used in laminates were for example PE offers protection against moisture.

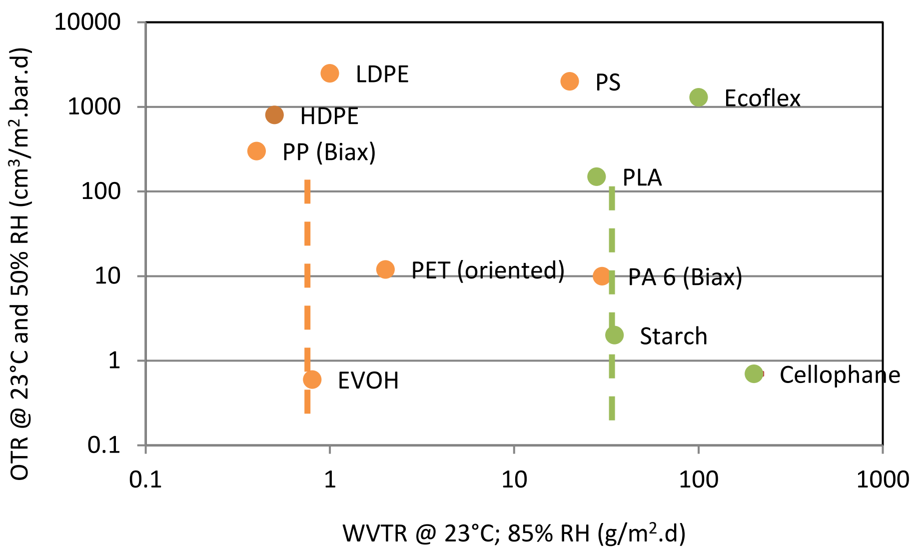

Figure 10. Barrier properties of various plastics commonly used in the packaging industry without the use of additional barrier coating (adapted from Schmid et al., 2012).

Generally, consumers are opposed to using (plastic) packaging of which it is not immediately clear what its function is. Consumers do see the downside (end-of-life) of using plastic packaging but are hardly aware of the benefits of using it. Since packaging materials add to the price of a product, producers have a natural barrier against over-packing. Still, for producers it is of utmost importance to maintain the quality of their product for as long as possible. This is why plastic packaging is very popular amongst producers. Plastic packaging helps to reduce (food) waste and in general the environmental benefits are much higher than the environmental costs. Although fresh products often have a peel that offers natural protection, still plastic packaging can further extend the shelve life and reduce food loss during transportation (Denkstatt, 2014). An example is the cucumber wrapped in a plastic film. Most consumers do not know that the purpose of the film is to extend the shelf life of the cucumber and so reduce food waste.

> *"For me there is no need to wrap organic bell peppers in plastic."*
>
> *"Cucumbers and bananas have a perfect shell that protects them."*

To ensure that (plastic) packaging materials can be safely used in contact with food, packaging materials have to comply with strict regulations. Bio-based and/or biodegradable plastics have to comply with the same regulations with respect to food safety. Many bio-based materials have certificates to proof that they can be used in food-contact applications. For specific bio-based materials it is more difficult to comply with food-contact regulations like for example for starch blends. Still, various starch blends are food-contact approved.

> *"How about food safety of bio-based and/or biodegradable plastics compared to conventional packaging materials?"*

5 End-of-life options

As with conventional plastics, the end-of-life options depend entirely on the application and the available infrastructure in the region where the product is to be recovered. Bio-based and biodegradable plastics are a large family of materials with widely varying properties. The most suitable end-of-life solution depends on the type of bio-based and biodegradable plastic and on the application it was chosen for. Apart from all the end-of-life options suitable for conventional plastics, various certified bio-based and biodegradable plastic products can also be composted.

5.1 Mechanical Recycling

Mechanical recycling of plastics involves the recovery of plastic waste through mechanical processes (separating, grinding, washing, drying, re-granulating and compounding) to produce recyclates that can be converted into new products. Opposed to organic and chemical recycling, mechanical recycling aims to reuse plastics on a material level and not on a building block level.

> *"To what extent can bio-based and/or biodegradable plastics be recycled, and is the amount large enough for a separate recycle stream?"*

The mechanical recycling of post-consumer plastic packaging waste is challenging. Post-consumer plastic waste is either separately collected by municipalities or mechanically recovered from municipal solid waste (MSW) (grey bin). The collected and recovered plastic concentrates are subsequently sorted into various 'sorted products'. Commonly sorted products include: Plastic Film, HDPE, PP, PET and mixed plastics. These are the sorted plastic products with sufficiently large volume to be economically mechanically recycled. Most other fossil and bio-based plastic types can be mechanically recycled, but at present their volume is not large enough. The mechanical recycling companies convert these sorted products into recyclates using processes like washing, density separation (float sink separation) and compounding. Additional separation technologies like flake sorting based on colour or NIR, and fine sieving, will improve the purity of the milled goods. However these technologies add costs and reduce the recycling yields. The recyclates are used in a broad variety of products including plastic lumber, piping, garden furniture and pallets. With the exception of PET bottle recyclates that have undergone advanced recycling processes, all post-consumer plastic recyclates are not used in food packaging products, a.o. because of food-safety regulations. This implies that in food packaging applications there is always a need for virgin materials.

> *"Assuming that recycling is performing well, is there a need for bio-based and/or biodegradable plastics?"*

Figure 11 shows a simplified process scheme for the sorting of post-consumer plastic packaging materials. In the first step organic contaminants and small plastic fragments are removed by screening. In the second step a plastic films concentrate fraction is collected by wind sifting. NIR sorting machines are used to separate the plastic objects on main plastic type. Sorted PET is upgraded (manually) by removing PET trays. The main products of a packaging sorting facility with product examples are:

- Film (DKR 310): flow packs, carrier bags other packaging films
- HDPE (DKR 329): flasks (food packaging and non-food packaging)
- PP (DKR 324): trays and pots
- Mixed Plastics (DKR 350): PS, PET trays, laminated flexible packaging, etc.
- PET (DKR 328-1): bottles and flasks
- Waste: PVC, black plastic, small plastic fragments, other waste

Sorting of cans (metal) and paperboard products (PMD collection) can be integrated in the packaging sorting schemes.

