Biobased Plastics in a Circular Economy

Policy suggestions for biobased and biobased biodegradable plastics

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Content

Summary

Introduction

In this report the following research question is addressed:

Under which conditions are biobased plastics (both biodegradable and non-biodegradable) compatible with the circular economy?

This was assessed by looking at:
1. The GHG balance; can biobased plastics contribute to lowering greenhouse gas emissions (CO_2-eq)?
2. The use of (natural) resources throughout the life cycle; can biobased plastics contribute to lowering demand for (fossil) resources?
3. Biodegradability; when is use of biodegradable plastics preferable to use of non-biodegradable plastics?
4. The influence on litter and plastic soup; Can biobased plastics play a role in limiting litter and minimizing plastic soup risks?
5. End-of-life; do biobased plastics influence end-of-life treatment options, and how? Which problems occur and which opportunities arise?

The term 'bioplastics' is often used for a group of different materials; materials based on biomass, materials that are biodegradable, or a combination of both. For example, there are fossil-based biodegradable materials and also biobased materials that are not biodegradable. Plastics can also occur in blends or in multilayer structures with fossil based plastics. Therefore, we use the term 'biobased plastics'.

> In this study the term 'biobased plastics' is used for *biodegradable or non-biodegradable polymers based on renewable (biomass) sources*. We focus on biobased plastics which are either already 100% biobased or have the potential of becoming 100% biobased. In the case something relates solely to biodegradable biobased plastic, this is explicitly mentioned.

When a material is biodegradable, it is converted into water and CO_2 by micro-organism in the presence of oxygen. The biodegradability depends on the 'aggressiveness' of the environment. Aggressiveness increases from marine water to fresh water to soil and to a composting facility (OWS, 2013).

In Table 1 an overview of biobased plastics is given.

Table 1 Overview of biobased plastics (thermoplastics)

	Non-biodegradable	Biodegradable (in industrial composting installation)	Biodegradable (in water in nature)
On the market today	Bio-PE (drop-in) PA11, PA10.12, PA4.10	PLA (and *PLA/PHA blends)* PHA (and *PHA/TPS blends)*	PHA Regenerated cellulose
Under development (not on the market yet)	PEF Drop ins: Bio-PP , Bio-PVC, Bio-PET, Bio-PTT PBT PA6, PA6.10, PA66, PA12	Bio-PBS Cellulose Acetate PGA *PLA/TPS blends* *Bio-PBS/TPS blends*	

Conclusions

The main findings of this report (answers to the questions above) are summarized in the following box.

Box 1 Biobased plastics in a circular economy: conclusions

1. Biobased plastics can contribute to lowering greenhouse gas emissions.
2. Biobased plastics can contribute to lowering demand for fossil resources, but contribute to increased use of natural resources.
3. Application of biodegradable biobased plastics is recommendable in those applications with either a direct functionality or those with co-benefits.
4. Biodegradable biobased plastics can contribute to lowering microplastics in soil and water for some applications, but are not a direct solution to the litter problem (degradation rate is too slow).
5. In a design for a circular and environmentally optimal system, mechanical recycling should be optimized and the input (virgin products) should be sustainable.

Conclusion 1: Biobased plastics can contribute to lowering greenhouse gas emissions

Biobased plastics, in most cases, realize a climate change impact reduction in comparison to fossil-based plastics. The whole life cycle was analysed in this study. Two aspects influence the GHG balance, 1) choice of raw material and 2) treatment at end-of-life:

1. The choice of raw material for production:
   - For plastics that need fermentable sugars, sugar cane and sugar beet are preferable to cereal crops. The production of sugars from lignocellulose seems promising, because by-products or wastes can be used and there is no competition with food production.
   - Biobased plastics made from sugar crops or (agricultural) waste have the lowest Indirect Land-Use Change (ILUC) risk.
   - By-products: use of by-products influences a products sustainability; when by-products are used for other purposes, part of the environmental impact is allocated to those purposes (in LCA). Care should be taken that soil quality (soil organic matter) is maintained at a sustainable level.
2. The end-of-life treatment of biobased plastics (in order of priority):
   - **Mechanical recycling** influences the GHG balance positively, and means a lower demand for raw materials.
   - **Incineration or digestion**. Incineration with energy recovery contributes to energy production, which has an environmental benefit. The main difference with incineration of fossil plastics is the emission of biogenic CO_2 instead of fossil CO_2. **Digestion** with biogas production also contributes to energy production and thus has a positive influence on the GHG balance.
   - **Composting** biodegradable biobased plastics is CO_2 neutral, composting of biodegradable plastics does not produce compost. Composting of biobased plastics is only favourable when it has added value; when it has co-benefits such as increasing the amount of food waste collected to be composted and reducing the amount of fossil plastics ending up in the food and garden waste which is composted. If a biodegradable biobased plastic has co-benefits it can contribute to lowering greenhouse gas emissions indirectly.

Conclusion 2: Biobased plastics can contribute to lowering demand for fossil resources, but contribute to increased use of natural resources
Because the feedstock of biobased plastics are biobased resources there is no direct input of fossil resources necessary. The energy used for the production of biobased resources could, however, still be fossil-based energy. As this is also true for fossil-based plastics, biobased plastics can contribute to lowering demand for fossil resources.

Production of biobased plastics requires natural resources, such as fertile land, fresh water and phosphate fertilizers. For raw materials, the order of preference based on environmental impact related to natural resource use is: waste materials, sugar crops (beet, cane) and starch crops (maize).
Last on the list are oil crops.
Sustainable agricultural practices, focussing on e.g. water and nutrient management and maintaining soil quality, help lower the impact of the use of these natural resources.

Conclusion 3: Application of biodegradable biobased plastics is recommendable in those applications with either a direct functionality or those with co-benefits
Biodegradability can be a functional characteristic, for example for applications in agriculture and horticulture. Also, in some agricultural applications, soil and marine biodegradable plastics can reduce litter and decrease the release of non-biodegradable plastics, e.g. foils which may not be completely removed after use.

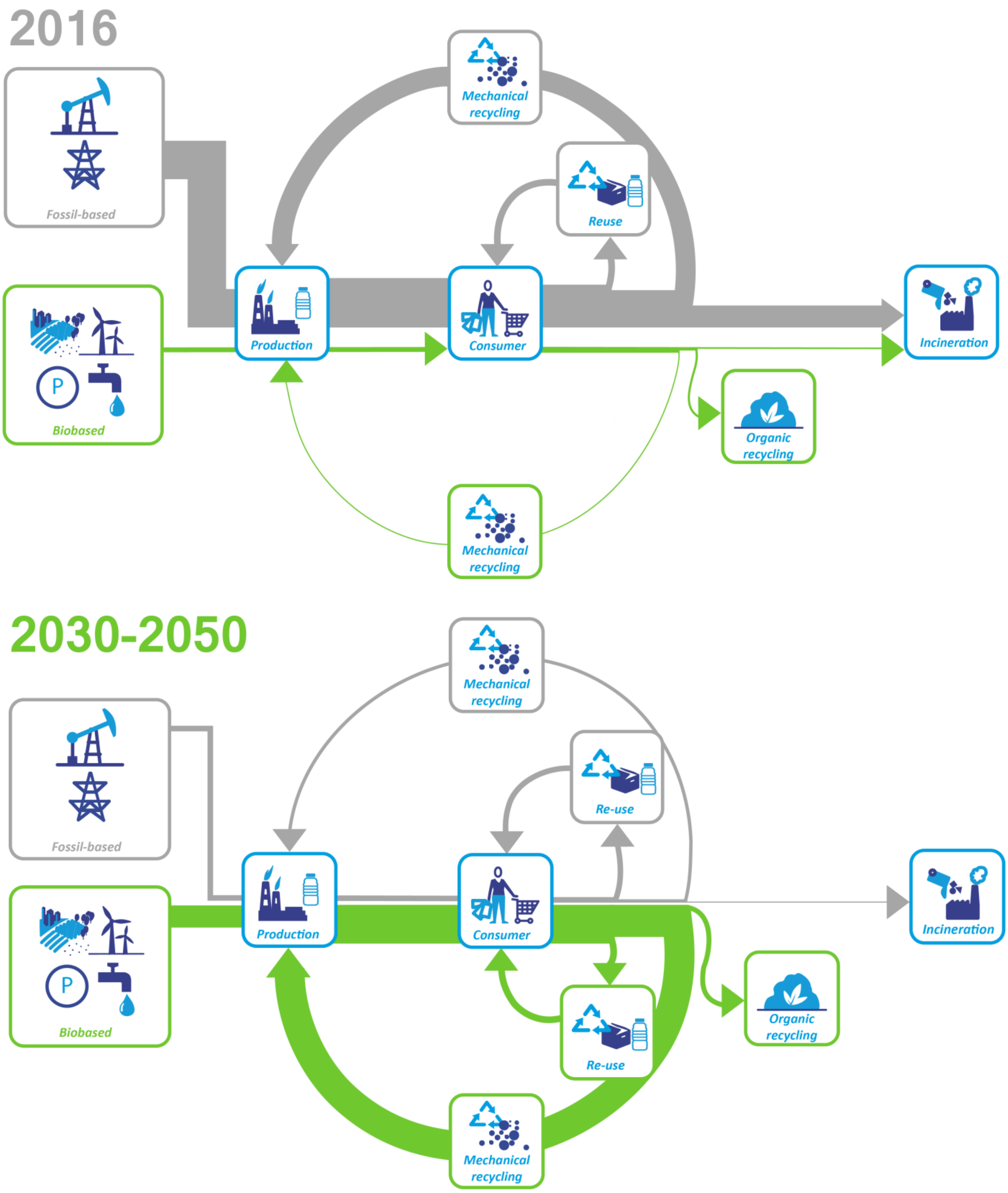
Application of biodegradable biobased plastics for packaging and food waste carriers has the potential to increase separately collected food and garden waste, and decrease contamination with non-biodegradable plastics (of the compost). In general, only when biodegradable plastics for such applications have clear co-benefits, such as increasing the separate collection of food and garden waste, their usage is attractive.

Conclusion 4: Biodegradable biobased plastics can contribute to lowering presence of plastics in soil and water, but are not a direct solution to the litter problem
Litter is an important source of plastic soup, and should be limited by education of citizens. Marine and soil biodegradable plastics can contribute to lowering the impacts of plastics of plastic soup for some applications, but caution is advised. Compostability is not the same as soil/marine biodegradability, and from an environmental point of view application of biodegradable plastics is only attractive when biodegradability is functional or if there are co-benefits.

Marine and soil biodegradable plastics can contribute to decreasing the plastic soup, when used for products which release micro plastics in the use phase. Use of soil and marine biodegradable biobased plastics in agricultural applications can also reduce plastic soup; the risk of unintentional disposal is high in such applications (such as foils). Also, replacing fossil non-biodegradable plastics used for certain food packaging by biodegradable alternatives, can contribute to lowering plastics emissions to soil through compost.

Conclusion 5: In a design for a circular and environmentally optimal system, mechanical recycling is optimized and the input is sustainable
Mechanical recycling is the most attractive end-of-life treatment option. This does, however, only become economically feasible at certain volumes. Some biobased plastic are already recycled in the current recycling system, these are the ones that are chemically identical to their fossil counterparts. In a sustainable circular system, mechanical recycling is optimized, and the additional primary input is as sustainable as possible. This is illustrated in Figure 1.

Figure 1 Plastics - a circular economy; transition from now to 2030-2050



Based on the conclusions above, the conditions for successful integration of biobased plastics in a circular economy are summarized in Box 2.

Box 2 **Biobased plastics in a circular economy: conditions**

- Optimize the input into the economy:
  - **require sustainable agricultural practices;**
  - **maximize CO_2-eq reduction;**
  - **minimize of (I)LUC risk;**
  - **phase out use of fossil resources.**
- Optimize the mechanical recycling treatment:
  - **minimize losses;**
  - **work towards treatment of (non-drop-in) bioplastics in recycling.**
- Treat litter as a separate problem**: biodegradables are not the solution.**
- Use biodegradables for applications in which biodegradability is functional **(e.g. agriculture, horticulture)** and/or in which it has co-benefits **(e.g. carrier for food waste and/or substitute for food packaging which currently leads to contamination in organic waste).**

Policy suggestions

In general we recommend integrating stimulation policies for biobased plastics in the current policy frameworks for waste (LAP 3) and the Circular Economy. The focus should be on prevention first, reuse second, recycling third and finally on biobased plastic as an interesting solution *if the biobased plastic fulfils sustainability criteria*. Many biobased plastics are environmentally attractive, but to reduce risks we advise to only stimulate actively those which meet sustainability criteria. We have nine policy suggestions:

Sustainability criteria as prerequisite for support:

1. Stimulate (in whichever way) only those biobased plastics that meet sustainability criteria. Introduce a set of sustainability criteria and quality criteria for certification systems for biomass used for the production of biobased plastics, based on work that has been done in cooperation between government, industry and NGO’s in this field (for instance the project group sustainable production of biomass (Cramer, Corbey), as part of the Energy Agreement and the Green Deal *Green Certificates*.
   Sustainability criteria could include:
   a A minimum CO_2-eq reduction percentage including ILUC, and a minimum biobased content[1].
   b A ban on direct land-use change (as in Green Deal Green Certificates).
   c Mandatory rules for sustainable agricultural practices (as in Green Deal Green Certificates).

[1] Additional to the CO_2 target a minimal biogenic carbon content should be determined. This can be proven by different methods, either physically (measured) or administratively (mass balance).

Regulation:

2. **Forbid to label (packaging) material as biodegradable**. Use the term 'industrially compostable' for compostable bags and packaging of food products whose contents may end up in the food and garden waste system and are subsequently composted.
3. **Adopt a (European) ban on oxo-degradable plastics**. These cannot be mechanically recycled and also do not biodegrade, causing all kinds of problems in the recycling treatment.
4. **Set specific standards regarding soil and marine biodegradability** for products with a high risk of unintended disposal.

Communication:

5. To minimize the environmental impact, it is important that consumers dispose of their waste in the right way. **Arrange for a campaign to stimulate proper recycling behaviour.** Inform consumers about the characteristics of biobased plastics and how to deal with them in the end-of-life phase. Suggestions:
   - clear logo's on packaging, as developed by KIDV;
   - disposing biodegradables with food and garden waste should only be promoted in the case of clear co-benefits.

Stimulation (those that meet sustainability criteria):

6. **Subsidies**: subsidize those biobased plastics which meet the sustainability criteria.
7. **Green procurement**: Include biobased (and also recycled) plastics in (governmental) green procurement.
8. **Financial instruments**: E.g. lower Dutch packaging Waste Funds Tariffs, and others as researched in a study about sustainable wood (CE Delft, 2015).
9. **Improve recycling systems for fossil plastics and biobased plastics.** Organize recycling for biobased plastics with growth potential, which are currently not sorted out in a mono stream. Make a plan for recycling of biobased plastics together with all parties involved. Broaden the scope of financial compensation of recycling to include products other than packaging.

Samenvatting

In dit rapport wordt de volgende onderzoeksvraag beantwoord:

Onder welke voorwaarden passen (niet-)biologisch afbreekbare biobased plastics in een circulaire economie?

Hiertoe zijn de volgende aspecten onderzocht:
1. De broeikasgasbalans: kunnen biobased plastics bijdragen aan het verminderen van de uitstoot van broeikasgassen (CO_2-equivalenten)?
2. Het gebruik van (natuurlijke) grondstoffen over de gehele levenscyclus: kunnen biobased plastics bijdragen aan het verlagen van de vraag naar (fossiele) grondstoffen?
3. Bioafbreekbaarheid: wanneer is gebruik van bioafbreekbare biobased plastics te verkiezen boven gebruik van niet-bioafbreekbare biobased plastics?
4. De invloed op zwerfvuil en de 'plastic soep': kunnen biobased plastics bijdragen aan het verminderen zwerfvuil en aan het minimaliseren van risico's gerelateerd aan plastic soep?
5. End-of-life: hoe beïnvloeden biobased plastics de verwerkingsroutes en welke problemen en mogelijkheden doen zich daar voor?

De term 'bioplastics' wordt gebruikt voor diverse materialen: kunststoffen gebaseerd op biomassa, kunststoffen die bioafbreekbaar zijn, of een combinatie van beiden. Er zijn fossiele kunststoffen die bioafbreekbaar zijn, maar ook op biomassa gebaseerd kunststoffen die niet bioafbreekbaar zijn. Ook zijn er materialen waarin verschillende materialen gemixt zijn, en materialen waarin verschillende kunststoffen gelaagd voorkomen. Om verwarring te voorkomen spreken we in dit rapport over '*biobased plastics*'.

Een materiaal is bioafbreekbaar als het in aerobe omstandigheden (er is zuurstof) door micro-organismen wordt afgebroken tot water en CO_2. Bioafbreekbaarheid hangt af van de omstandigheden; hoe agressief het milieu waar het materiaal in terecht komt is. Agressiviteit loopt op van zeewater (weinig agressief), via zoetwater en bodem, naar uiteindelijk een composteerinstallatie.

In deze studie gebruiken we de term '*biobased plastics*' voor *bioafbreekbare en niet-bioafbreekbare polymeren die geproduceerd zijn uit biomassa*. We leggen daarbij de focus op de op biobased plastics die óf al 100% biobased zijn, óf op (korte) termijn 100% biobased kunnen worden. Als het gaat om bioafbreekbare biobased kunststoffen wordt dit expliciet genoemd.

In Tabel 1 is een overzicht gegeven van de verschillende type biobased plastics.

Tabel 1 **Overzicht van biobased plastics (thermoplasten)**

	Niet bioafbreekbaar	**Bioafbreekbaar (in industriële composteerinstallatie)**	**Bioafbreekbaar (in water in de natuur)**
Nu op de markt	Bio-PE (drop-in) PA11 PA10.12 PA4.10	PLA PHA *PHA/TPS blends* *PLA/PHA blends*	PHA Geregenereerd cellulose
In ontwikkeling (nog niet op de markt)	PEF Bio-PP (drop-in) Bio-PVC (drop-in) Bio-PET (drop-in) Bio-PTT (drop-in) PBT PA6 PA6.10PA66 PA12	Bio-PBS Celluloseacetaat PGA *PLA/TPS blends* *Bio-PBS/TPS blends*	

Noot: Drop-in biobased plastics: chemisch identiek aan fossiele plastics.

Conclusies

Box 1 toont de belangrijkste conclusies (antwoorden op bovenstaande vragen) van dit onderzoek.

Box 1 **Biobased plastics in de circulaire economie: conclusies**

1. Biobased plastics kunnen bijdragen aan het verminderen van de uitstoot van broeikasgassen.
2. Biobased plastics kunnen bijdragen aan het verlagen van de vraag naar fossiele grondstoffen, maar dragen bij aan een toename van het gebruik van natuurlijke grondstoffen.
3. Toepassing van bioafbreekbare plastics is aan te raden voor toepassingen waar bioafbreekbaarheid de kern van de functionaliteit is of waar er additionele voordelen zijn (bijvoorbeeld GF-zakjes; meer inzameling van GF-afval).
4. Afbreekbare biobased plastics kunnen in sommige toepassingen bijdragen aan het verminderen van de uitstoot van plastics naar de bodem en naar water, maar vormen geen directe oplossing voor het zwerfvuil. Bioafbreekbare kunststoffen vormen geen oplossing voor de zwerfvuilproblematiek (afbraak is te langzaam).
5. Voor een circulair en milieukundig optimaal systeem dient mechanische recycling geoptimaliseerd en de input verduurzaamd te worden, deels met biobased plastics.

Conclusie 1: Biobased plastics kunnen bijdragen aan het verminderen van de uitstoot van broeikasgassen

In de meeste gevallen hebben biobased plastics een lagere klimaatimpact dan fossiele plastics. In deze studie is gekeken naar de hele keten. De klimaat-impact hangt vooral af van 1) het type grondstof dat gebruikt wordt en 2) de verwerking aan het einde van de levensduur van een product:

1. Grondstoffen:
   – De klimaatimpact wordt vooral beïnvloed door het **type grondstof** dat gebruikt wordt. Voor plastics die gebaseerd zijn op gefermenteerde suikers zijn suikerriet en suikerbiet te verkiezen boven graangewassen.

De productie van suikers uit lignocellulose lijkt veelbelovend te zijn, omdat afval- en bijproducten gebruikt kunnen worden en er geen competitie met de voedselvoorziening is.

- Biobased plastics gemaakt uit suikergewassen of (landbouw)afval hebben het laagste risico wat betreft indirecte veranderingen in landgebruik.
- Het gebruik van **bijproducten**, zoals bladeren, beïnvloedt de duurzaamheid van een product; als er bijproducten worden gebruikt voor andere doeleinden (bijvoorbeeld energietoepassing), wordt in een LCA een deel van de milieu-impact toegewezen aan die doeleinden. Dit verlaagt de milieu-impact van het primaire product. Het is hierbij wel belangrijk dat de bodemkwaliteit gewaarborgd blijft, onderploegen (in plaats van gebruiken voor andere toepassingen) van bijproducten kan helpen het gehalte bodemorganische stof op peil te houden, wat ook invloed heeft op de klimaatemissies.

2. Verwerking aan het einde van de levensduur (op volgorde van prioriteit):
   1. **Mechanische recycling** heeft een positief effect op de broeikasgassenbalans, en leidt tot minder vraag naar ruwe grondstoffen.
   2. **Verbranding of vergisting**; Verbranding met energieopwekking draagt bij aan de productie van energie, wat een milieuvoordeel geeft. Het belangrijkste verschil met het verbranden van fossiele plastics is de uitstoot van biogeen CO_2 in plaats van fossiel CO_2. Vergisting waarbij biogas geproduceerd wordt draagt ook bij aan de productie van energie en heeft daarom een positief effect op de broeikasgassenbalans.
   3. **Composteren** van biologisch afbreekbare biobased plastics is CO_2-neutraal; het draagt niet bij aan de productie van compost.
      Als het composteren van biobased plastics co-voordelen heeft kan het indirect bijdragen aan het verminderen van broeikasgassen, bijvoorbeeld wanneer het leidt tot een stijging van de hoeveelheid ingezameld voedselafval voor compostering, of een daling van de hoeveelheid fossiele plastics die bij het GFT-afval dat gecomposteerd wordt terechtkomen.

Conclusie 2: Biobased plastics kunnen bijdragen aan het verlagen van de vraag naar fossiele grondstoffen, maar dragen bij aan een toename van gebruik van natuurlijke grondstoffen

Biobased plastics kunnen bijdragen aan het verlagen van de vraag naar fossiele grondstoffen omdat zij gemaakt worden uit biobased grondstoffen. Hierdoor is er bij hun productie geen directe input van fossiele grondstoffen nodig.
Het feit dat de energie, die wordt gebruikt bij het produceren van de biobased grondstof, nog steeds uit fossiele bronnen afkomstig kan zijn, doet hier geen afbreuk aan. Dit geldt immers ook voor fossiele plastics. Voor fossiele én biobased plastics geldt: mechanische recycling vermindert de vraag naar primaire grondstoffen.

Voor de productie van biobased plastics zijn natuurlijke hulpbronnen nodig, zoals vruchtbaar land, zoetwater en fosfaat meststoffen. De voorkeursvolgorde (oplopende milieu-impact) als het gaat om ruwe grondstoffen is: afvalstoffen, suikergewassen (bieten, suikerriet), en zetmeelgewassen (maïs) en, tot slot, oliegewassen. Deze volgorde wordt vooral bepaald door de opbrengsten per hectare en het risico op landgebruiksverandering. Het verduurzamen van landbouwpraktijken door bijvoorbeeld water- en nutriëntenmanagement, het behouden van de bodemkwaliteit, en het minimaliseren van het risico op landgebruiksverandering, dragen bij het verlagen van de impact gerelateerd aan het gebruik van deze natuurlijke grondstoffen.

Conclusie 3: Bioafbreekbare plastics zijn voor bepaalde toepassingen aan te raden: waar afbreekbaarheid een direct functioneel voordeel geeft en/of waar er co-benefits zijn
In landbouwkundige toepassingen kan bioafbreekbaarheid een functionele eigenschap zijn, bijvoorbeeld bij plantenpotten die dan later niet meer verwijderd hoeven te worden. In de landbouw kunnen bioafbreekbare biobased plastics ook een voordeel hebben als het risico op zwerfvuil hoog is (bij folies bijvoorbeeld).

Gebruik van bioafbreekbare biobased plastics voor voedselverpakkingen en als drager van gf-afval kan als additioneel voordeel hebben dat er meer gf-afval door de consument ingezameld wordt. Gebruik van bioafbreekbare biobased plastics voor verpakkingen en dragers is milieukundig alleen aantrekkelijk als er dit soort additionele voordelen zijn. Dit kan alleen als de consument goed op de hoogte is van de juiste manier van afval inzamelen en scheiden.

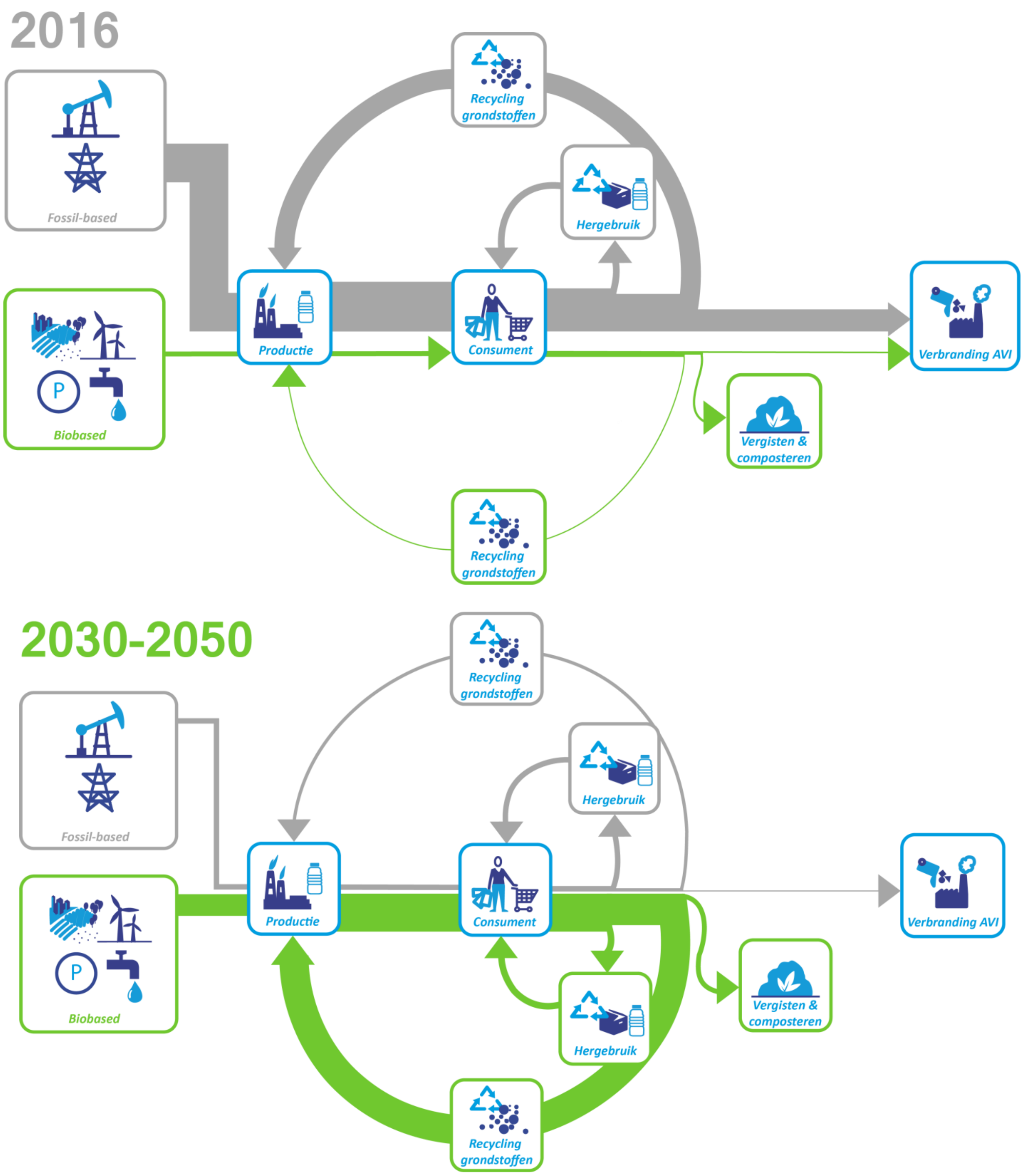
Conclusie 4: Biologisch afbreekbare biobased plastics kunnen bijdragen aan het verminderen van de uitstoot van plastics naar de bodem en naar water, maar vormen geen directe oplossing voor het zwerfvuil
Zwerfvuil is een belangrijke bron van de plastic soep, die moet worden verminderd door betere voorlichting aan burgers. In bodem en (zee)water afbreekbare biobased plastics kunnen in sommige toepassingen bijdragen aan het verminderen van plastic soep, maar voorzichtigheid is geboden. Composteerbaarheid is niet hetzelfde als bio-afbreekbaarheid in de natuur, en milieukundig is toepassing van bioafbreekbare plastics alleen interessant in functionele toepassingen of bij co-voordelen.

In water- en bodem afbreekbare plastics kunnen bijdragen aan het verminderen van de plastic soep als ze worden gebruikt in producten die plastics afstaan tijdens de gebruiksfase (bijvoorbeeld door slijtage, of door toevoeging van microplastics aan gebruiksproducten zoals cosmetica).
Het gebruik van in water- en bodem afbreekbare biobased plastics in land-bouwtoepassingen kan ook helpen bij het verminderen van de plastic soep; het risico van onbedoelde emissie is bij zulke toepassingen (bijv. voor folies) vaak hoog.

Daarnaast kan het vervangen van fossiele niet-biologisch afbreekbare plastics door biobased bioafbreekbare plastics, die gebruikt worden voor bepaalde voedseltoepassingen, bijdragen aan het verminderen van plastic emissies naar de bodem via compost.

Conclusie 5: Voor een circulair en milieukundig optimaal systeem wordt mechanische recycling geoptimaliseerd en de input verduurzaamd, deels met biobased plastics
Een aantal biobased plastics kan nu al goed verwerkt worden in het plastics inzamelingssysteem, omdat ze chemisch identiek zijn aan bepaalde fossiele plastics. Mechanische recycling is milieukundig het meest voordelig, maar inzameling wordt echter pas rendabel bij bepaalde volumes. Voor een duurzaam circulair systeem wordt enerzijds de recycling geoptimaliseerd, maar ook de primaire productie die nog nodig is. Dit is geïllustreerd in Figuur 1.

Figuur 1 Plastics - een circulaire economie; de transitie van nu naar 2030-2050



Op basis van bovenstaande conclusies, zijn in Box 2 zijn de randvoorwaarden voor een goede integratie van biobased plastics in de circulaire economie samengevat.

Box 2 **Biobased plastics in de circulaire economie: randvoorwaarden**

- Optimaliseer de inbreng in de economie:
  - **garandeer duurzame landbouwpraktijken;**
  - **maximaliseer verlaging van CO_2-eq;**
  - **minimaliseer indirecte veranderingen in landgebruik (ILUC);**
  - **bouw het gebruik van fossiele grondstoffen af.**
- Optimaliseer de mechanische recycling:
  - **minimaliseer verliezen;**
  - **werk toe naar de verwerking van (niet drop-in) biobased plastics bij recycling.**
- Behandel zwerfvuil als een apart probleem: **biologisch afbreekbare plastics vormen geen oplossing.**
- Gebruik bioafbreekbare bioplastic alleen als deze eigenschap functioneel is (**bijv. in land- en tuinbouw)** en/of als de eigenschap co-voordelen heeft **(bijv. als drager van voedselresten en/of als vervanging van voedselverpakkingen die nu leiden tot een vervuiling van de organische afvalfractie).**

Beleidsaanbevelingen

We raden aan beleid dat zich richt op het stimuleren van biobased plastics te integreren in de huidige beleidskaders voor afval (LAP 3) en de circulaire economie. Hierbij moet de nadruk komen te liggen op preventie (als eerste), hergebruik (als tweede), recycling (als derde) en daarnaast ook op verduurzaming van de productie van nieuwe plastics. Hiervoor zijn biobased plastics een interessante oplossing, *als het type biobased plastic voldoet aan duurzaamheidscriteria*. Biobased plastics bieden in de meeste gevallen milieuvoordelen, maar om risico's te vermijden en in te perken, stellen wij voor alleen actief te stimuleren als de plastics aan duurzaamheidscriteria voldoen. Wij hebben negen beleidssuggesties:

Duurzaamheidscriteria als voorwaarde voor stimulering:

1. Stimuleer (op welke manier ook) alleen biobased plastics die voldoen aan duurzaamheidscriteria. Introduceer een reeks duurzaamheids- en kwaliteitscriteria voor certificeringssystemen voor de biomassa die wordt gebruikt bij de productie van biobased plastics. Baseer deze criteria op werk dat is uitgevoerd in samenwerkingsverband tussen overheden, industrie en NGO's die zich bezighouden met dit onderwerp (bijvoorbeeld de projectgroep duurzame productie van biomassa (Cramer, Corbey), als onderdeel van het Energie Akkoord en de Green Deal *Green Certificates*. Deze duurzame criteria zouden kunnen bevatten:
   - een minimum CO_2-eq reductiepercentage, waarbij ILUC wordt meegenomen, en een minimum biobased inhoud[2];
   - een verbod op directe verandering in landgebruik (zoals in de Green Deal Green Certificates);
   - verplichtende regelgeving gericht op duurzame landbouwpraktijken (zoals in de Green Deal Green Certificates).

[2] Als aanvulling op de CO_2-doelstelling zou er een minimum deel biogene koolstof kunnen worden vastgesteld. Dit kan aangetoond worden met verschillende methoden, ofwel fysiek (gemeten) of administratief (massabalans).

Reguleren:

2. **Verbied het labelen van (verpakkings-) materiaal als biologisch afbreekbaar**. Gebruik de term ‘industrieel composteerbaar’ voor verpakkingen en dragers van voedselresten, waarvan de inhoud plus de verpakking/drager bij het GFT-afval terecht kan komen.
3. **Introduceer een (Europees) verbod op oxo-degradeerbare plastics**. Deze plastics kunnen niet (mechanisch) gerecycled worden, zijn niet bioafbreekbaar en kunnen problemen veroorzaken in het (mechanische) recycling systeem.
4. **Formuleer specifieke standaarden voor water- en bodem afbreekbaarheid** voor producten die een hoog risico hebben om onbedoeld in het milieu terecht te komen.

Communiceren:

5. Voor een minimale impact op het milieu, is het belangrijk dat burgers hun afval op de goede manier scheiden. Organiseer een **campagne die goed recyclinggedrag** stimuleert. Informeer burgers hoe om te gaan met biobased plastic afval. Suggesties:
   - logo’s op verpakkingen, zoals ontwikkeld door het KIDV;
   - afdanken van bioafbreekbare biobased plastics bij het GFT-afval alleen stimuleren in geval van co-benefits.

Stimuleren (biobased plastics die aan duurzaamheidscriteria voldoen):

6. **Subsidies**: subsidieer biobased plastics die voldoen aan de duurzaamheidscriteria.
7. **Duurzaam inkopen**: maak biobased (en gerecyclede) plastics onderdeel van het (overheids)inkoopbeleid.
8. **Financiële instrumenten**: bijv. lagere tarieven voor het Afvalfonds Verpakkingen, en andere instrumenten zoals onderzocht voor een studie naar duurzaam hout (CE Delft, 2015).
9. **Verbeter recyclesystemen** voor fossiele plastics en biobased plastics. Organiseer recycling voor biobased plastics met groeipotentieel, die nu niet uitgesorteerd worden in monostromen. Maak met alle stakeholders een plan voor recycling van biobased plastics. Zorg voor financiële compensatie voor recycling voor andere stromen dan verpakkingsafval.

1 Introduction

Plastic is a common material that is used for a wide range of applications. The need for alternatives grows with growing concerns about climate change, dependence on fossil resources and occurrence of persistent plastics in the environment. Also since the "Circular Economy" is central to resource policy in the Netherlands and Europe (Ministerie van I&M, 2016) the use of biomass by industry is often mentioned as a way to 'close the loop'. Produced sustainably, biomass is a renewable resource. When degraded or incinerated at the (ultimate) end-of-life only biogenic CO_2 is emitted. When recycled it avoids the use of other raw materials.

The Dutch Ministry of Infrastructure & Environment and the Ministry of Economic Affairs want insight into the desirability of biobased plastics to answer the following question: *'Under which conditions are biobased plastics (biobased plastics, both biodegradable and non-biodegradable) compatible with the circular economy?'*. To assess compatibility with the circular economy, the impact on climate change, the use of (natural) resources and the impact on plastic soup, as well as current and potential end-of-life options are explored.

1.1 Research questions

In this report the term 'biobased plastics' is used for all biobased plastics, either biodegradable or non-biodegradable. In the case something relates solely to biodegradable biobased plastics, this is explicitly mentioned. Use of a renewable resource does not, however, make a material necessarily sustainable, or more sustainable than the fossil alternative. For example, in some cases the energy use, the fertilizer use or the land-use (change) for the production of the biobased plastic influences the environmental impact negatively relative to its fossil counterpart. In order to make a sustainability assessment a number of aspects need to be assessed, among which are:
- reduction of CO_2-eq emission over the whole life cycle;
- use of (natural) resources, not only fossil fuels and metals, but also e.g. fertile land;
- reduction of 'plastic soup' (persistent plastics), especially in the marine environment.

Because of different (environmental) issues in different life cycle phases, it is important to look at the whole life cycle. This study therefore includes all life cycle phases: production, use and end-of-life, answering questions like:
- When is use of (biodegradable) biobased plastics preferable, based on criteria for CO_2 reduction, use of resources and plastic soup?
- When is use of biodegradable biobased plastics preferable to use of non-biodegradable biobased plastics?
- Can biobased plastics play a role in limiting litter and minimizing plastic soup risks?
- Do biobased plastics influence end-of-life treatment options, and how? Which problems occur?
- How can policy ensure consumers follow advice on proper disposal?