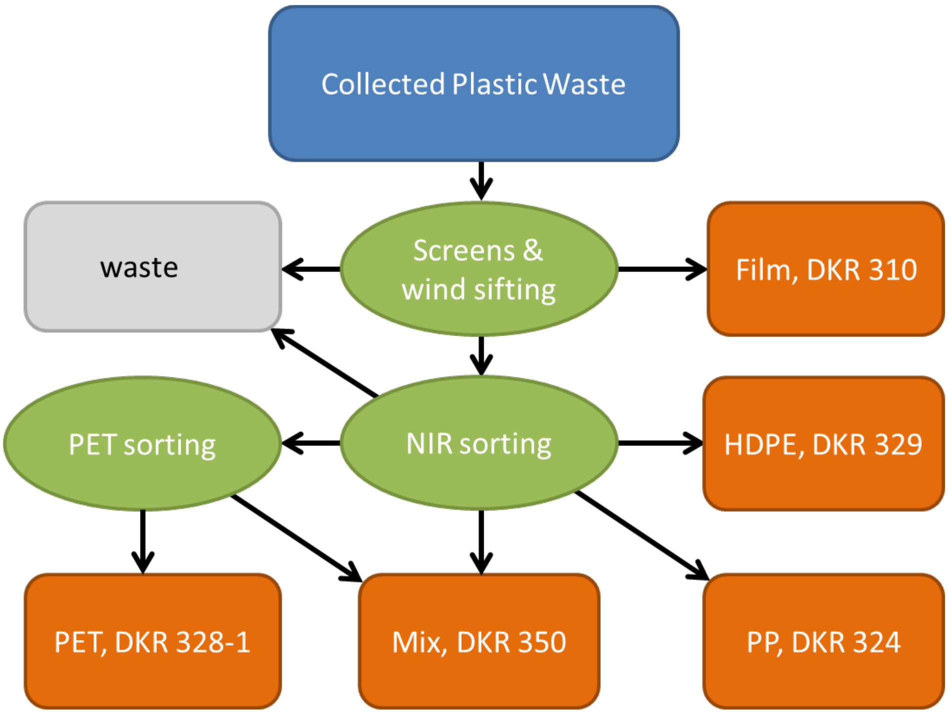

Figure 11. Simplified sorting scheme for post-consumer packaging plastics.

Independent of the sorting method (automated, manual or combinations), recyclates produced from post-consumer plastics are always blends, containing up to 10-15% of other polymers. The only exception is recycled PET bottles that underwent an advanced recycling process. However, the majority of the packaging plastics are PE and PP. For instance, post-consumer recycled PE contains substantial amounts of PP (and various other plastics in percent to sub-percent levels) and vice versa. The origin of (polymer) contaminants in the sorted products is twofold: sorting faults and packaging components that are attached to the main packaging material. Examples of contaminating packaging components are caps and labels. Sorting faults are the result of sorting mistakes or the positive sorting of agglomerated packages. Although it is possible to recognize and separate all plastic materials (except when they are black) with NIR, a 100% sorting efficiency is difficult to achieve and will negatively influence sorting economics. Although scientists have previously hinted on the blend-nature of recycled plastics (Luijsterburg & Goossens, 2014), the industries converting recycled plastics have not or hardly responded, by adjusting their process parameters accordingly. This implies that most recycled plastics are still processed as if they were virgin plastics and not under the optimal processing conditions.

Blends of different polymers originating from various packaging products are generally non-miscible or non-compatible, and therefore these blends are likely to have inferior properties as compared to virgin plastics limiting their application options. Considering that recyclates legally never can be used for food packaging, but rather for lower quality applications like roadside poles, and as part of the plastic products are subject to wear, new feedstock for production of plastics will always be required.

Since all post-consumer plastics are blends anyhow (except for recycled PET that underwent advanced recycling processes), the effect of the very small quantities of bio-based and/or biodegradable plastics (market is very small as compared to many fossil-based polymers) is not measurable (Thoden van Velzen, 2016c). In general WFBR does not find bio-plastic in (sorted) post-consumer plastics and when they are found, amounts are very low (Table 6) . This table shows the content of bio-based plastics in more than 200 (sorted) plastic waste batches collected during more than 5 years. In only 9 out of the over 200 batches (a small amount of) bio-based plastic was found. The sorting trials are not laid out to detect bio-plastics but sorters recognise materials by logo's or material type (PLA).

Table 6. Bio-plastics found in (sorted) plastic waste in more than 200 batches analysed over a 5 year period.

Date	**Waste Type**	**Batch size**	**Bioplastic type**	**Bioplastic amount**
29-03-2010	Mix DKR-350	10 kg	Starch film	0.12 %
29-03-2010	FKN *	12.8 kg	PLA film	0.14 %
December 2012	Film DKR-310	48.6 kg	PLA film	0.008 %
06-09-2010	Film DKR-310	38 kg	PLA film	0.01 %
19-11-2010	Rigid plastics	57 kg	Starch film	0.02 %
27-12 2012	Municipal Solid Waste	67 kg	PLA & PUR	0.3 %
08-02-2012	HDPE	39 kg	Starch blend	0.03 %
30-03-2012	Plastic Heroes before sorting	125 kg	PLA and starch film	0.02 %
08-09-2010	Plastic Heroes before sorting	162 kg	PLA film	0.08 %

* Fachverband für Getränkekartonverpackungen.

To assess the effect of bio-based polymers on the current mechanical recycling process it should be reviewed how these bio-based polymers behave in actual mechanical recycling processes. Based on the current plastic sorting schemes (see Table 7) it is possible to determine the most likely fate of these bio-based (and biodegradable) polymers when they enter current plastic recycling schemes. Table 7 lists a range of products and their fate depending on the sorting process.

Table 7. Bio-based products and their fate in post-consumer packaging sorting facilities.

Product type	Sorting type	Scenario
Bio-based film (independent of material type)	Automated sorting	Via screens and wind sifting to DKR-310 (film)
Bio-based film (independent of material type)	Manual sorting	To DKR-310 (film)
Bio-based trays (independent of material type)	Automated sorting	DKR-350 (Mixed plastics) or Waste
Bio-based trays (rigid PLA)	Manual sorting	DKR-350 (Mixed plastics)
Bio-based trays (semi flexible blends)	Manual sorting	DKR-329 (HDPE)
Bio-based bottles (PLA)	Automated sorting	Waste or DKR-350 (Mixed plastics)
Bio-based bottles (PLA)	Manual sorting	DKR-329-1 (PET)

Additionally bioplastics as such can be mechanically recycled. Looplife mechanically recycles post-consumer PLA (Looplife, 2016) and Bösel recycles pre-consumer PLA (IfBB, 2016b).

5.1.1 Film (DKR 310) and the influence of bio-based plastics

Film products are usually not NIR sorted and as a consequence of this the composition is a reflection of the consumption pattern of a certain country or region. Usually also seasonal influences on the composition are found. As can be seen in Figure 12, film products are generally mixtures of various plastics. The main component is PE (75%) and is contaminated with PP (10%), PET, (5%), PS (1%) and some PVC. Moreover, the sorted film product also contains approximately 6% of sorting faults (various rigid plastic objects).