1.2 Research approach

To answer these questions, a thorough literature study was done in which all important aspects for the relevant biobased plastics were summarized.
This information can be found in Annex A. This detailed literature study is not meant to be used to compare the different biobased plastics, but rather to extract the most important issues related to sustainability of biobased plastics in general.

The literature research was supplemented by interview with relevant stakeholders, from producers of biobased plastics to end-of-life treatment experts. The entire list of interviewed stakeholders can be found in Annex B.

Parallel to this study, a study was done by Wageningen University & Research Centre (WUR) on the characteristics of biobased plastics. Information between the two research groups was shared and synchronized.

1.3 Report guide

A more elaborate introduction on biobased plastics is given in Chapter 2 and 3; Chapter 2 focuses on the scope and Chapter 3 focuses on current production and applications.

Chapters 4, 5 and 6 respectively focus on issues related to the impact on climate change, resource use and the influence on litter and plastic soup.
Chapter 7 summarizes the options for end-of-life treatment and introduces a waste hierarchy based on the European waste hierarchy but translated to both non-biodegradable and biodegradable biobased plastics.

In Chapter 8 the main conclusions are summarized. In Chapter 9 these conclusions are translated to policy suggestions for biobased plastics in a Circular Economy.

Detailed info on different biobased plastics can be found in Annex B.
All interviews can be found in Annex C.

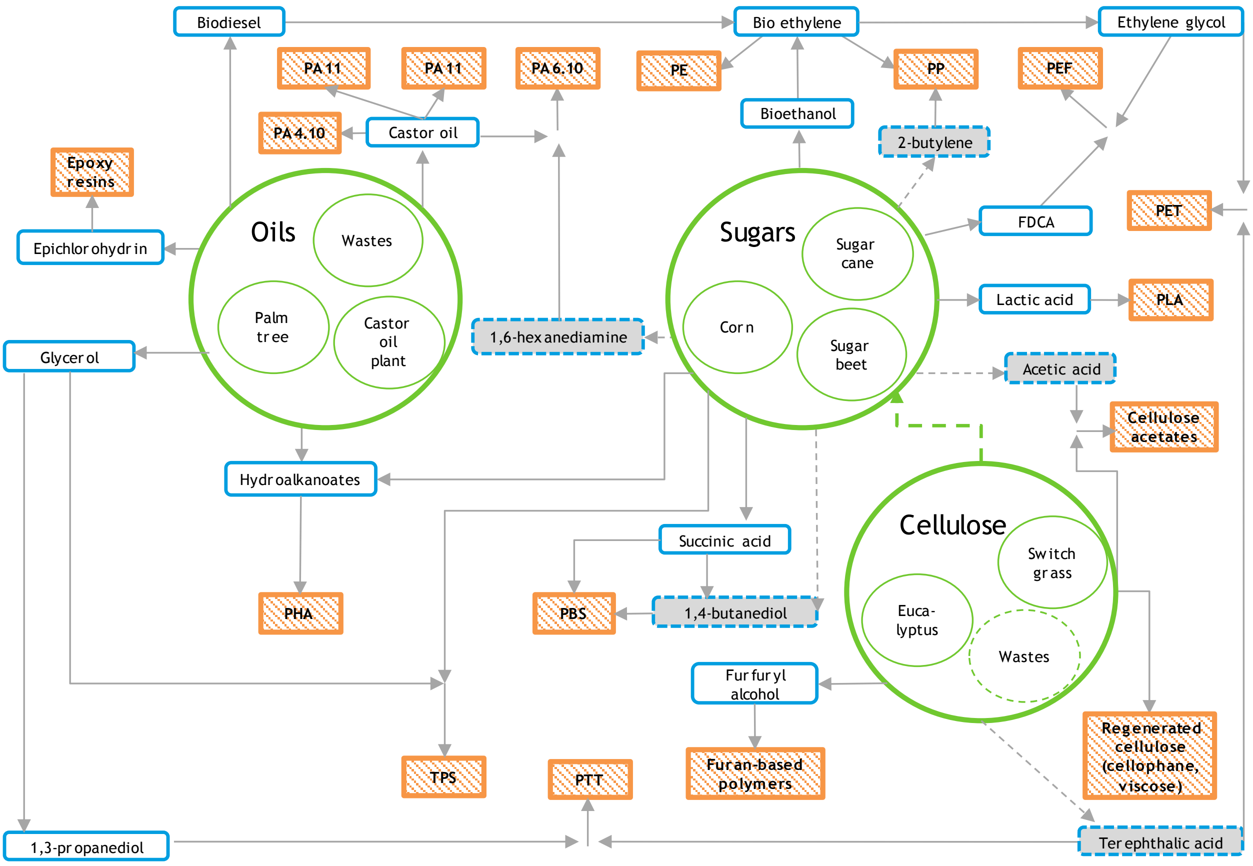
2 Biobased plastics

The term ‘bioplastics’ is often used for a group of different materials; materials based on biomass, materials that are biodegradable, or a combination of both. For example, there are also fossil-based biodegradable materials and also biobased materials that are not biodegradable. Biobased plastics can also occur in blends or in multilayer structures with fossil-based plastics. Therefore, we use the term ‘biobased plastics’.

> In this study the term ‘biobased plastics’ is used for *biodegradable or non-biodegradable polymers based on renewable (biomass) sources*. We focus on biobased plastics which are either already 100% biobased or have the potential of becoming 100% biobased. In the case something relates solely to biodegradable biobased plastic, this is explicitly mentioned.

Figure 2 shows the raw resources and intermediates used for the production of biobased plastics that are on the market today and that are either already 100% biobased or have the potential of becoming 100% biobased. As can be seen in the figure, a lot of different types of resources can be used, to produce a lot of different types of biobased plastics.

Figure 2 Biobased plastics, their intermediates and raw resources. Solid line: currently on the market, dashed line: future options



Orange boxes are biobased plastics, blue boxes are intermediates and green circles are raw materials. Blue boxes that are coloured grey are intermediates that could be produced from biobased resources but are currently still fossil-based. Green dotted lines indicate future developments.

There are three main categories of plastics:
1. Thermoplastics (thermosoftening).
2. Thermosets (resins).
3. Elastomer (rubber).

These categories will be used to categorize the different biobased plastics. The main focus of this study will be the thermoplastics. Different types will be examined in more detail, while the thermoset group and the elastomer group will be regarded as groups (Annex A).

2.1 Biobased thermoplastics

Thermoplastics are polymers which liquidize when heated and hard when cooled. The process is reversible; this means a product can be reheated and reshaped. This makes thermoplastics recyclable (PlasticsEurope, 2016). Different thermoplastics either already are 100% biobased or that could potentially be made 100% biobased are categorized in Table 2.

Table 2 Biobased thermoplastics

	Non-biodegradable	Biodegradable (in industrial composting installation)	Biodegradable (in water in nature)
On the market today	Bio-PE (drop-in) PA11 PA10.12 PA4.10	PLA PHA *PHA/TPS blends* *PLA/PHA blends*	PHA Regenerated cellulose
Under development (not on the market yet)	PEF Bio-PP (drop-in) Bio-PVC (drop-in) Bio-PET (drop-in) Bio-PTT (drop-in) PBT PA6 PA6.10PA66 PA12	Bio-PBS Cellulose Acetate PGA *PLA/TPS blends* *Bio-PBS/TPS blends*	

Plastics listed in the table are 100% biobased. Partially biobased versions of some of these plastics exist, such as bio-PET and Bio-PTT.
Note: Drop-in biobased plastics: chemically identical to their fossil counterparts.

The plastics listed in Table 2 could be mixed (blended) with PBAT or with PCL. PBAT is being developed to be partly biobased (it currently is fossil-based), while PCL is fully fossil-based. Both are biodegradable plastics.
Common blends are PBAT/PLA and PBAT/TPS.

Characteristics and other details specific to all these biobased plastics can be found in Annex A. Not all of these plastics are prevalent in the current market. More about the market of these different plastics can be found in Chapter 3.

2.2 Other biobased plastics – thermosets, bio-composites and elastomers

Biobased thermosets

Thermosets are plastics, which unlike thermoplastics, cannot be reheated and reformed. There are a few examples of 100% biobased thermosets which are already on the market (Oever & Molenveld, 2012a):
- furan-based polymers;
- bio-epoxy resins.

Bio-unsaturated polyesters (UPE) and bio-polyurethanes (PUR) are currently partially biobased.

Bio-composites

Bio-composites are built up out of a resin and a fibre. The resulting material has properties which are a mix of the individual materials. Either one or both can be biobased. Examples of natural fibres for biocomposites are: Flax, hemp, kenaf, jute, sisal, ramie, abaca, cotton and coconut.

Biobased elastomers

Elastomers have both viscosity and elasticity, making them pliable and withstanding deformation. Elastomers include natural and artificial rubber (PlasticsEurope, 2016). Fully biobased elastomers that are currently on the market are natural rubbers. Partly biobased rubbers include biobased EPDM.

2.3 Standards and certification schemes for biobased plastics

A number of standardization and certification schemes that focus on certain characteristics regarding the biodegradability and biobased nature of plastics are currently in operation. Here, several standards are summarized.

Organic carbon content

For the biobased content of plastics, the CEN (European Committee for Standardization) developed a method that specifies the calculation method for determining the biobased carbon content in plastic materials and products.

It still remains an issue of definition which percentage of biobased carbon content is deemed sufficient to be able to call a plastic product 'biobased': different standardization bodies use different minimum percentages of biobased carbon content. Vinçotte, an organization that certifies biobased products, lists two basic requirements for a plastic to be considered a biobased product: the total organic carbon content (TOC) of the material must be at least 30%, and its biobased carbon content (BCC) should be at least 20% of the TOC (Vincotte, 2013). DIN CERTCO provides a certification scheme that demands a minimum TOC of 50%, and a similar BCC of 20%.

The biobased content of plastics is especially relevant for plastics that are produced via production routes also used for fossil-based plastics. Examples of these are the bio-PE and bio-PP produced by Sabic, which are produced by adding animal fats and plant oils in addition to fossil-based feedstock to the production of plastics.

In Table 3, certificates that require a certain percentage of organic carbon content of a product are shown.

Table 3 **Certification schemes for biobased carbon content and biobased content**

Vinçotte: OK Biobased	
Basic requirements: – The product most have a total organic carbon content (TOC) of at least 30% *(expressed as proportion of the reference mass)* – The product must have a biobased carbon content (BCC) of at least 20% *(expressed as proportion of the TOC)* Number of stars: – 1 star: 20% ≤ BCC ≤ 40% – 2 stars: 40% ≤ BCC ≤ 60% – 3 stars: 60% ≤ BCC ≤ 80% – 4 stars: : 80% ≤ BCC	
DIN CERTCO: DIN- Geprüft	
Basic requirements: – The specified minimum organic proportion is 50% – The proportion of biobased carbon to total carbon must exceed 20% Different quality levels (based on biobased carbon proportion of total carbon): – 20 to 50% – 50 to 85% – > 85%	

Source: (Vincotte, 2013) & (DIN Certco, 2015).

For the certification of the biobased content of plastics, a new European biobased content certification system, based on EN16785-1, was launched at the 11th European Bioplastics Conference in Berlin on 29 and 30 November 2016. The certification system is available at www.biobasedcontent.eu.

Biodegradability and compostability

With regard to biodegradability and compostability, standards are more complex. In the presence of oxygen, biodegradable plastic is converted into water and CO_2 by micro-organisms. When no oxygen is present, methane can be produced. Both degradability as well as compostability depend on conditions such as temperature, the material and the application (European Bioplastics, 2016). Non-biodegradable plastics will not be converted by micro-organisms. Whether a plastic is biodegradable does not depend on the resource used; it depends on its chemical structure. This means biobased plastics can be non-biodegradable, whereas fossil-based plastics can be biodegradable (European Bioplastics, 2016), although most are not.

The biodegradability depends on the 'aggressiveness' of the environment. Aggressiveness increases from marine water to fresh water to soil and to a composting facility (OWS, 2013). An industrial composting installation creates a more aggressive environment than home composting.

The most important standards related to biodegradability and compostability are developed by ISO, CEN (The European Committee for Standardisation), ASTM (American Society for Testing and Materials), DIN (Deutsches Institut für Normung) and JIS (Japanese Institute for Standardisation).
Standards by these organizations are aimed at different ways of composting, at different user levels and at treatment/disposal in different environments.

The EU harmonized standard (EN 13432) that determines whether a plastic is biodegradable in an composting environment aims at packaging materials while the ‘sister’ standard EN 14995 (‘Plastics – Evaluation of compostability’) is exactly the same in content, but broadens the scope of plastics when used in non-packaging applications. The norms for industrial composting in both standards are:

– biodegradation: at least 90% of the materials have to be broken down to CO_2 by biological action within six months at 58°C +/- 2°C;
– disintegration: after twelve weeks, at least 90% of the product should be able to pass through a 2 x 2 mm mesh;
– chemical composition: certain limits regarding volatile matter, heavy metals and fluorine should be obeyed;
– quality of compost and ecotoxicity: the quality of the final compost should not decline as a result of the added packaging material.

For home composting, degradation in soil, in fresh water and in marine water several standards exist (OWS, 2013) but they are not harmonized EU-wide. An existing standard for biodegradation of plastics in marine environments is developed by ASTM (OWS, 2013).
Certification body Vinçotte provides additional certification schemes, largely based on EN 13432. Test temperatures and durations are, however, different. Table 4 summarizes Vinçotte’s and other relevant certificates, including certificates that apply to marine water, fresh water and soil environments.

Table 4 Certificates relating to the biodegradability or compostability of products. In the Netherlands, the Seedling logo is often used; the OK Compost logo is less common

Seedling logo – owned by European Bioplastics; – proves that a product is certified industrially compostable according to the EN 13432/14995 standards; – certification process is carried out by DIN CERTCO and Vinçotte.	
OK Compost – owned by Vinçotte; – ensures that (packaging) material meets all requirements of the EN 13432/14995 standards.	
OK Compost Home – owned by Vinçotte; – similar to OK Compost (meets EN 13432/14995 requirements), some differences: • biodegradation is tested at ambient temperatures (between 20 and 30°C) instead of 58°C +/- 2; • the period of application in the biodegradation test is maximum of 12 months (instead of 6 months).	
OK biodegradable SOIL – owned by Vinçotte; – EN 13432/14995 are adapted for degradation in soil, this includes the following adaptations: • the period of application for the biodegradation test has a maximum of 2 years (instead of 6 months); • no disintegration requirements have to be met.	

OK biodegradable WATER – owned by Vinçotte; – EN 13432/14995 are adapted for degradation in fresh water, this includes the following adaptations: • the biodegradation test temperature should be between 20 and 25°C); • 90% relative or absolute biodegradation should have occurred after 56 days of testing; • no disintegration requirement has to be met.	
OK biodegradable MARINE – Owned by Vinçotte. – Based on American Standard ASTM D 7081: “Standard Specification for Non-Floating Biodegradable Plastics in the Marine Environment”, and adapted for degradation in seawater (pelagic zone only). – It is not allowed communicate the certification (show logo) about products that are often littered and might encourage potential customers to produce litter. Only a few products that are functional in a marine environment (e.g. fishing lines and bait) are allowed to use this logo.	

3 Applications

Different biobased plastics are used for different applications. In Section 3.2 we zoom into the current production quantities for different applications. We zoom into the different types of applications and the characteristics needed for these applications (what are the quality demands in the use phase?).

The market volumes for biobased plastics are still low compared to conventional plastics' volume. The global production capacity of biobased plastics in 2016 is, according to Figure 5, around 4.2 million tons.
Global fossil-based plastic production is estimated at 311 million tonnes in 2014 (WEF, 2016). Currently, biobased plastics could thus (maximally) cover around 1.4% of the global plastic market.

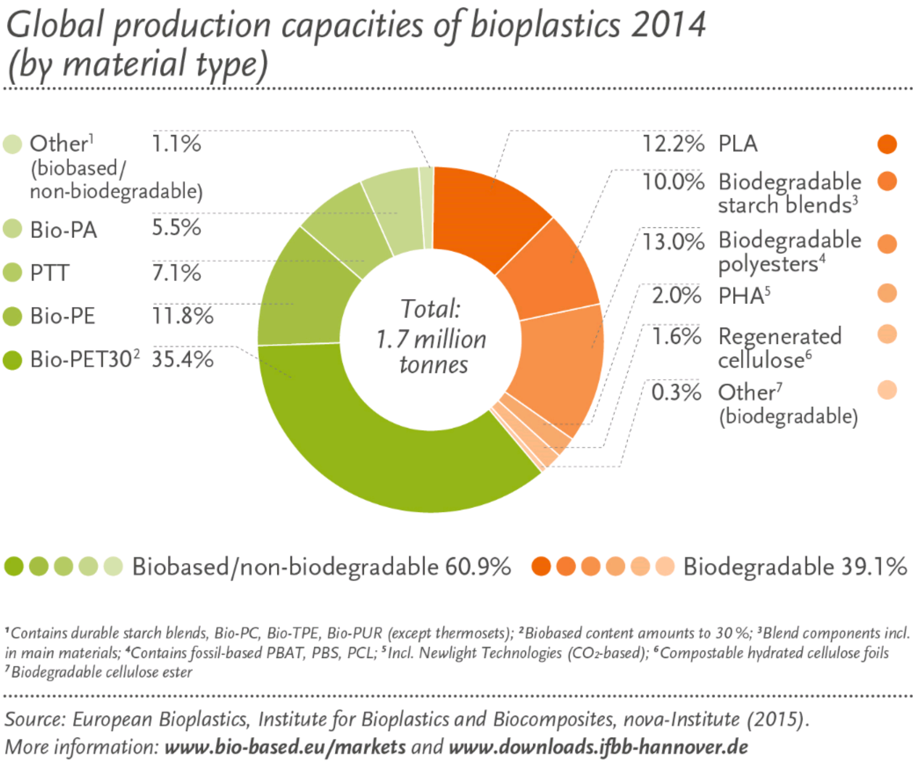
The share of biobased plastics in total production capacity is low if you compare it with the market share of biofuels, which replace fossil fuels (5-10% in the EU), or bio-energy (which also replaces fossil sources).
This difference is mainly caused by a different policy approach by governments. For biofuels there is an extensive policy scheme with policy goals, obligations, monitoring and sustainability criteria. For biobased plastics such policies are not present.

3.1 Biobased plastics and conventional plastics – production capacities

In 2013 polyethylene was responsible for the largest share of the market volume of conventional plastics, at around 35%. It was followed by polypropylene (24%), PVC (16.5%) and PET (8%) (Grand View Research, 2014).

For biobased plastics, as can be observed in Figure 3, the largest share of the production capacity is made up of bio-PET30, at around 35%. It was followed by biodegradable polyesters (13%), PLA (12%) and bio-PE (12%).

Figure 3 **Global production capacities of biobased plastics 2014**



Note: Biodegradable and non-biodegradable are just characteristics of the material and not as a qualification of sustainability.