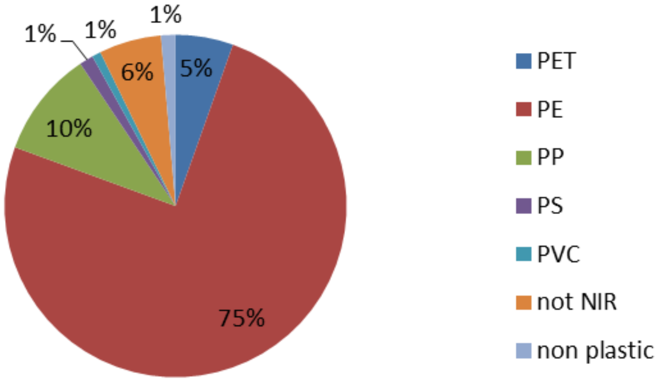

Figure 12. Composition of a DKR-310 sorted product (film) as obtained from a sorting facility.

The influence of bio-based packaging on the quality of recyclates should be measured in these complex mixtures and this was studied by Wageningen Food & Biobased Research within the EU FP7 Open-Bio project. Figure 13 shows the effect of a Mater-bi starch film and a PLA film on the mechanical properties of a sorted DKR-310 film mixture. Mater-bi and PLA film are added to the sorted DKR-310 film before entering the mechanical recycling process (washing, density separation, drying). No negative effects were found on the properties of film products. Considering the error margins (which can be high for plastic mixtures) as indicated in the graph, the mechanical properties of mixed film waste virtually do not decrease with the addition of bio-based plastic film. Rather, the trials indicate an increase in impact strength with the addition of PLA.

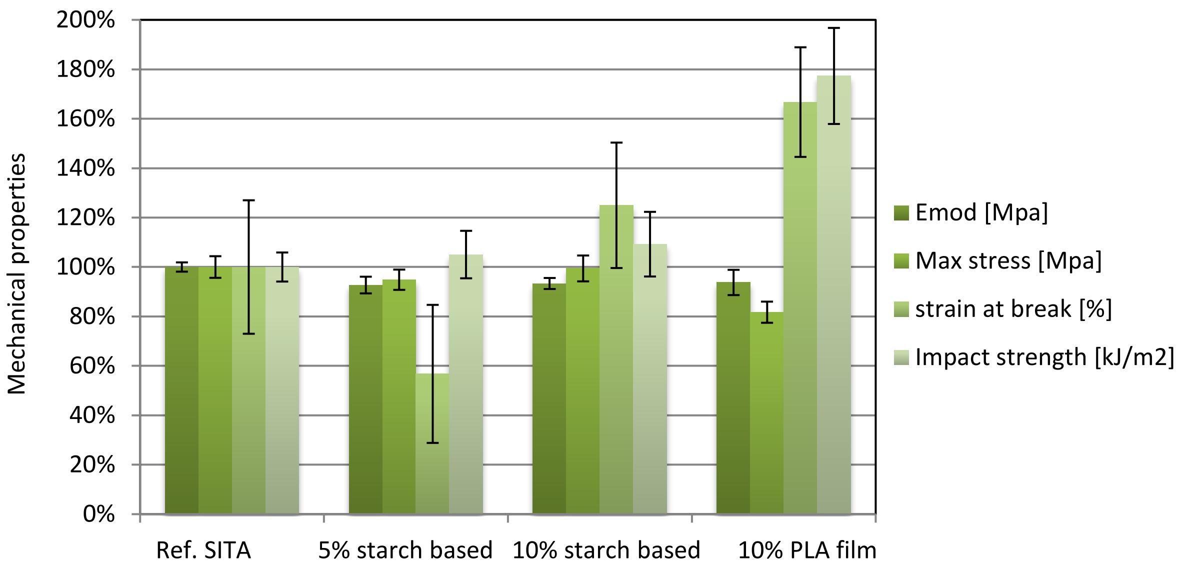

Figure 13. Influence of starch based films and PLA based films on sorted film (DKR-310). Mechanical properties of recycled films (from plastic collection) with added bio-based materials normalized to the reference. Percentile error bars are inserted.

5.1.2 rPET

> *"Does PLA disturb the PET recycle stream?"*

Since PET and PLA have a similar appearance, the recycling industry is afraid PLA may contaminate PET recyclates. The technical quality of rPET was assessed by Wageningen Food & Biobased Research for 'Stichting Afvalfonds' (Thoden van Velzen et al, 2016). PLA was studied as potential contaminant amongst 9 other contaminants. From this study it was concluded that PVC has a detrimental effect on the quality of rPET and there are concerns on the effect of EVOH. No specific threats were found of PLA contaminations.

5.2 Organic recycling: Composting and anaerobic digestion

Municipal organic waste (groente-, fruit- en tuinafval, GFT in Dutch) in the Netherlands is processed by various industrial composting and anaerobic digestion systems. The 23 processors basically all have a different approach regarding size reduction, screening prior to composting, application of anaerobic digestion for part of the organic waste stream, turning the compost during the composting process, re-feeding screened material after composting, etc. An example of a composting process scheme is presented in Figure 14. Today's common practice for industrial composting in the Netherlands takes about 3 weeks, including a legally required 3 days period at 55°C to kill pathogens (Brethouwer, 2016). The resulting compost may legally contain a maximum of 0.5% visual pollution on dry matter basis (Brethouwer, 2016b). To meet the requirements regarding visual contaminants screening is performed after composting, but in some composting facilities also prior to composting. Some organic waste processors mix the fraction >15 mm resulting from the screening after composting with a fresh batch of GFT entering the thermophilic composting cycle, thus providing desired structure to the composting material. Consequently, larger pieces of biowaste (and slowly degrading materials) pass multiple composting cycles at 55°C for 3 days. On average, the overall residual fraction amounts to about 3% of the incoming organic waste stream, and about 1% is estimated to be (fossil-based) plastics (Brethouwer, 2016). The share of the residual fraction varies very much between the various waste processors, in the range of 0.5 – 23% of the incoming organic waste stream for the various processors, the highest fraction obtained for a system which involves screening prior to composting.