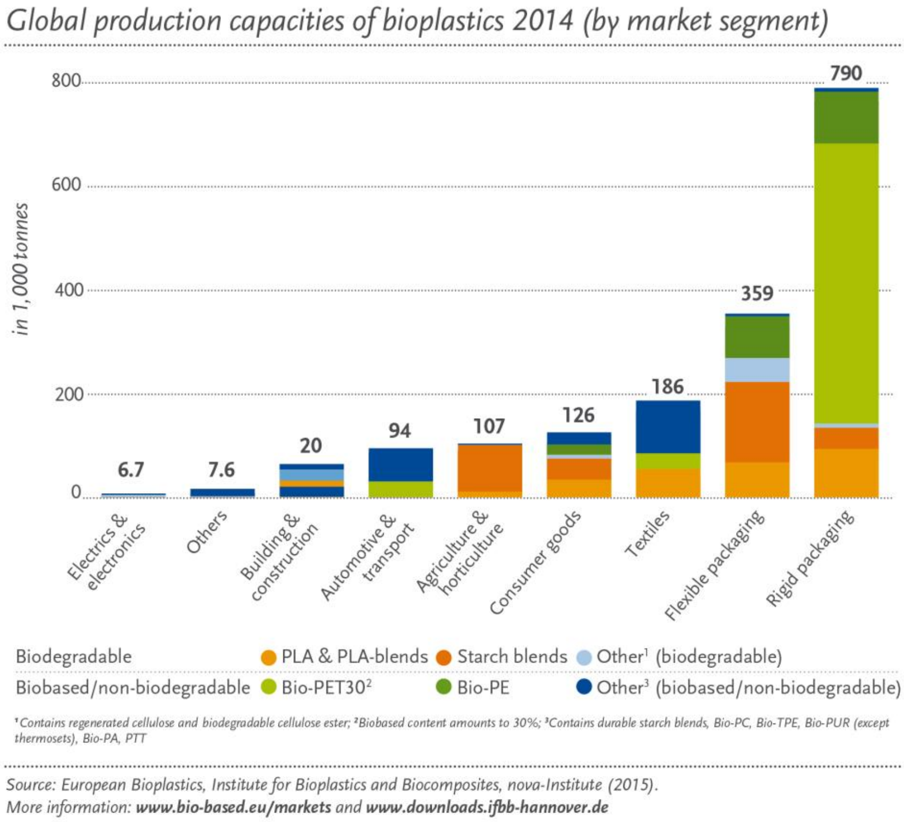
Source: (European Bioplastics, 2015).

Figure 4 shows the global production capacity per type of biobased plastic. Around 40% of the production capacity of biobased plastics consisted of biodegradable biobased plastics in 2014 (PLA, starch blends and other (biodegradable)).

It is unclear how many of these biobased plastics have or will be biodegraded at the end-of-life by means of composting or fermentation. Biodegradables are especially used in certain applications such as agriculture/horticulture. Of the non-biodegradable plastics, bio-PET30 was the largest category (30 indicates that the biobased content amounts to 30%).

The category rigid packaging is by far the largest category, and is projected to account for almost 75% the total production capacity in 2019.

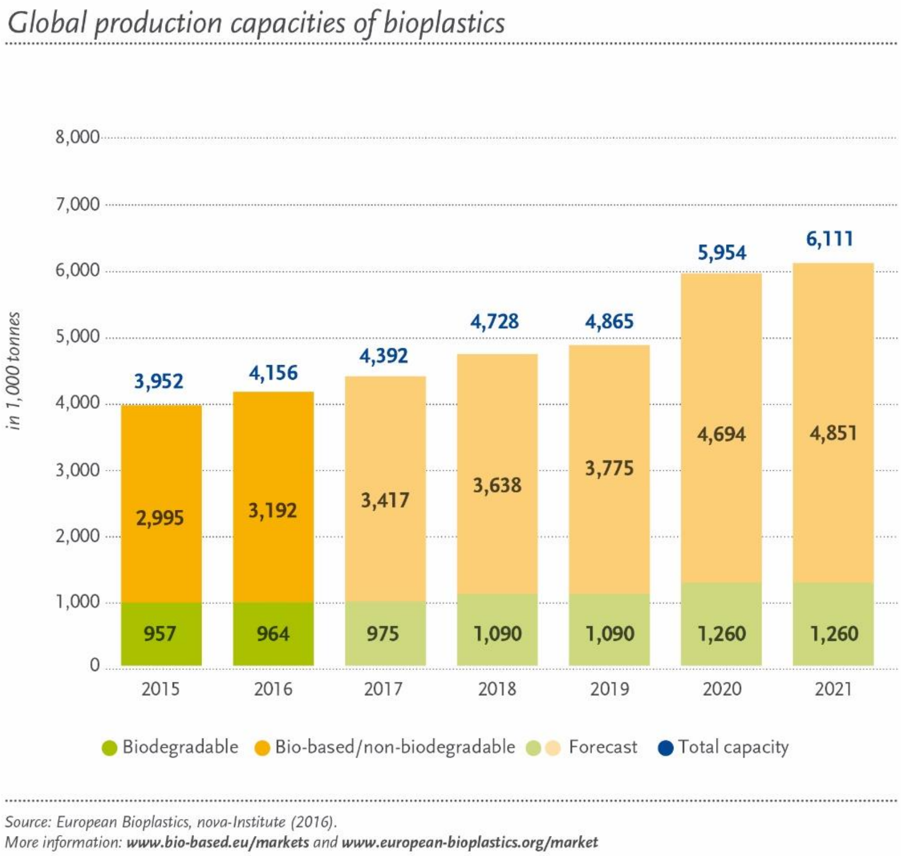
Figure 4 Global production capacities of biobased plastics 2014 (by market segment)



Source: (European Bioplastics, 2015).

Figure 5 shows the projection for global production capacity quantities of (partially) biobased plastics until 2021. Comparing the projected production capacities for 2021 with the production capacity in 2016 shows that production capacity of (partially) biobased plastics in this period will increase almost 1.5 times.

Figure 5 **Projected global production capacities of biobased plastics; 2015-2021**



Source: (European Bioplastics, Nova-Institute, 2016).

3.2 Different biobased plastics for different applications

As shown in Figure 4 and Figure 5 different biobased plastics can be used for different applications, and use of biobased plastics for different applications varies substantially. In Sections 3.2.1 to 3.2.7 we elaborate on these different types of applications, and describe their context in relation to the global market of fossil-based plastics.

3.2.1 Rigid packaging

Rigid packaging is responsible for the largest global share of production of biobased plastics. Many examples of rigid packaging are available: from beverage bottles, jars, cups, buckets, and containers to cosmetics packaging. As all packaging products, these products have relatively short useful lifetimes before ending up in waste- or litter streams.

Most often used biobased plastics for this application are bio-PET30, bio-PE and PLA.

In most European countries (also in the Netherlands since 2010) there are collection and recycling schemes for rigid plastic packaging. This makes the recyclability of this application of biobased plastic important.

Bio-PET and bio-PE are developed to emulate the properties of their fossil-based counterparts: they have equal lifetimes, applications and recycling capabilities (GESAMP, 2015). Biobased rigid packaging already forms part of today's recycling stream: bio-PET and bio-PE fit into existing recycling systems initially developed for fossil-based plastics (European Bioplastics, 2015; WUR, 2014). Rigid packaging is, together with commercial films, mentioned as segment within the plastic market that is likely to have the most attractive recycling cost-benefit balance (WEF, 2016).

3.2.2 Flexible packaging

Flexible (conventional) plastic packaging is the most widely used type of packaging globally: it accounts for almost 30% of volume share of all packaging types, including paper, metal and cartons (PMMI, 2015). Flexible films make up 55% of all (fossil and biobased) plastic packaging (Molenveld & Oever, 2015). Low density PE is the most used plastic film material, while PET and PP have many applications in flexible packaging as well. Flexible PVC packaging has almost disappeared, due to health risks associated with the release of phthalate plasticisers and due to problems with chlorine in the waste treatment phase.

Biobased flexible packaging is the second largest application of biobased plastics. Starch blends are used as biobased alternatives in flexible packaging. Thermoplastic starch however has limited uses, due to its ability to change its mechanical properties when exposed to humidity. PLA, which is from origin a rather brittle material, can also be modified or used in blends to make it suitable for application as flexible packaging (Shirai, et al., 2013).

PHA (blended) can also be used in films, but is still relatively expensive and has the disadvantage of not being transparent. Currently and as projected for the coming years, PHA has a negligible market share. Stretch film can also be produced from bio-PE.

In some cases, biodegradable plastic packaging has functional benefits, such as wrappers for tablets with dishwasher detergent. Biodegradable flexible packaging can also create a co-benefit when used in combination with organic material such as bags to collect kitchen and garden waste and packaging for fruits and vegetables; either more food and garden waste can be collected or the collected food and garden waste is not contaminated with fossil plastics.

3.2.3 Textiles

Textiles form an important application of fossil-based plastics. More than 60% of the global production of PET is used in fibres for the textile industry, while 30% is used in plastic bottles (Park & Kim, 2014). Globally, just over 50% of PET is collected for recycling. However, only 7% is recycled bottle-to-bottle, while 72% of recycled PET is converted into fibres (WEF, 2016). These fibres can subsequently be used in many types of textiles, depending on their linear density and quality.

Biobased plastics can be used in textile products such as clothing, carpets, furniture, and automotive parts. Biobased plastics used in textile products are PLA, PHA, cellulose, bio-PET, and bio-PTT. The former three are, however, hardly used, and mainly bio-PET and bio-PTT are currently applied in textile products.

Domestic washing of textiles as a source of plastic microfiber emissions has received much attention in literature. It is estimated that 0.0012 weight percent of loose microfibers is released into wastewaters during every washing (Pirc, et al., 2016). These microfibers accumulate in oceans, together with plastic (micro)material from other sources, where they form an ecotoxicological and ecological threat. While certain biobased plastics show good results in terms of lowering CO_2 emissions, applications aimed at targeting this issue are not widespread.

3.2.4 Consumer goods

The category consumer goods is very diverse, which is reflected in the variety of different types of biobased plastics as shown in Figure 4. Examples of consumer goods made from biobased plastics that are currently on the market are tableware, toys and disposable cups. The type of materials used in these goods depends on their required durability. Consumer goods made from biobased plastics can, depending on their biodegradability, be disposed similarly to conventional plastics.

Consumer goods are, in contrast to larger-scale applications, usually disposed through conventional waste systems. This means that they are either recycled or incinerated after post-consumer separation, incinerated or recycled after being collected separately, or disposed along with food and garden waste (e.g. compostable bags).

3.2.5 Agriculture and horticulture

In the EU, around 2 to 3 million tons of plastic is used each year in agricultural applications (Glenn, et al., 2014). About half of this plastic consists of films. While PE is still widely used for these films, (partially) biobased and biodegradable alternatives have become increasingly popular.
These alternatives are mainly based on starch blends, and have three major applications: the covering of greenhouses, as agricultural mulch film, and as materials that enable the controlled release of fertilizers (Lu, et al., 2009). Plastic in the Netherlands is hardly ever used to cover greenhouses, but the other two applications are relevant.

After use, starch-based films can be ploughed into soil and will biodegrade over time, instead of being collected and landfilled, recycled or burned. They should fulfil the requirements for biodegradability in soil.
If biodegradable plastics are biodegradable in soil they provide an advantage over their non-degradable fossil counterparts, since parts of such films will remain in the soil. This is also true for specific products like pots for water plants, ties and tapes (currently often PVC).

3.2.6 Automotive and transport

In 2010, the average automotive vehicle used +/- 150 kg of plastics and plastic composites and 1163 kg of iron and steel (Szeteiová, 2010). Three types of plastic constitute around 66% of this weight: polypropylene, polyurethane, and PVC. Plastics are used in virtually all parts of cars (interior, seating, bumpers, exterior, electrical components, etc.). Also, natural and synthetic rubber is used in car tires.

A number of applications for the use of biobased polymers in cars has been identified, some of which are currently commercially applied. Examples of biobased polymers used in cars are; bio-resins, biobased polyurethanes have started to replace fossil-based foams in cars and PLA is applied in for example fibres. Also, biobased polyamides have technical potential to replace petrochemical PA’s.

The use of rubber in car- and truck tires results in substantial emissions of microplastics into the environment. In the Netherlands, each year, 17,300 ton of rubber microparticles are released from road vehicle tire wear (Verschoor, et al., 2016).

3.2.7 Building and construction

Globally, the construction industry is the second largest consumer of plastic, after packaging. In many aspects of construction, different types of plastic have an important role: examples are piping, insulation and wall-covering.

The use of biobased plastics in the construction- and building segment is generally very low, especially in relation to the overall size of the market. As plastics used for construction purposes have long lifetimes, biodegradability is not an asset in this market segment. Some applications of biobased plastics do, however, exist, and have been on the market for some time. For instance, fossil-based insulation materials are sometimes replaced by PLA or bio-polyurethane. Also, the use of biobased composites as construction materials has some attention, while bio-PE could also be applied in piping applications.

4 Climate change

Based on a detailed analysis of different biobased plastics (as shown in Annex A) it can be concluded that biobased plastics, in most cases, lead to a climate change impact reduction in comparison to fossil-based plastics.

Box 3 Conclusions: Climate change

- Biobased plastics, in most cases, realize a climate change impact reduction in comparison to fossil-based plastics.
- To prevent confusion we advise to use a cradle-to-gate analysis to compare biobased and fossil-based plastics. In this analysis the biogenic carbon uptake into the biobased plastic is taken into account.
- The cradle-to-gate climate change impact is mostly influenced by the type of raw material being used. Also the type of electricity being used in the production of biobased plastics has a significant influence, while the transportation distance of the raw materials is less important.
  - For plastics that need fermentable sugars, sugar cane and sugar beet are preferable to cereal crops. Also the production of sugars from lignocellulose seems promising. The greenhouse gas emission savings in comparison to fossil-based plastics is not as high if maize starch is used.
  - By-products: use of by-products influences a product's sustainability; when by-products are used for other purposes, part of the environmental impact is allocated to those purposes (in LCA). Care should be taken that soil quality is maintained at a sustainable level.
- Biobased plastics made from sugar crops or (agricultural) waste have the lowest Indirect Land-use Change (ILUC) risk.
- For biobased plastics, recycling is the most environmentally friendly option for EOL treatment. For some biodegradable plastics no choice needs to be made for EOL treatment, because the biodegradability determines EOL treatment (e.g. plant pots or bags for food waste).

A sustainability scheme for biobased plastics could help to prevent (in)direct land-use change and set targets for GHG emission reduction.

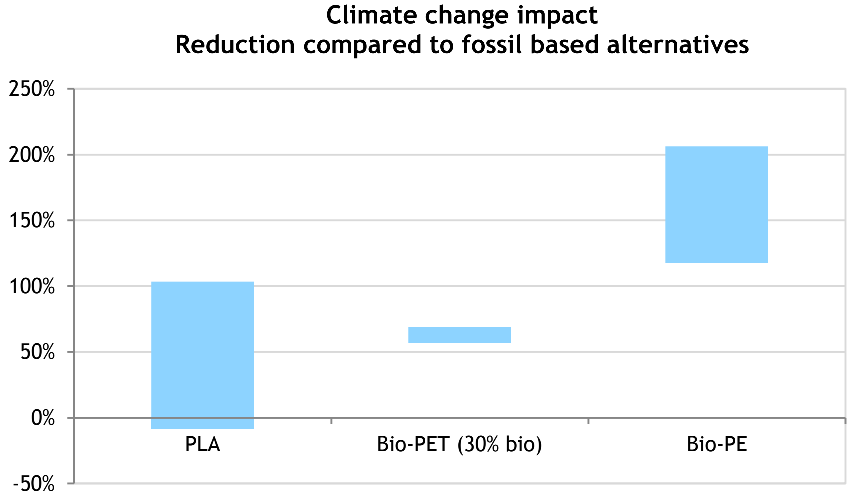
In the detailed study on the climate change impact of different biobased plastics, we found that the climate change impact can differ widely between biobased plastics, and also for one type. This chapter will explore the question; *What are the most important aspects that influence the climate change impact of biobased plastics?*

Figure 6 shows the reduction of climate change impact of three commonly used biobased plastics in 2014 (as shown in Chapter 3). A reduction of 0% means a climate change impact equal to the fossil alternative.

The figure shows the reduction in comparison to the fossil-based alternative. Both PLA and bio-PET are compared to fossil-based PET and bio-PE is compared to fossil-based PE. The figure shows ranges of reduction in cradle-to-gate climate change impact based on different feedstocks. For example, the range for PLA shows the production of PLA from European maize (lowest reduction potential) to production of PLA from Brazilian sugar cane (the highest reduction potential).

The reduction of the climate change impact of bio-PE is greater than 100% and this is due to the relatively high uptake of CO_2 in the biomass, as well as efficient production.

Figure 6 **Climate change impact reduction of three biobased plastics**



Note: Emissions per kg biobased plastic are based on data shown in Annex A. For bio-PE this refers to PE production based on fermentation. The range indicates the difference for use of different raw materials (high reduction potential for sugar cane and a lower reduction potential for maize). The biobased plastics are compared to fossil-based PET (for PLA and bio-PET) and to PE (for bio-PE) from (Ecoinvent, 2016).

Subsequently we will look into the following aspects, from which climate change impact or reduction can arise:
- production of biobased plastics (discussed in Section 4.2);
- indirect land-use change (discussed in Section 4.3);
- treatment at end-of-Life (discussed in Section 4.4).

4.1 Methodology to assess the climate change impact of biobased plastics

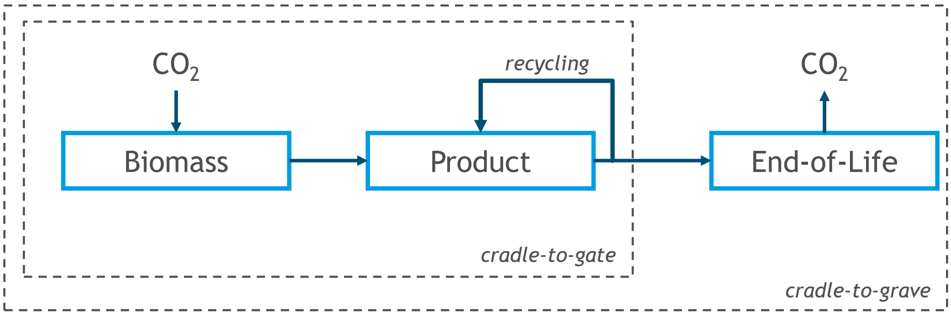
The analysis of different biobased plastics shows that the methodology used for the assessment of the climate change of different plastics is not always comparable among different studies. Biomass absorbs CO_2 in the agricultural phase, and releases it back when it degrades to CO_2 at the end-of-life.
The EN16760 standard specifies that two options can be chosen:
- CO_2 uptake by biomass is included in the model as a negative GHG emission, and at end-of-life when emitted is included as a positive GHG emission;
- CO_2 uptake by biomass is set at zero, CO_2 release at end-of-life when emitted is also set at zero.

These two options give the same results in a cradle-to-grave assessment, although the contributions of different life cycle phases to the overall result will be different. When looking at the impact on climate change of biobased plastics, it is important to choose the right system boundaries. Because end-of-life treatment can vary, comparing a biobased product to a fossil product is more transparent on a cradle-to-gate basis.

In some of the LCA studies we looked at for the elaborate summary of biobased plastic types in Annex A, the CO_2 uptake into the biomass used to produce biobased plastics was not taken into account in cradle-to-gate data. This should be done to make a fair comparison between biobased plastics and fossil-based plastics on a cradle-to-gate base.

Another option is to look at the cradle-to-grave values. In a cradle-to-grave assessments the CO_2 which is absorbed into biomass used for the production of biobased plastic is emitted again at the end-of-life when the biobased plastic is incinerated or biodegraded in case of a biodegradable plastic. Therefore in cradle-to-grave analyses for biobased plastics, a CO_2 uptake should be accounted for in the agricultural phase, and an CO_2 emission should be included in the end-of-life phase when relevant. For fossil-based plastics a CO_2 emission should be included in the end-of-life phase. In case of recycling, the product serves as a carbon sink, at least temporarily. This is shown in Figure 7.

Figure 7 Cradle-to-gate vs. cradle-to-grave



To prevent confusion we advise to use a cradle-to-gate approach in which the biogenic carbon uptake into the biobased plastic is taken into account when a comparison is made on a product level. This approach is also more practical if biobased plastics and fossil plastics are mixed and if the material is not incinerated after use but recycled a number of times. Note that this means that no CO_2 benefit for biobased plastics should be calculated when biobased plastics are incinerated. This is in line with the first option for carbon accounting given in the EN16760 standard.

In Annex A the characteristics of each type of biobased plastic are elaborated on, including the impact on climate change relative to a comparable fossil-based plastic on a cradle-to-gate basis.

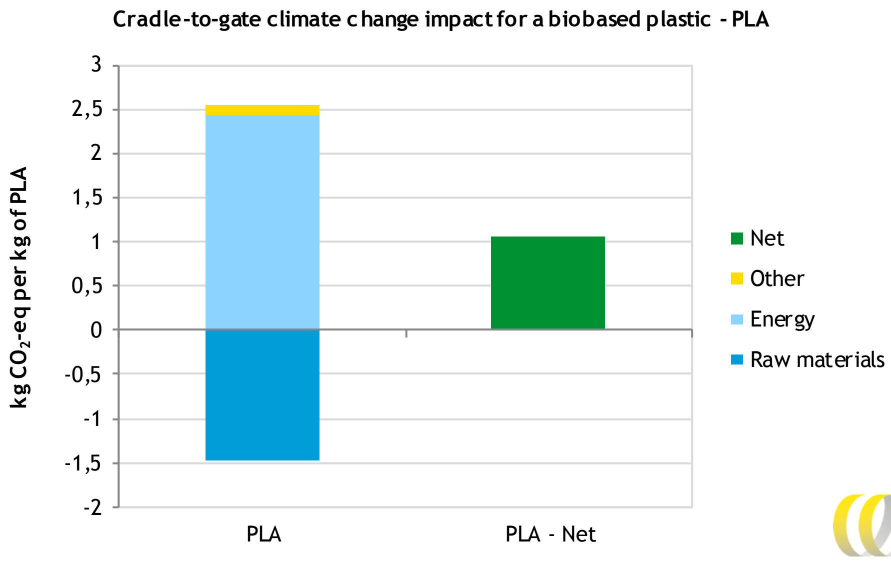
4.2 Production of biobased plastics

Important life cycle phases which influence the climate change impact of biobased plastics are the production of biomass (agricultural phase, including CO_2 uptake) and the processing of biomass. In most LCA's studied in Annex A the life cycle phases were not distinguished, and it was therefore unclear which phase contributes most to the climate change impact of biobased plastics.

For PLA more information is available. Figure 8 shows that the cradle-to-gate climate change impact of PLA is mainly dependent on the raw materials being used (and the CO_2 captured in these materials) as well as the energy used for the production of these biobased plastics.

Figure 8 shows the production of PLA based on (Ecoinvent, 2016). This dataset is based on the production of PLA by NatureWorks in Nebraska[3]. The value for 'raw materials' shown in the figure includes a carbon uptake of 1,833 kg CO_2 per kg PLA, as well as the greenhouse gas emissions related to the production of maize (related to e.g. machinery, fertilizers).

Figure 8 Cradle-to-gate climate change impact of a biobased plastic - PLA



Based on (Ecoinvent, 2016), the PLA process is based on data for production of PLA from NatureWorks in Nebraska, but with an amended energy input.

The following paragraphs delve further into the raw material and energy use of the production of biobased plastics. Transport of the raw materials was also considered, but this aspect generally contributes little to the overall impact (as can also be seen in Figure 8).

Type of raw material used

The GHG savings of biobased plastics are dependent on the type of raw material used. With current technology the lowest greenhouse gas emissions of plastics are achieved when sugar cane is used (Joint Research Centre, 2015). Sugar beet potentially has an even lower GHG emission, but this crop is not often used yet. Also corn stover (a lignocellulose) leads to less greenhouse gas emissions than the use of maize starch for a multitude of plastics studied (Joint Research Centre, 2015).

A quick scan analysis of the net climate change impact of PLA is low, but can be reduced by 80% by using sugar cane as raw material instead of maize starch.

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[3] This process has been amended by Ecoinvent for the specific energy used during production because this is site specific.

(Hermann, 2010) states that with future technologies, for plastics that need fermentable sugars, sugar cane is preferable. Also the production of sugars from lignocellulose seems promising. The greenhouse gas emission savings in comparison to fossil-based plastics are not as high if maize starch is used.

Potentially, wastes and by-products have even higher greenhouse gas emission savings.

Energy used for production

The GHG savings of biobased plastics are dependent on the type of energy being used in the production of the plastics; the climate change impact of different types of energy mixes differs substantially. For example the electricity produced by a coal-fired power plant has much higher GHG emissions per unit energy than electricity produced by means of a hydropower plant.

The climate change impact of a TPS blend reduces ~35% when the plastic is produced with hydropower instead of the typical Dutch energy mix. The electricity produced in the Netherlands is mainly from coal-fired power plants.

This dependency on the energy used is of course also a factor for fossil-based plastics. Fossil-based plastic could be made less CO_2 intensive if more renewable energy would be used in the production.

Use of by-products

By-products are produced during the production of the raw materials used for the production of biobased plastics. An example is the production of bagasse that originates from sugar extraction from sugarcane. If and how by-products are used has an influence on the climate footprint of the biobased plastics.

If the by-products are used as fodder or as feedstock for other biobased products then the carbon footprint of the produced biobased plastic decreases. This is due to the fact that part of the burden of the production of the biobased plastics can be allocated to the co-product (e.g. fodder).

In the case of PLA production from sugar cane net energy is used when the by-products are unused while there is a net-production of energy if the by-products are used as feedstock for energy production (Bos, et al., 2012). The exact impact on the GHG emissions for PLA (or another biobased plastic) of the efficient use of by-products is unknown.

When using agricultural residues it is important to realize that for a sustainable system, not all residues should be removed from the land.

4.3 Risk of land-use change

Here we focus on the potential risks related to potential land-use change(s), as such changes can influence the climate change impact.

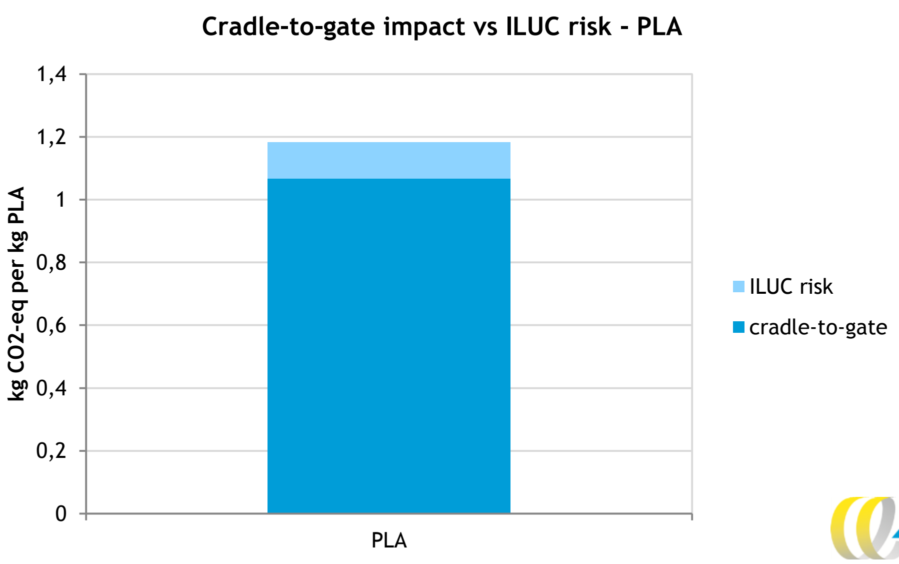
When demand for biomass for new applications increases, there is a risk for (in)direct land-use change. Indirect land-use change (ILUC) is the effect that increasing the market for an agricultural product will expand the total area for production of that product and will increase the amount of deforestation with large GHG and biodiversity effects.

For non-food applications, this is an indirect effect: increasing production for biobased applications forces agriculture for food to seek agricultural land elsewhere, and expand in areas not used for agriculture before. Of course, expansion of land under cultivation is not the only option to increase production; increasing yields is also important, and in many areas the yield gap (gap between current and potential yield) is substantial.

Indirect land-use change (ILUC) factors are uncertain, and the debate is ongoing as to which factors should be used. This is a discussion particularly relevant for biofuels, because biofuels are stimulated by governments to reduce GHG emissions. It can be extended to all biobased products, which do not yet have substantial market shares (in terms of demand for biomass), but for which government stimulation may be an option in the future.

To put this issue in perspective, the ILUC risk (based on biofuel ILUC risk) for the biobased plastic PLA is compared to the cradle-to-gate emission for this plastic. PLA production can be based on maize, and as can be seen in Figure 9 the contribution to the cradle-to-gate climate change impact is limited.

Figure 9 **Cradle-to-gate climate change impact and ILUC risk for PLA from maize**

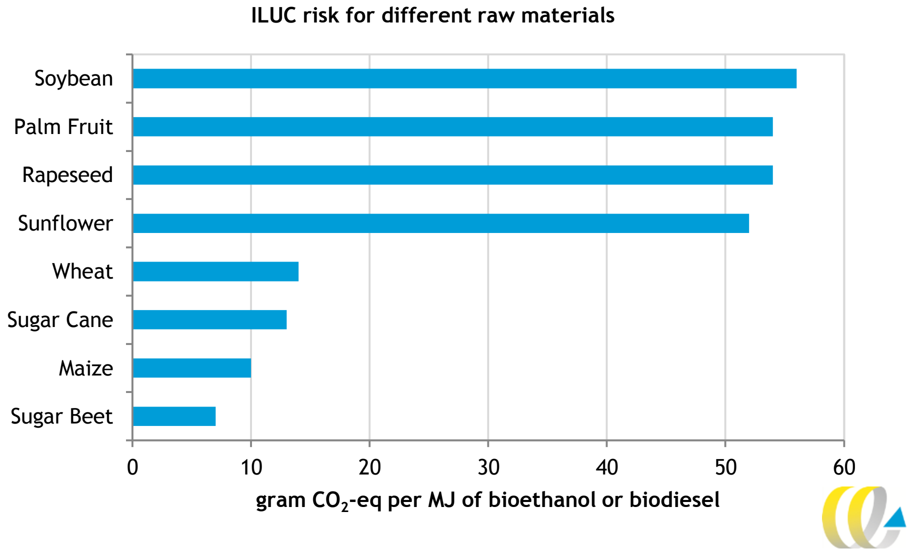


Based on (Ecoinvent, 2016) the PLA process is based on data of production of PLA from Natureworks in Nebraska, but with an amended energy input. ILUC risk is based on (IFPRI, 2011).

Differences in ILUC risk for materials made from the same raw material stem solely from differences in raw material requirements. What is more interesting are differences between different (types of) raw materials. To give an indication of the ILUC risk for different raw materials, the ILUC risk per MJ of biofuel is given for different raw materials in Figure 10. Oil crops have the highest ILUC risk, while cereal crops and sugar crops have a much lower ILUC risk. For biobased plastics, a similar picture is likely; which make sugar crops the most attractive raw material from an ILUC risk on climate change impact perspective.

Although most biobased plastics are made from cereal and sugar crops it is possible to use oil crops. As shown in Figure 10 in case of use of oil crops (soybean, palm fruit) the ILUC risk is much higher and has to be considered.

Figure 10 **ILUC risk for different raw materials**



Source: (IFPRI, 2011).

In general co-products and wastes have no ILUC risk if this coproduct or waste cannot be used for other purposes like feed for animals. If it is used for other purposes, use for production of biobased plastics can indirectly lead to increased demand and an ILUC risk.

Direct land-use change risk

For biofuels only indirect land-use change is quantified, because direct deforestation of land for crop production for biofuels is forbidden under European law. For biobased plastics an international sustainability criteria scheme is not in place and therefore it is theoretically possible that biobased plastics will be made from crops which are produced on recently deforested land. In this case the GHG balance is far worse than if crops are grown on land already used for agriculture.

In the Netherlands, the (voluntary) Green Deal Initiative on Sustainable Provision of Raw Materials for the Material Use of Biomass (called 'Groen-certificaten') includes principles and criteria which prevent direct land-use change (RVO.nl, n.d.). This approach could be introduced in the EU, to ensure prevention of direct land-use change internationally.

Conclusions land-use change, direct and indirect

It can be concluded that the ILUC risk is small (max. 10% of emissions) for wheat, sugar cane, maize and sugar beet. For oil crops the risk is considerable. It would be wise to implement sustainability criteria internationally for biobased plastic sources, similar to those for biofuels, to prevent (in)direct land-use change.

4.4 Influence of treatment at End-of-Life (EOL) on Climate Change

A variety of end-of-life treatment options exist for biobased plastics, most of which are different for non-biodegradable and biodegradable plastics.
Below, the influence on the impact on climate change is summarized, from most to least favourable.
EOL options and their impacts are also elaborated on in Chapter 7.
We consider non-biodegradable biobased plastics and biodegradable biobased plastics separately.

This section is limited to description of the climate change impact of waste treatment options and does not look at the EOL phase for products with functional biodegradability.

Non-biodegradable biobased plastics

For non-biodegradable biobased plastics, the environmentally preferred order of end-of-life treatment is:

1. **Mechanical recycling**
   Environmentally, recycling is the most favourable option, as energy inputs for recovery and recycling are generally substantially lower than primary inputs. Drop-in plastics (e.g. bio-PE) are currently already recycled. Other biobased plastics can likely be recycled, but volumes are currently too low to make this financially attractive.
2. **Incineration with energy recovery**
   When biobased plastic are incinerated with energy recovery, the energy produced is carbon neutral because CO_2 has first been sequestered into the biobased plastic.
3. **Incineration without energy recovery**
   When non-biodegradable thermoplastics are incinerated, biogenic CO_2 is emitted. If production of a biobased plastic (cradle-to-gate) results in less CO_2 emissions than production of its conventional counterpart, the biobased plastic has a lower impact on the environment (cradle-to-grave) when incinerated.

Biodegradable biobased plastics

For certain applications biodegradability has clear advantages. An example is agricultural/horticultural application, in which products can be added to the soil without having to take them out later (e.g. pots) or for example mulch films which can contribute to litter when parts are left on the field. Another example is applications which contribute to the separate collection of food and garden waste. In these cases, no choice has to be made for EOL treatment, as the biodegradability and application together determine this. Either the plastics biodegrade in nature, or they end up in a digester/composting facility.

When biodegradability is not an important functionality the use of non-biodegradable biobased plastics is preferable. Currently there are, however, cases in which biodegradable plastics are used for products which do not necessarily end up in either nature or a digester/composter. In those cases, when a choice for EOL treatment is available, the following prioritization can be made:

1. **Mechanical recycling**
   The environmentally most favourable option is recycling. Because volumes are low, however, this is currently not done from mixed consumer wastes. In some cases, large ‘point source’ volumes are recycled, such as PLA cups at festivals. For biodegradable plastics, it is important to determine

whether they are sufficiently stable to be recycled in multiple cycles (Annex B.8).

2a. Incineration with energy recovery
Incineration with energy recovery of biodegradable thermoplastics has a similar climate effect as the incineration with energy recovery of non-biodegradable thermoplastics.

2b. Anaerobic digestion (production of biogas)
Like incineration with energy recovery, additional climate benefits are achieved when biogas is produced by fermentation of biodegradable plastics. Biogas replaces fossil energy. Anaerobic digestion is categorized as organic recycling in European legislation. Not all biodegradable plastics can, however, be digested in an anaerobic digestion (AD) plant. The fossil biodegradable plastic PBAT is often used in blends, but cannot be digested (Hermann, et al., 2011) (it can be composted). Anaerobic digestion is usually followed by composting in the Netherlands.

3. Incineration
Incineration of biodegradable plastics has a similar climate effect as the incineration of non-biodegradable plastics.

4. Composting
While composting of biodegradable biobased plastics is CO_2 neutral, composting of biodegradable plastics does not produce compost. Composting of biobased plastics is only favourable when it has added value; when it has co-benefits such as increasing the amount of food waste collected to be composted and reducing the amount of fossil plastics ending up in the food and garden waste which is composted. Composting of packaging waste is categorized as organic recycling in European legislation.

5 Use of (natural) resources

The detailed analyses of different biobased plastics show that the following (natural) resources are important to consider in a sustainability assessment of biobased plastics:
- fertile land, including land-use change;
- fresh water;
- phosphate fertilizers;
- energy resources.

In Annex A the characteristics of each type of biobased plastic are elaborated on, including the use of natural resources.

Box 4 Conclusions: use of (natural) resources

- Finite (and/or natural) resources will remain necessary when moving towards a circular economy with biobased plastics.
- The type and amount of finite resources used for biobased plastics are different than those used for fossil-based plastics.
- Biobased plastics need fertile land, fresh water, phosphate fertilizers and because energy is still predominantly fossil-based: non-renewable fossil resources.
- ILUC risk increases with increasing production. Low-ILUC crops (sugar crops) are a first solution, biomass certification and rules for CO_2 accounting for biobased plastics including ILUC a second.
- The order of preference based on environmental impact for raw materials is: waste materials, sugar crops (beet, cane) and starch crops (maize). Last on the list: oil crops.