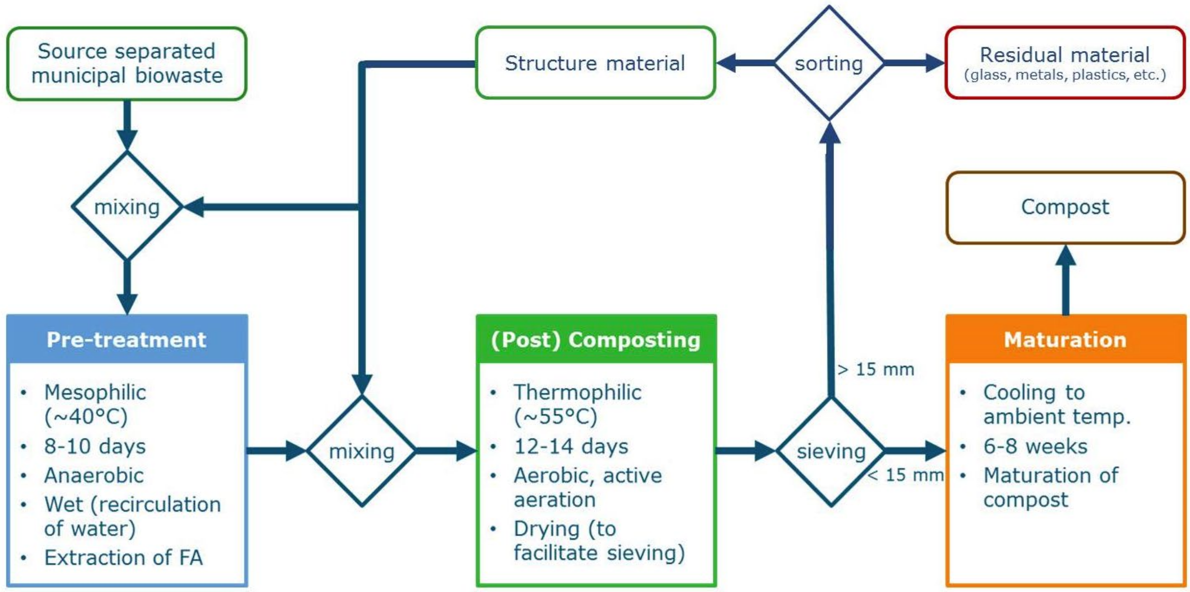

Figure 14. Schematic presentation of the composting process at Attero facility – location Venlo (adapted from Van der Zee, 2015).

> *"Should compostable plastics be disposed in the green bin or not?"*

Since 2003, the Dutch Waste Management Association – department Bioconversion (Vereniging Afvalbedrijven [7], VA) accepts the use of compostable plastic or paper bags as a carrier for municipal kitchen waste (GF). The driver for the waste processors is to collect a larger share of the actual GF waste from households. However, so far some waste processors have been hesitating to generally accept compostable plastics. The hesitation relates to the following questions:

- Quantity of plastic residue stream: Will acceptance of compostable packaging result in the introduction of more non-biodegradable (fossil or bio-based) plastics?
- Biodegradability rate of the compostable plastics: Do the requirements in the current compostability standard EN 13432 meet todays' industrial composting practice?
- Quality of the compost: Will acceptance of compostable products increase the amount of (visual) contaminants and thus negatively affect the compost quality and the (marketing) value?

Quantity of plastic residue stream

The origin of the (non-compostable) plastics found in the organic waste stream is not exactly clear, however, a significant amount originates from GF collection. Waste processors fear that accepting compostable plastics in the GFT waste stream will encourage (accidental or deliberate) disposal of non-compostable plastics via GFT too. On the other hand, the use of compostable plastics could also contribute to an increased collection of organic waste. In the Netherlands

[7] http://www.verenigingafvalbedrijven.nl/

about 1.3 million tonnes of organic waste is collected per annum. Next to that, the residual waste (grey bin) contains a significant amount of organic waste. The VA estimates that about 0.4 million tonnes of food waste could be diverted from incineration to composting. Targeted promotion of compostable bags may stimulate consumers to dispose more food waste in the green bin instead of in the grey bin (ISWA, 2015), or may stimulate them to stop using non-compostable plastic to collect food waste for disposal in the green bin (estimated 0.3% of 1.3 million tonnes corresponds to 4 ktonnes/a). Unclear communication, however, may result in people using non-compostable bags for this purpose, thus increasing the amount of this plastic in the organic waste stream.

Biodegradability rate of the compostable plastics

The rational for the waste processors to accept compostable plastic bags as a carrier for GF waste was to increase the collected share of the actual GF waste from households. At the time, these plastics were mainly starch based plastics, which show acceptable disintegration in the industrial composting processes. Other compostable packaging items so far have not been accepted by all composters. The VA and Holland Bioplastics are working on a covenant on the acceptance of compostable plastics in the green bin. According to the VA, some waste processors have performed a few trials with the composting of PLA-based products, showing disappointing results which make the waste processors raise the question whether the EN 13432 composting standard should be adapted to current Dutch industrial composting practice (Brethouwer, 2016). The reason for incomplete disintegration of PLA could be due to the fact that the industrial composting conditions in the Netherlands (see above) may differ from the conditions in the EN 13432 standard. This standard requires measuring disintegration by sieving after 12 weeks of composting according to ISO 16929, simulating the thermophilic composting phase (including eventual recirculation of larger pieces of biowaste) and the subsequent maturation phase. On the other hand, other trials have shown that 10x10 cm sized blocks of PLA foam disintegrated completely within one cycle of 2 weeks of tunnel composting with 3 days at a temperature >60°C (Van der Zee, 2015).

Quality of the compost

One of the critical requirements of compost quality determining its value is the maximum level of visual contaminants: the overall visual pollution legally has to remain below 0.5%, and higher quality 'keurcompost' may contain up to 0.05 – 0.2% of visual pollution for classes A to C on dry matter basis (Brethouwer, 2016b). The visual contaminants causing problems are usually small fossil-based plastic fragments that have passed the sieve < 15 mm. Plastic films are highly visible and the flexible nature allows plastic pieces which are larger than the screen holes to pass it. Waste processors fear that the wide acceptance of compostable plastics in the municipal GFT waste will lead to an increase of the visual contaminants, resulting in higher costs to screen the contaminants out or resulting in a higher level of pollution in the compost and a lower value. Whether the expected increase in visual contaminants will originate from increased introduction of non-compostable products, or from partially disintegrated compostable plastics, is not clear but that does not alter the negative expectations. In a key issue paper, ISWA states that compostable bags themselves do not introduce additional contamination in the final compost produced (ISWA, 2015).

5.3 Incineration

> *"Incineration is a pity."*
>
> *"Incineration is one of the least environmentally sound routes to dispose of waste."*

In Europe in 2014 over 25 million tonnes of post-consumer (fossil) plastic waste ended up in the waste systems. 31% of this plastic waste was sent to landfill, 40% to energy recovery (incineration) and 30% was recovered through mechanical recycling (Plastics Europe, 2015). In the Netherlands Nedvang monitors and reports the recycling and incineration of packaging waste (Afvalfonds, 2016). According to their measurements, 51% of the Dutch packaging waste is mechanically recycled and 7% is incinerated (measurements in 2014 and 2015). These measurements implies that roughly 50% of the total plastic packaging waste is incinerated (Thoden van Velzen et al, 2016b). In these measurements there are no corrections for attached dirt and residual waste. Thoden van Velzen reports that using corrected values in the Netherlands about 30% of plastic packaging waste is mechanically recycled and roughly 70% is incinerated.

While in most regulations (mechanical) recycling is the preferred route, incineration with energy recovery is very much preferred over land-filling. Additionally plastics have a high caloric value and can be used in general waste incineration to avoid the use of addition of fossil fuels (Eriksson and Finnveden, 2009; Tyskeng and Finnveden, 2010). When comparing environmental impacts of recycling and waste incineration, Tyskeng indicates that there are various factors influencing the results and conclusions. Important factors are system boundaries, but also assumptions on "what replaces what?". For example, does heat from waste combustion replace heat from biomass or heat from coal? With respect to plastics they conclude that recycling saves energy compared to incinerations with 3 exceptions (Tyskeng and Finnveden, 2010; Michaud et al, 2010):

1) If recycled plastics replace wood instead of other plastics
2) If plastic packaging is highly soiled (left over of the content)
3) If a high substitution factor is required (e.g. 2 kg of recycled plastics are required to replace 1 kg virgin plastics).

Incineration will lead to CO_2 emissions and climate changes whereas the effects of land-filling are more difficult to measure. This leads to the rather controversial conclusion of Eriksson et al. that from the perspective of climate change land-fill disposal of plastics should in most cases be preferred over incineration.

It may be noted that incineration of bio-based plastics results in emission of CO_2 which was recently captured and will be captured again when new bio-based products will be produced, whereas incineration of fossil plastics emits CO_2 which was captured long time ago, thus contributing to an increase of green house gas concentration in the atmosphere. Therefore, bio-based plastics may be a good alternative for fossil plastics which are incinerated at end-of-life, e.g. laminates or plastics with low volumes.

5.4 Collection and sorting

> *"In which bin should I deposit the bio-based and/or biodegradable plastics: Organic waste, Plastic Hero, or 'grey waste'?"*
>
> *"Compostable plastic may not enter the Plastic Hero stream, because it reduces the quality of the recycled plastic."*
>
> *"Is composting of compostable plastic better than burning?"*

Collection and sorting largely determine the efficiency of waste management systems. This implies that consumers and their behaviour are an important factor for waste processing efficiency. Since disposal of packaging waste can be confusing for consumers, pictograms have been introduced to indicate the preferred disposal route (Figure 15). For compostable packaging products that are certified according to EN13432 a new pictogram that shows the product can be disposed in the GFT waste has been introduced recently (most right pictogram in Figure 15). The environmental effect of compostable packaging in the disposal phase is not primarily determined by the packaging product itself but much more by its potential to increase the collection of organic and food waste for disposal via the composting route. The incentive of consumers to separate organic waste is rather low, and consequently a considerable part of our organic waste is incinerated. Due to the high moisture content of organic waste, incineration is not energy efficient. Compostable packaging products and bin liners can help to increase organic waste collection and in this manner they contribute to a reduced environmental impact.

There are various misconceptions on the effect of compostable plastics on the quality of recycled plastics. At present the effect is not measurable due to the very low quantities of compostable plastics on the market. This is illustrated by findings of WFBR measuring the composition of sorted plastic waste (Table 6). 'Compostable' does not imply that materials are unstable, easily hydrolysed or degraded when subjected to mechanical recycling processes. Studies performed by WFBR in the EU Open-Bio project indicate that impurities caused by compostable plastics have a highly similar effect as impurities caused by the presence of other (petrochemical) plastics (Figure 13). Moreover, in our current plastic recycling system the presence of PVC still causes the largest problems in plastic recycling. Additionally it should be mentioned that most compostable plastics have a high density and can be easily separated from sorted PE and PP based on this density. Studies indicate that the presence of PLA in recycled PET is not a high concern, whereas the presence of PVC is very harmful (Thoden van Velzen et al, 2016).

Virtually clean compostable plastic which does not help to collect organic waste, and which is not interesting for mechanical recycling due to too low volumes, can be incinerated with energy recovery.

If choices need to be made about what makes most sense, composting or incineration, assessments (e.g. LCA's) need to be made not only on product level but on waste stream level. Many LCAs are performed on product level, not taking into account other variables like adhering material and other components in the waste stream, thus often leading to wrong conclusions.

The study by Tyskeng (2010) implies that capturing a waste system in an LCA is extremely difficult and therefor conclusions on the preferred disposal route should be treated with great care.

Figure 15. Pictograms to indicate best disposal route for particular packaging materials as communicated (KIDV, 2016 [8]).

[8] https://www.kidv.nl/6428/weggooiwijzer.pdf

6 Environmental impact

6.1 Food versus Bio-based plastics

"Will prices for food increase, with the use of bio-based plastics?"

The relation between food and bio-based plastic basically is twofold: food and bio-based plastic might compete for the same feedstock and bio-based plastic can be used as food packaging.

The food versus bio-based plastic debate resembles the food versus fuel debate, albeit at a much smaller scale. During the strong spike in food prices around 2008, the use of edible feedstock for the production of biofuels was strongly criticized for being a large driver for the food price rise (Mitchell D, 2008). Later publications however reported a more moderate influence of the production of biofuels on food prices (a.o. OECD, 2008). During the Dutch Food – Fuel debate in 2013/2014 there was consensus among businesses, NGOs, knowledge institutions and government authorities that "biofuels can offer opportunities as well as threats to food security, and that the ultimate effect strongly depends on *how* biofuels are produced" (2014). A recent paper by Kline et al (2016) shows that a sustainable co-production of biofuels and food is possible when the right measures are taken, and that biofuels production may in fact serve as a stabilizer for food prices, providing farmers with more secure markets and thereby leading to more sustainable production.