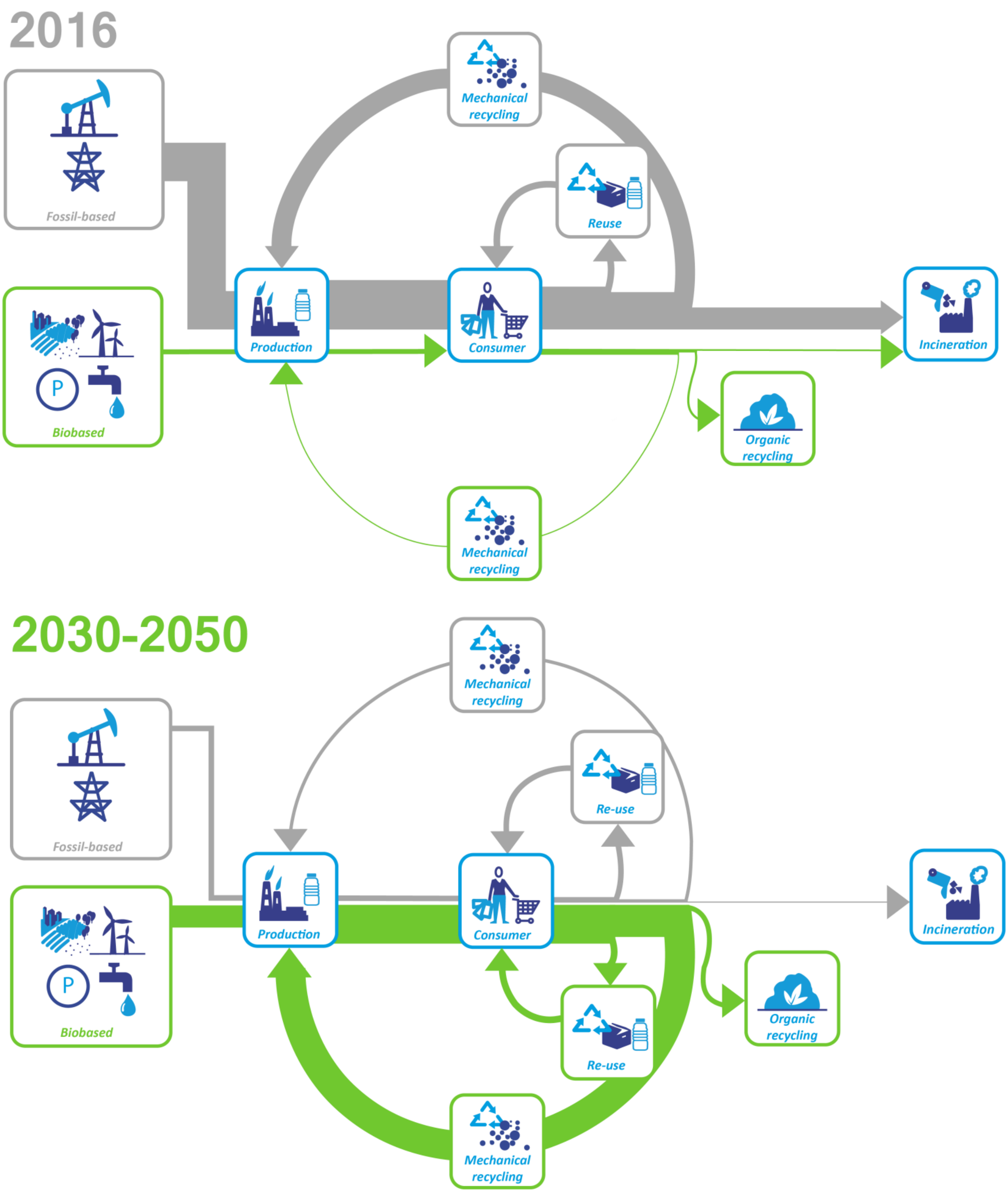
5.1 Influence of circular economy on use of raw materials

Recently the Dutch government has published its programme on a circular economy in the Netherlands (Ministerie van I&M, 2016). This programme initiates a movement towards a circular economy in 2050. Biobased plastics are seen as an integral part of the future circular economy.

Figure 11 shows that to move towards a circular economy two shifts in the plastics sector are necessary:

Shift towards optimal recycling loop: First of all more plastics should remain within the economy and should therefore be recycled. However a complete closing of the loop is unlikely because endless recycling of plastics without quality degradation is impossible and because of inevitable losses from recycling.
Shift towards optimal input: The recycling loop is unlikely to be 100% circular and plastic production is likely to keep increasing. This means that in 2050, and along the pathway towards 2050, new plastic production will remain necessary. The second shift is therefore a shift towards renewable inputs: a shift from fossil-based to biobased plastics. This means a shift from fossil resources to natural resources. Furthermore, energy inputs are necessary to produce biobased plastics, so a shift to renewable energy is also needed for a circular economy.

Figure 11 Plastics - a circular economy; transition from now to 2030-2050

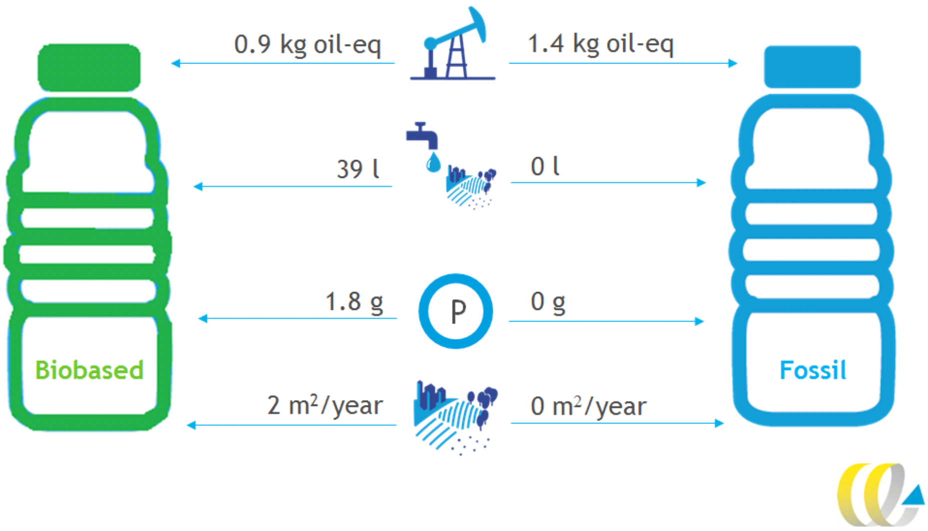


Not only oil, gas, coal and metals that are extracted can be seen as finite resources. Also fertile land, fresh water and nutrients in nature can be seen as finite resources because we are dependent on them for growing food and the provision of ecosystem services. Finite resources that are currently used for fossil-based plastics are non-renewable energy and fossil primary material while the finite resources used for the production of biobased plastics also include phosphate fertilizers, fertile land, fresh water and non-renewable energy. The consequences of the use of these types of finite resources for the production of biobased plastics are discussed in Section 5.2.

5.2 Use of (natural) resources

In Figure 12 the input of resources for PLA (biobased biodegradable plastic) and PET (fossil-based plastic) are compared. It shows that for the production of PLA, fertile land and phosphate is used, while fossil resources are used for the production of PET (much more than for PLA). The production of PLA still requires fossil resources because non-renewable energy is used for the production.
Fertile land is renewable if the land is not degraded. We refer to land as being a finite resource because even if fertile land is not degraded there is still a limited area of land available.

Figure 12 Resource use for the production of plastics (per kg plastic)



Based on PLA and PET from (Ecoinvent, 2016).

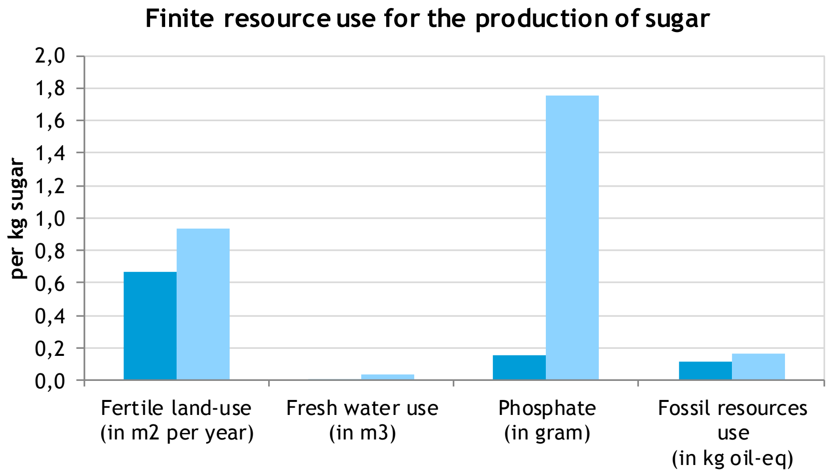
Figure 12 shows the land use per year based on Ecoinvent data. The agricultural land use is higher than that shown by (Vink & Davies, 2015). It is, however, in line with the production of PLA by Corbion as given in by (Groot & Borén, 2010). Fertile land use per kg of PLA differs per production location and feedstock used, but will always be higher than of the production of a fossil-based plastic (under normal production circumstances). Figure 12 shows the direct use of fertile land, and not the land that might be polluted because of the production of either of the two plastics.

Biobased plastics can be made from sugars, starch, plant oils and cellulose. Currently the most commonly used biobased materials for biobased plastics are sugar cane and maize. The influence on the amount of finite resources being used differs per biobased material. The use of finite (natural) resources might decrease in the future if more waste material is used for biobased plastic production.

In Figure 13 resource use for the production of sugar (used for production of bio-PE, PEF, PBS and bio-PET) is compared for sugar from beet and from cane. It shows that for sugar from sugar beet, fewer resources are needed. The production of sugar from sugar cane demands a larger use of fertile land, fresh water, phosphate fertilizer and non-renewable energy. Whether production is sustainable does, however, very much depend on local and regional characteristics (e.g. water supply, soil composition). Therefore, Figure 13 illustrates that resource use differs for the different possible feedstocks for biobased plastics, but cannot be used to state one is more sustainable than the other. Because there are differences in use of (natural) resources, these aspects should be taken into account in sustainability analyses, alongside the impact on climate change.

The four resources shown in Figure 13 are elaborated on in the following paragraphs.

Figure 13 Finite resource use for the production of sugar



Based on production of these two sugars as available in the Agri-Footprint (Blonk Consultants, 2014) database. The fresh water use only includes irrigation water.

Fertile land

As shown in Figure 12 the use of fertile land is higher in the production of biobased plastics than it is in the production of fossil-based plastics. This is of course due to the fact that agricultural land is necessary for the growing of biobased resources.

The pressure on fertile land as a resource can be reduced by using biobased resources that use less land and have a higher yield per hectare. An example of this is the use of sugar beet in comparison to the use of sugarcane, as shown in Figure 13. Also the use of by-products or agricultural residues in the future could play a role in reducing fertile land use for the production of biobased plastics in the future.

Agricultural land needs a certain level of soil organic carbon. This can be maintained by e.g. leaving agricultural residues after harvest, or by growing green manure and ploughing this under in between harvests. Therefore, when using agricultural residues it is important to realize that for a sustainable system, not all residues should be removed from the land.

Another land related aspect is the conversion of forest into agricultural land (through direct land-use change and indirect land-use change). This does not only affect the climate change impact of a commodity, but also has an impact on biodiversity.

Fresh water

Water used in agriculture is divided into two types: rain water and irrigation water. The water used for irrigation comes from groundwater or surface water or finite aquifers. Use of these sources affects the water scarcity in a region, because they can only be used once at a specific time at a specific location. As shown in Figure 12 the use of irrigation water in the production of the biobased PLA is higher than in de production of the fossil-based PET. Whether or not fresh water is a scarce resource in a certain environment is, however, highly location specific.

If water is scarce in a certain region, the impact of using irrigation water is higher than in a non-water scarce region. As Figure 13 shows the production of sugar from sugar beet in the Netherlands needs no water for irrigation because of the available rainfall while for the production of sugar cane in Brazil irrigation is necessary. Therefore, in this case the impact on water scarcity is higher in Brazil. If in both cases the amount of irrigation water would be the same, one would have to take location (or region) specific water scarcity into account to make a fair comparison.

Phosphate fertilizers

Phosphate is a finite resource that is used as a nutrient in fertilizers. It is vital for agricultural production globally. Phosphate fertilizers are mostly produced from phosphate rocks found in Morocco and Western Sahara, China and the United States.

The production of fossil-based plastics does not require the use of phosphate fertilizers while the production of biobased plastics does. As Figure 13 shows there is a large difference in the use of phosphate fertilizers for different feedstocks of sugar. Agricultural practices influence phosphate use, and can help minimize required phosphate input. Furthermore, recovering phosphate from waste streams can help achieve a more circular phosphate economy. Still, resources are finite, and decreasing phosphate resources are of global concern.

Energy resources

Fossil resources are needed for the production of fossil-based plastics. What is often overlooked in the discussion about biobased plastics is that current production of these plastics also requires fossil resources. These resources are not used as feedstock but are used in the production of non-renewable energy.

To be able to become truly circular the production of biobased plastics will need to move away from the use of non-renewable energy and switch toward the use of renewable energy.

Furthermore, biobased plastics are currently often not completely biobased. As described in Annex A (per biobased plastic), some still need intermediates based on fossil resources, while others are produced in a blends (combination of different materials) with either chemically equal fossil-based polymers (drop-in type), or a different, but fossil-based, polymer. The drop-in plastics (such as bio-PE and bio-PET) fit in a transition to a circular economy because recycling is already possible, and biobased content can be increased over time. Mono-material biobased plastics also fit in the transition, especially when recycling practices are development or changed to include these plastics. Fully biobased blends, however, do not fit this transition because they are difficult to recycle.

An exception can be made for fully biobased blends that are biodegradable and provide co-benefits when being used in combination with agricultural and food products. Furthermore, blends including the fossil-based PBAT and PCL polymers (when non-recyclable) do not fit in a circular economy because they rely on fossil-based resources.

Dutch Green Deal *Groen Certficaten*: voluntary sustainability criteria

In the Netherlands, the (voluntary) Green Deal Initiative on Sustainable Provision of Raw Materials for the Material Use of Biomass – Green Certificates (‘*Groencertificaten*’) aims at sustainable provision of biobased resources (RVO.nl, n.d.).
This Green Deal involves a large number of principles and criteria that aim to guarantee the sustainable production (environmental, social and economical) of agricultural commodities. These principles and criteria can, when applied in the production of feedstock for biobased plastics, reduce the natural resource use associated with biobased plastics production.

The Green Deal Green Certificates includes criteria that have an influence on reducing the pressure on fertile land. The Green Deal aims at preventing direct land-use change, includes criteria on preserving of soil quality and the avoidance of soil erosion. There are also criteria on controlled water consumption and the controlled use of fertilizers included in the Green Deal.

The approach taken by the green deal could be introduced in the EU, to ensure reduction of natural resources use for the provision of biobased resources internationally.

6 Litter and plastic soup

In this chapter the following question is addressed:
Can biobased plastics play a role in limiting litter and minimizing plastic soup risks?

From the detailed analyses of different biobased plastics and the interviews carried out, a number of aspects which influence litter and plastic soup arose:
- consumer behaviour;
- technical aspects (biodegradability of products).

For policy, it is important to make the distinction between litter and plastic soup, while noting that litter plays an important role in the creation of plastic soup. Both are caused by a range of factors that do not 100% overlap and therefore the type of solutions and the role that biodegradable biobased plastics might play in these could also differ for both problems.

Plastics can end up in the environment in different ways:
- Litter is the result of intentional and unintentional disposal in nature.
- Microplastics which are added to consumer products, which cannot be used without disposing the microplastic in the environment (eventually), such as cosmetics.
- Unintentional dispersion of (micro)plastics because of wear and tear in the consumer phase, such as tyres and clothing.

Litter is discussed in Section 6.1. and plastic soup in Section 6.2. We use the term plastic soup for all types and sizes of plastics in the environment. In Section 2.1 biobased plastics are categorized according to their biodegradable characteristics.

Box 5 Conclusions: litter and plastic soup

- Biodegradable plastics are not the solution to the litter problem or the macroplastic component of the plastic soup problem (nor do they contribute significantly to these problems at the moment).
- Some marine biodegradable plastics may be effective in decreasing the plastic soup problem if they are used in applications which emit plastics during the use phase (such as wear and tear of textiles) or in applications where it is likely that products unintentionally end up in soil or marine environments (e.g. agricultural applications like mulch films, or fishery gear).
- Both litter and plastic soup can be limited by education of citizens and companies on how to dispose of plastics. Strict standards should be implemented to support this.

6.1 Litter

Unfortunately, littering is still a wide-spread problem. In the Netherlands alone, keeping public spaces free of litter costs around 250 million euro annually (Ministerie van I&M, 2016). Not only is littering a burden to society from a financial perspective, littering also leads to dirty and possibly unhealthy living circumstances. Litter in the public realm is seen as one of the top 3 annoyances about the own neighbourhood in the Netherlands (Milieu Centraal, 2016).

Figure 14 Consequences of littering

Littering has a negative impact on the environment. The impact can either be direct as shown in the picture of the bird above, or littering can lead to plastic soup and the creation of microplastics when the litter ends up in the marine environment.

Solution to littering

Non-biodegradable biobased plastics are not a solution for the impact that littering causes because these plastics behave in exactly the same way in the environment as their fossil-based counterparts.

Biodegradable plastics cannot minimize the problems caused by littering. First, they do not limit the nuisance experienced by people of litter in the streets. Also, as (UNEP, 2015) states; *'On the balance of available evidence biodegradable plastics will not play a significant role in reducing marine litter.'* It has even been suggested that consumers are more likely to litter biodegradable plastics than plastics that do not biodegrade (UNEP, 2015).

Another reason that biodegradable plastics are not a solution for littering is that 'biodegradability' does not necessarily mean that a plastic degrades well in the environment it ends up in. Often biobased plastics are referred to as biodegradable if they are biodegradable under circumstances that can be found in industrial composters, where conditions for biodegradation are optimized. For instance, temperatures of 60 degrees Celsius are reached, and sufficient oxygen and nutrients are available to feed the degrading micro-organisms. Examples of biodegradability standards can be found in Section 2.3). 'Biodegradable' plastics are not necessarily also biodegraded in nature, where conditions for biodegradation are often far from favourable.

The main cause of littering is consumer behaviour. The largest part of the coarse litter (larger than 10 cm) consists of packaging which is discarded by consumers (Milieu Centraal, 2016). The best solution for littering and thus also for limiting the amount of plastics ending up in the plastic soup is by communicating to citizens how to dispose of plastics (see interview with Holland Bioplastics in Section B.4).

6.2 Plastic soup

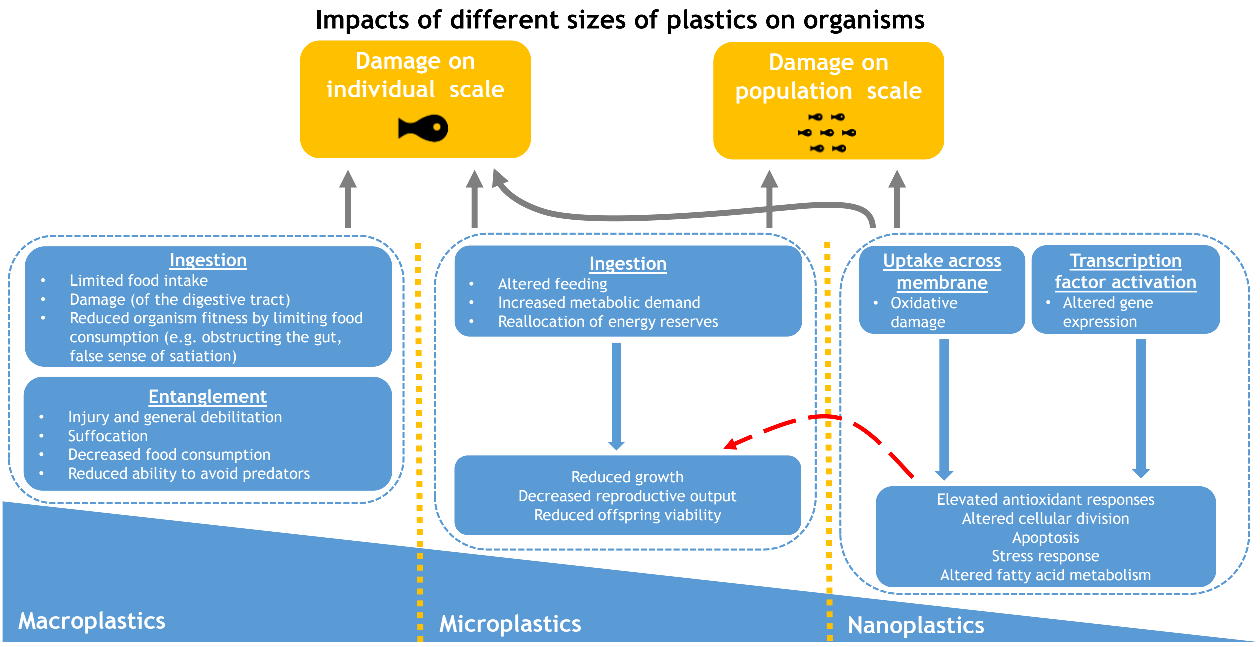
Plastic soup consists of different types and sizes of plastic which have ended up in the environment. The different sizes of plastics in the plastic soup are often divided into the following three different categories:
- macroplastics, plastics that are 2.5 cm or larger;
- mesoplastics, plastics between 5 mm and 2.5 cm in size;
- microplastics, plastics smaller than 5 mm in size that have either ended up in the environment as such or come from macroplastics and mesoplastics which have turned into microplastics because of weathering, photo degradation or mechanical forces (Li, et al., 2016).