Bio-based plastics may use the same feedstock as biofuels, thus a similar discussion applies, the scale of feedstock production for bio-based plastics is however much smaller than for biofuels. The present world-wide production capacity of bio-based and biodegradable plastics lies around 1.7 Mtonne in 2014 (IfBB, 2015). Added to this is the 850 ton of cellulose acetate production (Section 3.1). Compared to the total amount of biomass produced and harvested each year, which lies around 11.5 Gtonne (Piotrowski et al, 2015), this is very small. European Bioplastics has calculated that the land needed to grow the feedstock for bio-based plastics amounted to 0.01% or the agricultural area in 2013 and it may grow to 0.02% by 2018 (European Bioplastics, 2015). Growing demand for bio-based plastics will of course increase the demand for feedstock. From the work of Bos and Sanders (2013) it can be calculated that even if we would base *all* present world-wide fossil plastics production on biomass as feedstock instead, the demand for feedstock would be in the order of 5% of the total amount of biomass produced and harvested each year. But such scenarios may not happen since it is expected that the industry will develop alternative feedstocks for example lignocellulosic feedstocks for chemical building blocks, presently being explored by companies such as Biochemtex in Italy[9] and Avantium[10] among many others. Also the direct utilization of carbon dioxide and methane in fermentation can lift the pressure on feedstock and is presently receiving much R&D attention. Nevertheless, the recent insights on the possibility of sustainable co-production of biofuels and food will also apply

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9 *www.biochemtex.com*

10 *https://www.avantium.com/renewable-chemistries/zambezi/*

in this case, providing an additional market for biomass, next to food, feed and energy (Elbersen and Bos, 2016).

Although most of the bio-based plastics are presently produced from starch or sugar, much development is done both by industry and knowledge institutes to employ interesting molecules from side-streams of the agro-industry (such as beet-pulp) for the production of bio-based plastics. Cosun among others is very active in this field (BioBased Press, 2016). Especially biopolyesters are interesting candidates to produce from these kinds of feedstock. This would provide the agro-industry with a high value outlet for part of their side-streams and also diminish the food-feedstock demand for bio-based plastics.

Bio-based and biodegradable plastics form an interesting packaging materials for food. For instance in the case of in-flight meals (plates and cutlery) biodegradable plastics can be composted together with the meal remains, which saves the necessity to clean and dry. Generally this leads to a favourable LCA.
Furthermore, some bio-based and biodegradable plastics, such as PLA, have barrier properties that can help food to stay fresh longer. For instance the shelf-life of lettuce packed in PLA can be extended by two days. It is well known that approximately 30% of the total food production is wasted, part of this occurs in the supermarket, due to passing of the sell by date, and part of it occurs at home. Extension of the shelf life of perishable products due to the application of bio-based and biodegradable plastics can be an effective way to battle at least part of this food waste. A rough calculation (Bos, 2016) shows that if the packaging can decrease the waste of lettuce by 10%, the land use saving due to the reduction of food waste outweighs the additional land use for the production of the packaging. This applies if a first generation feedstock is assumed, application of a side stream for the plastics production would lead to an even more favourable outcome.

6.2 Environmental impact of bio-based plastics compared to fossil-based plastics

"Do bio-based and/or biodegradable plastics have a lower environmental and ecological footprint compared to fossil plastics?"

The production of bio-based plastics and the production of fossil plastics have different effects on different impact categories. Non-renewable energy use and greenhouse gas emission are generally more favourable for bio-based plastics, the substitution of fossil plastics by bioplastics thus leads to lower non-renewable energy use and GHG emissions (Figure 16). The use of land for the production of feedstock for bioplastics may however lead to direct and/or indirect land-use change, which may negatively influence the GHG emission reduction. The size of this reduction is still under considerable debate (EP, 2015). The GHG emission reduction that is reached by bioplastics is generally significantly larger than that by biofuels (Bos et al, 2010; Bos et al, 2012), the relative impact of ILUC on GHG emissions will therefore be smaller for bioplastics than for biofuels.

On the other hand, for the categories related to agriculture, such as eutrophication and acidification, bio-based plastics generally have a higher impact than fossil plastics. Because there are large differences in impact both in the family of bio-based plastics as well as in the family of fossil plastics no absolute rule can be given.

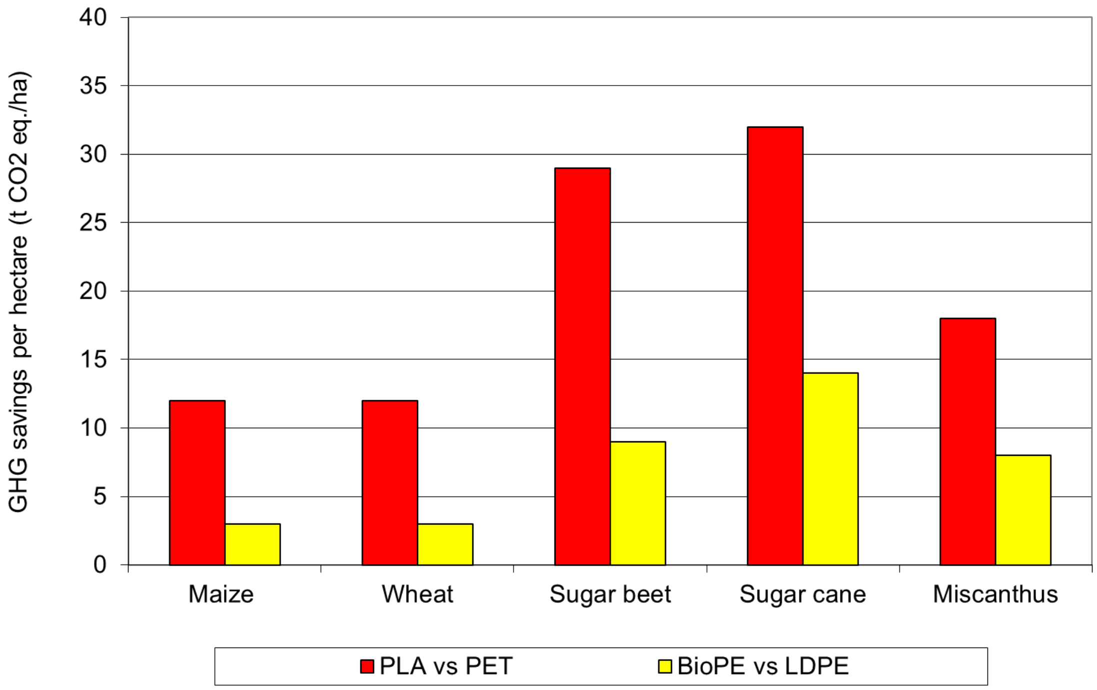

Figure 16. Greenhouse gas savings (GHG) per ha for production of bio-based plastics relative to fossil-based plastics (adapted from Bos et al. 2012).

6.3 Bio-based and biodegradable plastics from genetically modified organisms

"Are genetically modified plants harmful for the environment?"

Genetic modification, also called genetic engineering (GE), can be employed to alter the composition and size of plants, improve their fruit yield or enhance their resistance to e.g. pesticides and insects (Gould, 2016). However, genetic modification has run into fierce resistance from environmental groups who are concerned about the potential risks related to the application and use of genetically modified organisms (GMO) like human health effects, unintentional spreading of GMO to conventional crops, insect resistance and diversity.

A US committee of researchers, complemented with a researcher from Mexico and one from the Netherlands, has recently published a review paper where they state to have "found no cause-and-effect relationships between GMO crops and environmental effects. However, the complex nature of assessing long-term environmental changes often made it difficult to reach definitive conclusions" (Gould, 2016). In a review of European GMO research, it has been stated that "25 years of field trials have not shown evidence of environmental harm" (Van Montagu, 2010).

On the other hand, Greenpeace communicates examples of GM crop studies indicating adverse effects to non-target (insect) species and beneficial insects, and refers to research results indicating cumulative toxic effects in soil and aquatic ecosystems, and new pests filling the void left by the absence of rivals initially controlled by GM crops (Greenpeace, 2011).

It may be concluded that there is still quite some scientific and societal controversy regarding the effects of GMO in open ground cultivation. The issue is so big because 1) the potential gain is huge, 2) the potential risks are complex and possibly potentially huge as well, and 3) it takes a long time before definitive conclusions on the use of a particular GMO crop can be drawn.

GMO crops may be cultivated after passing a risk analysis. Since the first commercial GMO crops cultivation in 1996, the cultivated area has steadily grown to a total GMO crop cultivated area amounting 180 million ha in 2015, about 13% of total global arable land (ISAAA, 2016; FAO, 2015). In Europe however, only a very limited area of GMO crops is grown. PLA is produced based both on GMO and non-GMO corn and non-GMO sugarcane (Molenveld and Van den Oever, 2015). GMO crops are not required to produce PLA.

Genetically modified (micro)organisms (GMOs) are not necessary for the production of many bio-based plastics. Some monomers like succinic acid and 1,3-Propanediol and a polymer like PHA can be produced via fermentation with GMO strains (Table 8). The fermentation is usually performed in closed systems, so the GM organisms can be controlled (white biotechnology). The conversion of woody biomass to fermentable sugars for the production of second-generation polymers is also often performed using GMO strains (in closed systems).

Table 8. Use of GMO feedstock and white biotechnology for production of bio-based plastics today.

Polymer	
Bio-PE	Non-GMO sugar cane
Bio-PET	Non-GMO sugar cane
Cellophane	Non-GMO wood
PBS	White biotechnology for production of Succinic acid
PHA	White biotechnology for production of polymer
PLA	GMO and non-GMO corn or non-GMO sugar cane
PTT	White biotechnology for production of 1,3 Propanediol
Starch	Non-GMO potato or wheat and GMO corn

6.4 Disposal in the environment

"Can I throw biodegradable plastics in the roadside?"

Biodegradable plastics are not and should not be considered as a solution to the problem of litter. Littering should never be promoted or accepted for any kind of waste, neither on land nor at sea, including all varieties of plastics. Instead, the issue needs to be addressed by educative and informative measures to raise awareness for proper and controlled ways of management, disposal, and (organic) recycling.

A product should be designed with an efficient recovery solution. In the case of biodegradable plastic items, it merely means that besides regular material and energy recovery options, there is an additional recovery option to consider; i.e. organic recovery (see section 5.2). Designing a product 'for littering of any kind' would mean encouraging the misuse of disposal, which is unfortunately widespread. Consequently, biodegradability does not constitute a permit to litter.

6.4.1 Effect in marine environment

"Can biodegradable plastics help to solve the plastic soup issue?"

The by far largest share of marine litter is made up of fossil-based plastics, which, when ending up in the seas or washed ashore, can pose a threat to living organisms, especially due to ingestion or entanglement. Marine debris originates from a variety of sources, with ineffectively managed landfills and public littering being the main land-based sources.

The UNEP report on 'bioplastics and marine litter' (UNEP, 2015) recognises that polymers, which biodegrade on land under favourable conditions, also biodegrade in the marine environment. The report also states, however, that this process is not calculable enough at this point in time, and biodegradable plastics are currently not a solution to marine litter. A material that breaks down at sea will require a much longer time than in, say, forest soil or water treatment installations. Also, marine conditions are very diverse in the several seas and oceans during the several seasons. Further, there is no objective acceptable degradation time scale for litter: when is it slow, when is it too slow? It is therefore a misconception that biodegradable plastics immediately disappear once they enter the sea. And therefore biodegradable plastics are not the perfect solution to the issue of plastic litter in the ocean. The global prevention of litter, proper waste management and public awareness are much more important aspects to address in order to tackle the problems with marine litter.

This does not mean, however, that biodegradability cannot be a useful characteristic for specific marine related applications. Lobster cages and fishing line are often lost at sea, for instance, which results in so-called ghost fishing. If these products were to be made out of marine biodegradable plastics, it would at least result in a lower risk of harmful consequences than if they fail to break down at all. The UNEP report indeed mentions such applications as useful alternatives. And these are only a few examples of how polymers with proven biodegradability can be useful for specific applications. Application of these materials does require the biodegradability to be measurable under specific practical marine conditions. This measurability is under development but still far from mature (Tosin et al, 2016). The current standards and certification scheme OK Biodegradable MARINE (exploited by Vincotte) based upon these standards, are therefore generally considered as premature. Being well aware of misunderstandings that can however easily arise amongst consumers, the OK biodegradable MARINE certification scheme makes a clear distinction between certification of the claim of marine biodegradation and authorization to communicate about this certification, and only for a very limited group of products which are actually used in the marine environment (e.g. fishing lines, etc), authorization to communicate on the product about the OK biodegradable MARINE certificate is allowed (Vinçotte, 2016b).

6.4.2 Disposal in soil

Several plastic products end up in the soil. For example in agriculture plastic mulch film, ropes and plant support items are used. These products are partly or even not at all recovered after use/harvest. For use and disposal, the same considerations as mentioned for disposal in the marine environment apply. For mulch film the certification scheme OK Soil is available. The OK Soil certification scheme is not universally accepted so far.