Environmental impact of the plastic soup

Plastic soup has a negative effect on the environment in three main ways (Li, et al., 2016);
- the ingestion of plastics by marine life (see Figure 14) which can lead to suffocation;
- the entanglement of marine life;
- chemical effects on marine life because of the plastic being a transport vehicle of persistent organic pollutants and plastic additives mimicking hormones.

All effects are summarized in Figure 15, subdivided for effects of macroplastics (here categorised as >5 mm), microplastics (<5 mm) and nanoplastics (<100 µm).

Figure 15 Impacts of different sizes of plastics on organisms



Source: (de Blois, 2017).

Consequently, the plastics in the plastic soup also end up higher in the food chain. This means that for example humans ingest the plastics from the ocean via fish that we eat.

Causes of the plastic soup

Part of littered plastics eventually become plastic soup: they end up in the marine environment. It is thus one of the causes of the plastic soup.
Other reasons for plastic ending up in the ocean are, according to (UNEP, 2015):
- inadequate waste management/illegal practices;
- accidental input from land-based activities and the maritime sector;
- a lack of awareness on the part of consumers about daily practices.

Table 5 summarizes the causes of plastics soup, categorised for macroplastics and microplastics, which can be found in the plastic soup.

Table 5 Causes of the plastic soup for macroplastics and microplastics

Size of plastic	Cause
Macroplastics > 5 mm	Litter on land ending up in the sea Purposeful marine litter (illegal practices) Accidental marine litter
Microplastics < 5 mm	Degraded macroplastics from litter Use of microplastics in consumer products (e.g. cosmetics) Degradation of consumer products during use phase (e.g. tyres)

Plastic ending up in the marine environment can come from inadequate waste management and illegal practices. Examples of illegal practices are dumping of waste created at sea from commercial fishing or cruises. Unintended spilling of waste during waste management and other activities is also possible.

These, however, are not the only source of the plastic soup. In the use phase, plastics can also result in plastic soup, for instance rubber particles from car tyres or the washing of synthetic clothing. Also, plastics end up in the soil through the application of compost (which is contaminated with fossil plastics, from e.g. coffee pads, tea bags and packaging). This is something that most consumers are unaware of.

In general 80% of all plastic ending up in the ocean comes from land-based sources, while the remaining 20% is spilled or littered on the ocean (Li, et al., 2016).

Dealing with the plastic soup and the role that biobased plastics can play

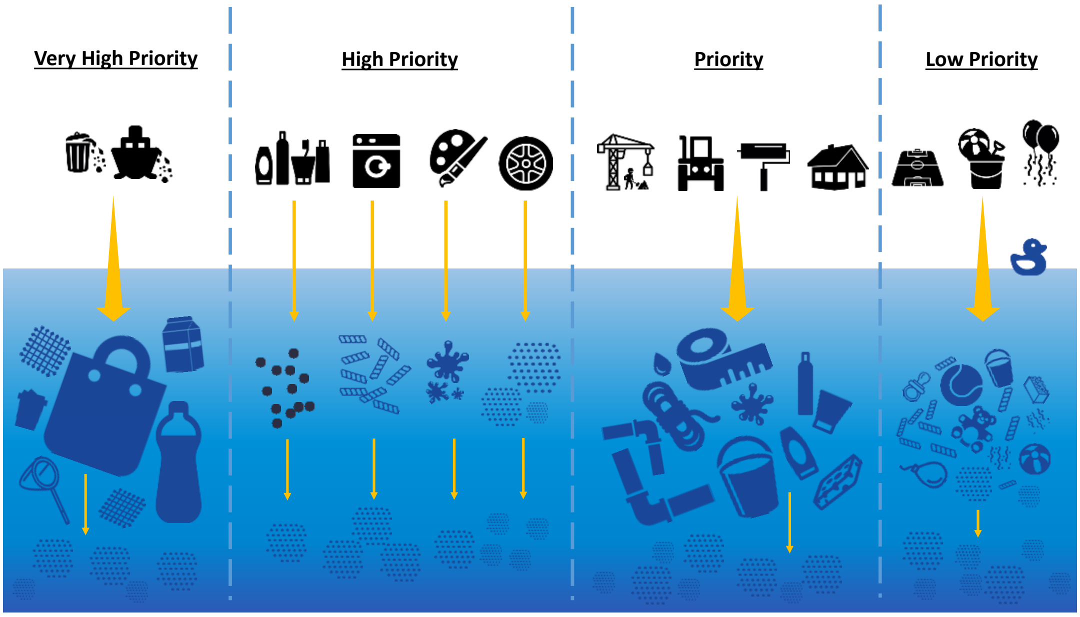
The macroplastic part of the plastic soup is caused by littering (either marine or on land, either intentional or accidental). Therefore the solutions for the reduction of the macroplastic component of the plastic soup are the same as those for littering. As discussed before; the best solution for littering and thus also for limiting the amount of plastics ending up in the plastic soup is by communicating to citizens how to dispose of plastics.

Microplastics are difficult to deal with because they are so small. It is unlikely that these microplastics will be removed from the environment (GESAMP, 2015), simply because it would be too expensive. Microplastics from solid synthetic polymers create a risk if they do not disappear because they are not soluble or degradable in natural environments (Verschoor, 2014).

One of the most effective ways of minimizing the amount of microplastics in the ocean is reducing the amount of macroplastics ending up in the ocean (GESAMP, 2015).

It is possible to prioritize different sources of microplastics based on the risk they pose to the environment. Figure 16 (de Blois, 2017) gives a prioritization of sources of microplastics (which end up in the marine environment), based on information from RIVM (Verschoor, 2014).

Figure 16 Prioritization of sources of microplastics



Source: (de Blois, 2017).

Figure 16 indicates the different sources of micro plastics; littering (very high priority), consumer products and use (high priority), industrial and agricultural products (priority) and miscellaneous use such as recreation and sports (low priority).

Biodegradable plastics can be seen as a potential risk for plastic soup if they are not soluble and do not (quickly) degrade in the ocean (Verschoor, 2015). Therefore as (GESAMP, 2015) states, biodegradable plastics will in most cases not lead to a reduction in microplastic formation. They will also not lead to a reduction of macroplastics and its effects, because of the relatively long degradation time. Biodegradable plastics can be a (partial) solution in the case of the use of consumer products and in agricultural products. In all other instances biodegradable and biobased plastics are not a solution for the plastic soup.

Oxo-degradable plastics are conventional plastics which degrade to microplastics when exposed to sunlight or heat. The degradation time therefore strongly depends on environmental conditions, but can take between 2-5 years. They are not compostable, reusable only to a limited extent, and not suitable for recycling in current recycling schemes (Thomas, et al., 2010). Such plastics therefore do not contribute to the circular economy or the reduction of the plastic soup.

The solution for littering has already been discussed above. Below we discuss the solutions for the other main causes of plastic soup: use of consumer products and industrial and agricultural products.

Use of consumer products

Microplastics originating from the use of consumer products include;
– microplastics used in cosmetics;
– synthetic fibres washed out from clothing;
– paint particles degrading;
– rubber particles originating from car tires or soccer fields.

The first question that needs to be asked in this regard is whether or not plastics should be used in these applications at all. Several initiatives aim at reducing the use of microplastics in cosmetics (for example The 5 Gyres Institute and 'beat the micro bead').

If plastics are necessary in consumer products then minimizing the impact of this type of microplastic on the environment is possible by substituting non-biodegradable plastics with marine biodegradable biobased plastics.
It is important that in such cases biodegradable biobased plastics are chosen that can biodegrade under in the marine environment. An example is Tencel, which is used in textile applications and has the MARINE OK Biodegradable certificate (Vincoitte, 2016).

Industrial and agricultural products

In some instances soil and marine biodegradable plastics for industrial and agricultural products can be a solution to plastic soup. This is the case when biodegradable plastics come in contact with organic material, and are likely to be left unintentionally in nature (whole or partially). Unintentional disposal occurs because e.g. a piece is ripped off, or in case of storms (unintentional disposal). Examples of products are the films used around fertilizers in agriculture & horticulture or fishing gear.

To limit litter it should, however, be made unattractive to dispose of the complete product in nature, as is for example sometimes done with fishing gear. Prevention of disposal in nature is always the most attractive, environmentally.

7 End-of-life treatment

The type of end-of-life treatment of biobased plastics influences their impact on climate change, their use of (natural) resources, and problems such as litter and the plastic soup. The chemical composition, biodegradability, and collected volume of biobased plastics determine the most currently appropriate treatment route. To gain insight in these treatment routes of biobased plastics, the current end-of-life treatment systems for conventional plastics are described, after which the role of biobased plastics within these systems is evaluated.

Box 6 Conclusions: End-of-life treatment

- Mechanical recycling is the most environmentally attractive option. Bio-PE, bio-PP and bio-PET currently can be (and are) recycled in the schemes for packaging.
- Other biobased plastics can also be recycled (both non-biodegradable and biodegradable), but due to low volumes this is currently not interesting (financially) for recycling schemes.
- Biodegradable plastics in themselves have no added benefit in composting facilities. In digesters they yield biogas. They can be attractive when there are co-benefits, such as increasing the separation of food and garden waste.
- Currently, biodegradable plastics are not recycled, and can influence the quality of mechanically recycled plastics (this is also true for other plastics, e.g. PET influencing PE). Therefore, clear communication about the appropriate disposal routes for biodegradable plastics is needed.
- Biodegradable plastics can have a benefit replacing non-biodegradable materials which are likely to end up in organic waste recycling (such as e.g. coffee pads, tea bags).

There are different treatment options for biobased plastics which have (some) environmental benefit: recycling and incineration with energy recovery are options for the non-biodegradable plastics. For biodegradable plastics composting or digestion with subsequent composting (treatment along with food and garden waste) is an additional option.

For conventional plastic waste from consumers in Europe, 26% is recycled, 36% is incinerated with energy recovery, and 38% is landfilled (KIDV, 2016). The European Commission has adopted a recycling goal of 55% in 2025 for plastics. In the Netherlands, 50% of plastic household waste was separately collected (at consumer or post-consumer) for recycling in 2014.

7.1 Mechanical recycling

7.1.1 The mechanical recycling system

Plastic that is recycled is, in the Netherlands, collected in three different ways: by source separation, by post-consumer separation, and through a deposit system. After collection or after post-consumer separation, the plastics are sorted according to type. This happens by removing metals and films, and using near-infrared spectroscopy machines to sort the plastics (Jansen, et al., 2015). Hereafter, the plastic are baled. This results in streams which are in accordance with the 'Raamovereenkomst Verpakkingen'. These streams are PET, PE, PP, film, and mixed plastics.

The mixed plastics stream accounts for 40-50% of the collected plastics, and consists of non-pure PE, PP, PET, PVC, PS, multilayer foils and composites and a very small amount of biobased plastics. The mixed plastics stream is processed mechanically in facilities in Germany.

Some materials, including plastics, are classified as 'residues'. This fraction is incinerated, and might contain some plastics.

All mono-streams are baled, and these baled materials are then traded to recycling facilities. There, some leftover residues and other types of plastics are removed. In post-consumer separation facilities, these residues are either processed in a digester when they are small (<5 cm) or incinerated (>5 cm). At the recycler, the mono-streams of plastic materials are subsequently shredded and washed, and extruded to granulates. These granulates can subsequently be used in the production of new products and materials.

These streams are subject to certain quality standards (specifications). The so-called DKR specifications describe the material content, the required purity and maximum allowed fraction of impurities, and the required delivery form as minimum set of quality standards.

Plastics are for a large part used for food packaging. The recycled granulates cannot, however, be used for food packaging due to quality restrictions. To achieve circularity and recycling, this issue needs to be addressed.

7.1.2 The mechanical recycling of biobased plastics

Biobased, non-biodegradable drop-in plastics

Biobased, non-biodegradable drop-in plastics such as bio-PP, bio-PE and bio-PET are chemically identical to their fossil counterparts. Therefore, they are compatible with the current recycling system: they are sorted out in the same mono streams as conventional plastics, and are recycled similarly when they end up in treatment facilities. In general, no additional processes or investments are necessary to recycle drop-in biobased plastics.

Other biobased plastics

For a number of reasons, most other biobased plastics will end up in the mixed fraction or in the residue during the sorting process and are eventually incinerated. The streams of these types of biobased plastics still constitute less than 1% of the total amount of plastics. Omrin states (see Annex B.3) that although it is technically possible to sort out biobased plastics with NIR technology, systems are currently not equipped to do so. The primary reason is the high initial investment cost, especially in relation to the small size of the streams. In this respect, (non-biodegradable) biobased plastics are similar to certain fossil-based plastics, like multilayer materials and fossil-based plastics with low volumes, which are also not sorted out. According to Suez (see Annex B.1), if collected plastic waste would contain between 5 to 10% of one type of biobased plastic, it will become economically feasible to sort out such biobased plastics in a separate stream, similarly to PE, PP, PET and foils. A difficult issue here that is emphasized by the KIDV, is that the current recyclability of plastics might influence decision makers (developers or buyers of packaging) to (not) support their usage.

Another issue is that blends of biobased plastics (as well as blends of fossil plastics) are not compatible with sorting in polymer-specific mono streams, even in larger quantities. Finally, an underlying reason for the fact that treatment facilities are not recycling certain biobased plastics is, according to Omrin, that Dutch municipalities are not financially compensated for the consumer separation, post-consumer separation or recycling of certain biobased plastics. When the volume increases for a new material, a new specification could be added to the system, ensuring recycling of this (relatively new) stream.

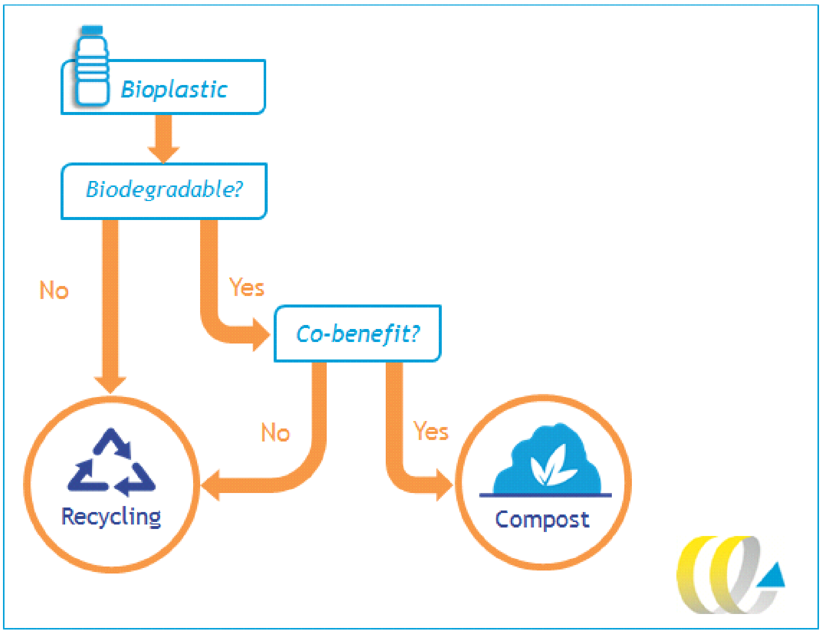
Recycling issues related to biodegradable biobased plastic

Sorting installations remove much (90-95%) of the impurities. Such impurities may contain a very small amount of biodegradable plastics. PLA, for instance, has a similar density as PET, making it difficult to remove during the processing of waste streams. Contamination can cause difficulties for recycling facilities. Therefore, states Omrin (see Annex B.3), when biodegradable plastics end up in the current plastic recycling system, they may influence the DKR quality of the recycling streams. This is also true for other materials, such as multi-layered materials. In the foils-stream, this contamination issue is most apparent, since separation of different plastic-types of foil is technically difficult. Research by Wageningen Food & Biobased Research shows that no negative effects (of a contamination of up to 10% biodegradable biobased plastics) were found on a sorted DKR-310 mixture (van den Oever, et al., 2017). To summarize: purity of the sorting output is important to ensure the quality of recycling. Materials other than those sorted out, among which are biodegradable plastics but also other materials, may contaminate the mono streams. At the moment, the biobased plastics stream is relatively small and there are other streams which pose a greater risk of contamination. Optimizing the mechanical recycling system, not just from a biobased plastics point of view, is important to achieve optimal recycling and circularity. Furthermore, insight into the effect of contaminants is necessary throughout the supply chain, to be able to ensure materials are used optimally.

In Figure 17 the preferred end-of-life treatment for biobased plastics is schematically represented, current practice is different. If a biobased plastic is biodegradable and has co-benefits, such as a food waste carrier, the preferred treatment is composting. If a biodegradable plastic does not have co-benefits, preferred treatment is recycling. Currently volumes of biodegradable plastics are too small to sort out. In some cases biodegradable plastics are advantageous when used in applications with a litter risk (and therefore plastic soup risk). An example is cups at festival, for which PLA is sometimes used currently. The cups are collected separately (and are subsequently recycled) in large volumes, while limiting plastic soup risk because of their biodegradability (in case some cups end up in the environment).
Such streams are completely separated from conventional recycling, and therefore disadvantages related to conventional recycling do not apply.

If a biobased plastic is not biodegradable the preferred treatment option is always recycling. Some biobased plastics are already recycled, others are not. Practice therefore does not coincide with the theoretically optimal situation, and further optimization of the recycling systems is desired.

Figure 17 Preferred end-of-life treatment biobased plastics (biodegradable and non-biodegradable)



7.2 Incineration with energy recovery

7.2.1 The incineration of plastics

In the Netherlands, in 2013, 14% of the household waste that was incinerated consisted of plastics (KIDV, 2016). This includes plastic which was not source separated or post-consumer separated, as well as plastic residues from the recycling system (plastics which are lost due to high impurities).