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Appendix A List of abbreviations

1,3-PDO	1,3-Propanediol
^{14}C	Radioactive carbon atom containing 6 protons and 8 neutrons instead of most common carbon containing 6 protons and 6 neutrons
AlOx	Aluminium oxide (film coating to protect against light and oxygen)
ASTM	American Standard for Testing and Materials
Bio-PE	Polyethylene containing bio-based materials
Bio-PET	Polyethylene terephthalate containing bio-based materials
DKR	Deutsche Gesellschaft für Kreislaufwirtschaft und Rohstoffe mbH
BOPLA	Biaxial oriented PLA
CA	Cellulose acetate
CH_4	Methane
CO_2	Carbon dioxide
EN	European standard
EPLA	Expandable bead foam based on PLA
EPS	Expanded polystyrene
EVOH	Ethylene vinyl alcohol
FA	Fatty acids
FOB	Free on board
HDPE	High-density polyethylene
HIPS	High impact polystyrene
ISO	International Organization for Standardization
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
NEN	Dutch Standard (Nederlandse Norm)
OTR	Oxygen transfer rate
PA	Polyamide
PBAT	Poly(butylene adipate-co-terephthalate)
PBS	Polybutylene succinate
PBSA	Polybutylene succinate adipate
PCL	Polycaprolactone
PE	Polyethylene
PEF	Polyethylene furanoate
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoate
PHB	Polyhydroxybutyrate
PHBV	Poly(hydroxybutyrate-co-valerate)
PLA	Polylactic acid
PP	Polypropylene

PS	Polystyrene
PTT	Polytrimethylene terephthalate
PVC	Polyvinyl chloride
PVdC	Polyvinylidene chloride
RH	Relative humidity
SiOx	Silicon oxide (coating on film to improve barrier properties)
WVTR	Water vapour transfer rate

Appendix B Bio-based content

Many materials and products consist of a range of ingredients in order to achieve an optimal mix of required properties. When all ingredients are from biomass origin, the product may be called entirely or 100% bio-based. However, many products are partly bio-based and partly fossil-based. The bio-based content indicates the ratio between material originating from biomass and the total material.

The background of products being partly bio-based relates to the following: Because a product needs to meet particular properties which cannot instantaneously be met by 100% bio-based content, researchers and plastic manufacturers choose to develop bio-based plastics step by step, starting with the component which can be made bio-based most easily. An example is for instance bio-PET (PolyEthylene Terephthalate): first the ethylene glycol monomer has been replaced by bio-based ethylene glycol (plant bottle reference) and now researchers are working to produce bio-based terephthalic acid at commercial scale. Another option is to replace the terephthalic acid by furan di-carboxylic acid, a slightly different molecule, because it can be more easily produced from biomass.

The bio-based content is currently usually derived from determination of the bio-based carbon content through ^{14}C measurement according to e.g. EN 16640 (2015), ISO 16620-4 (2016) or ASTM D6866 (2012). These methods are based on the radio-active decay of ^{14}C, which can be used to estimate the age of organic materials up to roughly 60,000 years old. The ^{14}C method for estimating the bio-based content is therefore based on the fact that fossil-based materials such as oil and gas will contain no ^{14}C as a result of radio-active decay, whereas bio-based materials will contain new ^{14}C, taken up from the atmosphere. Results based on the ^{14}C methodology are expressed as a fraction of bio-based carbon on the total carbon content of the sample. In some cases the bio-based weight fraction of a product can differ substantially from the bio-based carbon weight fraction. For example, products in which part of the raw materials has been replaced by bio-based alternatives containing other elements like O, N and H (such as carbohydrate-based products) will indicate a lower bio-based fraction when this is only derived from the bio-based carbon content. Some typical examples are given in Table 9.

Table 9. Example of differences in bio-based carbon content and biomass content of specific materials (Van den Broek et al, 2015).

	bio-based carbon content (%)	**bio-based content (%)**
Composite based on 70% PE and 30% cellulose	18	30
Bio-PET-30[1]	20	31
PVC[1] based on bioethylene	100	43
Cellulose triacetate (fossil oil based acetic acid)	50	55
Coating (with bio-based resin)	76	15

[1] The suffix '30' indicates that the PET contains 30% bio-based content.

Due to these limitations there was a demand for a method to determine the bio-based content of products. The method EN 16785-1 on 'Determination of the bio-based content using the radiocarbon analysis and elemental analysis' has recently been published (2015). Another one is still under development: prEN 16785-2 on 'Bio-based products - Bio-based content - Part 2: Determination of the bio-based content using the material balance method' (2016).

<u>Certificate 'bio-based'</u>

Some manufacturers of plastics add some bio-based feedstock in their naphtha crackers, together with fossil oil based feedstock, in order to acquire a certificate 'bio-based' (groencertificaat) for the related (small) part of their plastic production. In Europe, certification of such plastics is provided by Vinçotte and DIN Certco. When analysing with ^{14}C method, however, virtually no bio-based carbon will be detected due to the relatively small amount of bio-based feedstock compared to the fossil-based feedstock.

<u>Communication</u>

When communicating about the bio-based content of a product, it is important to be clear on whether the stated percentage refers to the bio-based content or the bio-based *carbon* content. And in case of the latter, whether it is related to the *total* carbon content of the product (e.g. according to EN 16640), or to the *organic* carbon content (e.g. according to ASTM D6866). Terms like 'bio-based' get a meaning particularly when used in combination with the method applied to determine the bio-based content.

Appendix C Sustainability of bio-based plastics

As far as bio-based materials are renewable materials (see section 1.3), they are sustainable regarding the CO_2 balance of the raw biomass itself. Bio-based materials consume atmospheric CO_2 during their growing stage which is released again during the disintegration stage. This is opposite to fossil-based materials which release CO_2 which has been fixed millions of years ago, thus increasing the CO_2 concentration in the atmosphere. So, when only looking at the material carbon, bio-based products have a significant advantage over fossil-based plastics. However, for the net greenhouse gas balance over the total life cycle also the CO_2 emissions of production have to be taken into account.

Further, sustainability includes more aspects than climate change alone, such as other environmental issues (eutrophication biodiversity, erosion), processing parameters (resource use efficiency, energy and water consumption), and social and economic aspects (labour conditions, fair trade, child labour, corruption). Although one particular sustainability aspect of a product often may be considered more relevant than another, claiming sustainability for a product based on one aspect of sustainability alone is misleading as far as it ignores other aspects. Examples are e.g. 'sustainable coffee' by explaining having paid a fair price to the farmer or 'the most sustainable coffee cup' is claimed because of the low CO_2 footprint 'alone'. Further, the concept of sustainability requires that one product is compared to another product, in order to see which of the 2 or more products scores best.
In conclusion, sustainability of a product becomes a meaningful term only when 1) the reviewed sustainability aspects have been indicated and 2) comparison to other products has been made clear. For the environmental part of a sustainability assessment the tool life cycle assessment (LCA) can be used.
A key difference between fossil and bio-based plastics is the origin of the feedstock. Often the rest of the life cycle is more or less the same. To secure that the feedstock of a bio-based plastic is produced in a sustainable way the industry, together with its stakeholders, has developed over the years sustainable feedstock growing certification schemes such as ISCC PLUS, Bonsucro, RSB and the assessment schemes developed by BFA (Biobased feedstock alliance). Compared with the fossil polymers, there are no schemes in place which assess the sustainable production of these raw materials.