The incineration of plastic in installations in the Netherlands yields energy. The amount and type (electricity, heat) depends on the specific incineration plant. Incineration of biobased plastics will result in emissions of biogenic CO_2, as opposed to fossil CO_2 from conventional plastics. Still, several LCA's show that recycling of plastics has a higher environmental benefit than incineration with energy recovery and is therefore the preferable option (KIDV, 2016),

7.2.2 The incineration of biobased plastics

As mentioned previously, biobased plastics other than drop-in biobased plastics such as bio-PE and bio-PET (and potentially bio-Pp in the future), are likely to be incinerated. This then leads to the production of renewable energy at the end-of-life. They are not sorted out, since systems are, for economic reasons, currently not equipped to do so.

7.3 Organic recycling – the food and garden waste system

7.3.1 The food and garden waste system

37% of household waste in the Netherlands is food (~50%) and garden (~50%) waste (Vlaco/Attero, 2016). Approximately 60% is collected separately (of which approximately 20% is food waste), while the rest (mostly food waste) is found in residual waste. Food and garden waste is processed in installations that either ferment and compost the organic waste, or only compost it. From the fermentation process, biogas is produced in anaerobic digesters.

7.3.2 Treating biobased plastics along with food and garden waste: composting and digestion

The treatment of biodegradable biobased plastics along with food and garden waste is subject to discussion. There is some debate about the degree to which biodegradable plastics that are certified with the Seedling logo can be composted in industrial composting installations. The general opinion is that when the characteristics of biobased plastics are in line with the EN 13432 standard, they can be composted by industrial composters in the Netherlands without complications. However, Suez states (see Annex B.1) that there are applications with a Seedling logo which require 13 weeks of composting, while many composting installations only run for 8 weeks. The Dutch Waste Management Association (VA) states that composting time is even shorter: 2-3 weeks. After this period of time, these plastics will not be fully composted, and need to be or will be sieved out.

In addition, not all plastic products made from biodegradable polymers will meet the requirements laid down in EN13432. If the product exceeds a certain thickness limit, it will not pass the test and cannot be identified as 'industrially compostable'. An example is cutlery made of biobased plastics: the composition and thickness might cause the product not to compost in time.

In Table 6, the biodegradability of different biobased plastics is shown; whether these plastics can be treated by (industrial or home) composting, or can be treated by digestion. Biobased plastics' ability to be digestible will become more important in the future, as more composting installations employ an anaerobic digester integrated into a larger composting operation. This might be a problem particularly for blends including PBAT (a fossil plastic often blended with biobased plastics), which is compostable but not digestible (Hermann, et al., 2011).

Table 6 Digestibility and compostability of biobased plastics

Digestible	Compostable
Starch	Starch
Starch/PCL	Starch & PCL blend
PHA	PHA
PLA (only in thermophilic digestion)	PLA (only in industrial composting installations)
	PBAT (fossil plastic, but used in blends with e.g. PLA and TPS)

Source: (Hermann, et al., 2011).

The actual biodegradability of biodegradable plastics and whether or not these fit within practices of industrial composters is also a concern raised by the bioconversion department of the Dutch Waste Management Association (interview VA, Section B.9), as they state composting time averages 2-3 weeks. Standards should match practice (composting time), in order for the system to run optimally.

The main conclusion concerning biodegradability and end-of-life treatment is that communication to consumers' needs to be very specific and clear. Furthermore, standards should conform to end-of-life treatment practices.

Biodegradable biobased plastics do not negatively influence the quality of the compost (Song, et al., 2009). The added value of compostable plastics partially lies in their co-benefits. For instance, compostable plastics make the collection of organic kitchen waste easier. Therefore, the amount of collected kitchen waste will be larger than when no compostable bags are used.
This increase in the amount of kitchen wastes is beneficial for the yield of fermentation installations.

With regard to packaging, the KIDV considers the use of biodegradable biobased plastics to be desirable mostly when such co-benefits are achieved. The members of the Dutch Waste Management Association have also indicated to be mainly interested in compostable biobased plastics which serve as carrier for food and garden waste.

The Dutch Waste Management Association (VA) and Holland Bioplastics are working on an agreement on the use of biodegradable plastics. The parties promote the use of biodegradable plastics that can improve both the quantity and the quality of the separated biowaste. This can be done in three different applications:
- carriers of biowaste (such as waste bin liners for biowaste);
- packaging used with cooled or fresh food that are used in the kitchen as well as packaging of flowers;
- products of which plastic components are difficult to separate from organic products (such as teabags).

In these applications members of the Dutch Waste Management Association will accept biodegradable plastics that are certifiable compostable in industrial composting facilities.

7.4 Biobased plastics, end-of-life and the circular economy

Non-biodegradable and biodegradable biobased plastics are elaborated on separately.

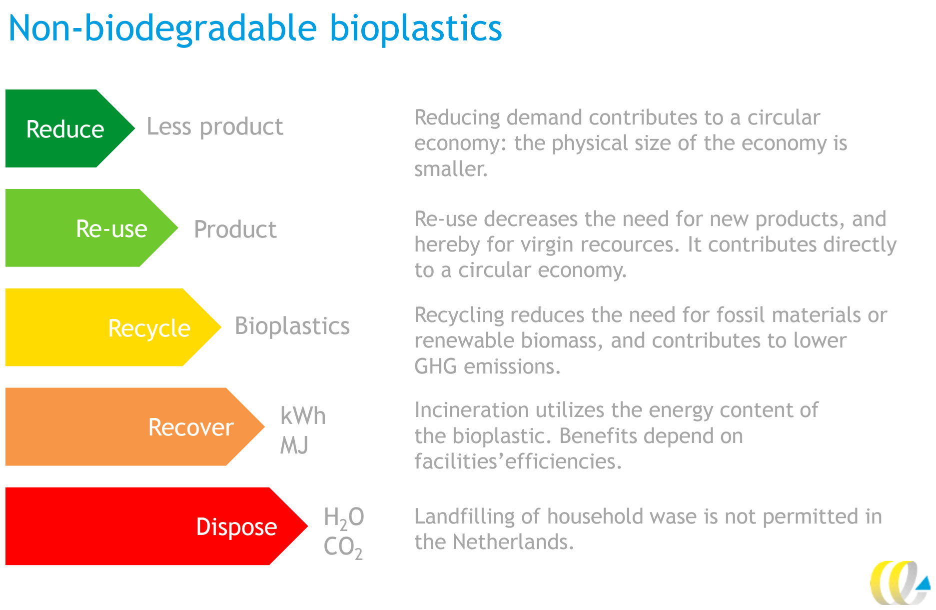
7.4.1 Non-biodegradable biobased plastics

In Figure 18, the fate of biobased plastics in all phases of the European waste hierarchy is summarized, based on the information given in the previous sections.

Moving away from fossil resources towards biobased resources is essential for achieving a circular economy. However, the most *efficient* method to achieve a circular economy is reducing the demand for plastics in general. Hereby, the physical size of the economy becomes smaller, and less waste will be produced and processed. The re-use of plastic products is second in the waste hierarchy, decreasing the need to produce new (bio)plastic materials. Then, recycling follows, which has some interesting implications in the case of biobased plastics. While drop-in biobased plastics such as bio-PP, bio-PE and bio-PET can be processed using the current recycling infrastructure, other biobased plastics are not recognized as a separate stream due to their small volumes. In addition, biodegradable biobased plastics that end up as contamination in plastic waste streams can influence the quality of recycling streams (this is also true for other impurities and materials).

One suggested solution to optimize the current recycling system for biobased plastics would be to decrease the number of types of plastics. Hereby, the ‘mixed’ plastic stream will be decreased, allowing the market to further increase recycling rates. For biobased plastics, this would mean that bio-PP, bio-PE, and bio-PET will be the desirable materials to stimulate. On the other hand, other non-drop-in biobased plastics such as PEF or PLA can already technically be recycled. When these biobased plastics increase in volume, it becomes economically feasible to collect them in separate mono-streams for recycling too.

Figure 18 Waste hierarchy for non-biodegradable biobased plastics



7.4.2 Biodegradable plastics

For biodegradable plastics, an important functionality is the biodegradability. For certain applications this has advantages. An example is agricultural/horticultural application, in which products can be added to the soil without having to take them out later (e.g. pots) or for example mulch films which can contribute to litter when parts are left on the field. Another example is applications which contribute to the separate collection of food and garden waste.
In these cases, no choice has to be made for EOL treatment, as the biodegradability and application together determine this. Either the plastics biodegrade in nature, or they end up in a digester/composting facility.

There are, however, cases in which biodegradable plastics are used for products which do not necessarily end up in either nature or a digester/ composter. In those cases, when a choice for EOL treatment is available, the following prioritization (based on environmental benefit) can be made:

1. Mechanical recycling.
2. Incineration with energy recovery or anaerobic digestion with biogas production.
3. Incineration without energy recovery or composting.

8 Conclusions

The main question in this report is: *Under which conditions are biobased plastics (biobased plastics, both biodegradable and non-biodegradable) compatible with the Circular Economy?*

1. Optimize the input into the economy:
   - require sustainable agricultural practices;
   - maximize CO_2-eq reduction;
   - minimize of (I)LUC risk;
   - reduce use of fossil resources.
2. Optimize the mechanical recycling treatment:
   - minimize losses;
   - work towards treatment of (non-drop-in) biobased plastics in recycling.
3. Treat litter as a separate problem: biodegradables are not the solution.
4. Use biodegradables for applications in which biodegradability is functional (e.g. agriculture, horticulture) and/or in which it has co-benefits (e.g. carrier for food waste and/or substitute for food packaging which currently leads to contamination in organic waste).
5. Use biodegradables for applications with plastic soup risks in the use phase (from wear and tear), or prohibit use of plastics in such applications altogether.

In Figure 19 the transition from the current situation to a more circular situation is illustrated.

8.1 When is use of biobased plastics preferable to use of fossil-based plastics, based on criteria for CO_2 reduction and use of resources?

CO_2 reduction

Compared to fossil-based plastics, most biobased plastics realize a reduction in climate change impact. The cradle-to-gate climate change impact is mostly influenced by the type of raw material being used. Also the type of electricity being used in the production of biobased plastics can have a significant influence, while the transportation distance of the raw materials is insignificant (Section 4.2).

For plastics that are produced from fermentable sugars, use of sugar crops (sugar beet and sugar cane) is preferable to use of cereal crops. The production of sugars from lignocellulosic materials (from wastes and non-food biomass) seems a promising development. The risk of indirect land-use change for biobased plastics made from sugar crops or (agricultural) wastes is small compared to edible oils. Compared to biobased plastics produced from fermentable sugars, biobased plastics made from edible oil have a low CO_2 reduction potential, and a relatively high risk of ILUC (Section 4.3).

Currently there is a small risk of *direct* deforestation by production for biobased plastics, which would directly negatively affect the CO_2 balance. A sustainable sourcing scheme for biobased plastics could prevent direct deforestation, such as already included in the voluntary Dutch Green Deal

Green Certificates. A sustainable sourcing scheme could also ask for a minimum CO_2 reduction target.

Use of resources

While some biobased plastics may have a small or negligible impact on climate change, they may score unfavourably on use of fertile land and water, which should therefore be taken into account. Optimal use of by-products influences the environmental impact. Also, efficiency can often be increase, and good agricultural practices/sustainable agriculture can help to reduce and optimize the use of resources (Section 5.2).

8.2 When is use of biodegradable plastics preferable to non-biodegradable biobased plastics, based on criteria for CO_2 reduction and use of resources?

CO_2 reduction

The use of biodegradable biobased plastics in terms of climate change is not better or worse than the use of non-biodegradable biobased plastics as long as the biodegradable biobased plastic is treated at the end-of-life in an evenly or more favourable way of recycling than non-biodegradable plastics.
Section 7.4.2 elaborates on the discussion of the end-of-life treatment of biodegradable plastics.

Use of resources

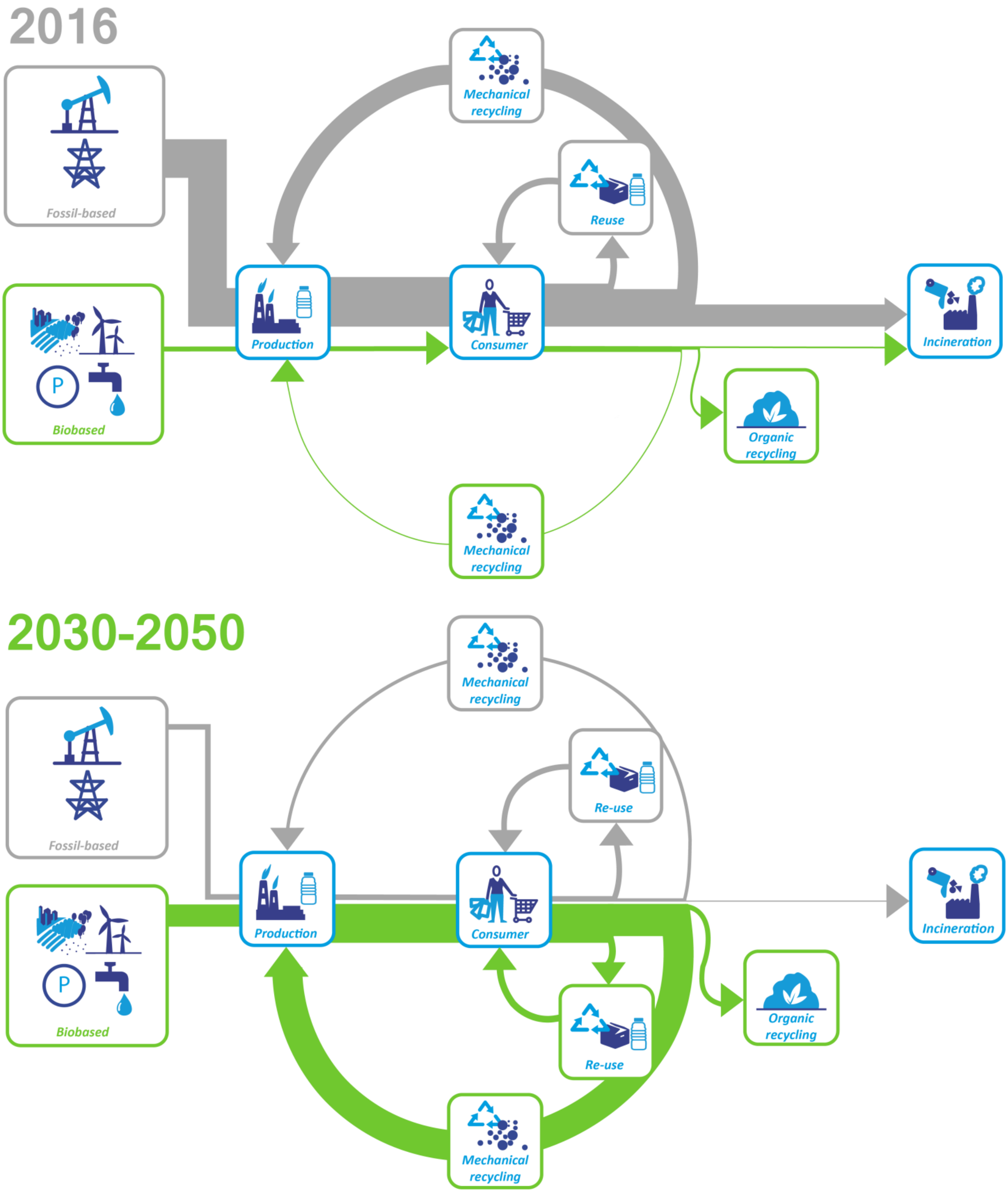
For both biodegradable and non-biodegradable biobased plastics, resources such as fertile land, irrigation water and fertilizers are needed. In case biobased plastics are recycled, the required input of resources into the economy is reduced. Biodegradable biobased plastics can positively affect resource use when they have co-benefits such as increasing the amount of separately collected food waste, which is processed into compost (Section 7.4).

8.3 Can biobased plastics play a role in limiting litter and minimizing plastic soup risks?

The main source of plastic soup is litter that ends up in the ocean. The amount of litter can be limited by education of citizens and companies on how to dispose of plastics. In general, biodegradable plastics are no solution to this problem because they degrade too slow or not at all in the marine (or soil) environment (with litter problems in the meantime – Section 6.1). Furthermore, degradability may be limited to industrial installations, meaning biodegradable plastics can still contribute to plastic soup when they end up in the environment. Also, because litter attracts litter, there may be the indirect effect of more fossil-based non-biodegradable litter. There is one notable exception: marine biodegradable materials may help reduce plastic soup when used in specific applications (e.g. those which have plastic soup effects in the use phase – Section 6.2).

Some biodegradable plastics could be effective in decreasing the amount of microplastics ending up in the oceans if they are used in consumer products which emit plastics during the use phase (textiles, paint and rubber tires). Also, in some agricultural applications, soil and marine biodegradable plastics can reduce litter and decrease the release of non-biodegradable microplastics, e.g. foils which may not be completely removed after use (Section 6.2).

Figure 19 Plastics - a circular economy; transition from now to 2030-2050



8.4 What waste management strategy should be applied to biobased plastics?

Moving away from fossil resources towards biobased resources is essential for achieving a circular economy. However, the most *efficient* method to achieve a circular economy is reducing the demand for plastics in general. Hereby, the physical size of the economy becomes smaller, and less waste will be produced and processed. The re-use of plastic products is second in the waste hierarchy, decreasing the need to produce new (bio)plastic materials. Only then recycling follows. Recycling options include mechanical recycling and organic recycling.

8.5 What are the options for mechanical recycling of biobased plastics?

Drop-in biobased plastics (biobased plastics which are chemical identical to a fossil plastic) can be (and are) recycled along with their conventional fossil counterparts without any issues. When the volumes of the other biobased plastics (non-drop-ins) increase, or if they are collected in large mono stream from e.g. industrial applications, separate recycling pathways are or will become attractive. Currently, however, their volumes are still very low.

In some cases biodegradable plastics are used in applications with a litter risk (and therefore plastic soup risk), but are still collected separately (and are subsequently recycled) in large volumes, such as cups at festivals or agricultural applications. Such streams are completely separated from conventional recycling, and therefore disadvantages related to conventional recycling do not apply.

8.6 What are the barriers to optimal organic recycling of biodegradable plastics?

Application of biodegradable biobased plastics for packaging and food waste carriers has the potential to increase separately collected food and garden waste, and decrease contamination with non-biodegradable plastics (of the compost). In general, only when biodegradable plastics for such applications have clear co-benefits, such as increasing the separate collection of food and garden waste, their usage is attractive.

Organic recyclability deserves further attention because there seems to be a discrepancy between regulations and (perceived) degradability. A number of recyclers have questions about the digestibility and compostability of biodegradable biobased plastics. Although the Seedling and OK Compost labels verify a materials' ability to be industrially biodegradable, apparently this is not always (perceived to be) the case in practice (whether the processing time corresponds to the degradation time). Standard and practice should coincide.

8.7 How can policy ensure consumers follow advice on proper end-of-life disposal?

Clear, up-to-date and unambiguous communication to consumers about the proper disposal method of biobased plastics will increase their environmental benefits and possibly their market adoption rate. In this advice the effects on litter and plastic soup should be included, for example by banning the mentioning of 'biodegradable' on packaging. To avoid the introduction of fossil plastics in food and garden waste due to incorrect disposal (currently already a problem), a clear logo on food carriers and packaging of perishable food helps, if it is stimulated that biodegradable plastic food packaging is collected together with food waste. Such a logo has recently been developed in the Netherlands.

8.8 How should biobased plastics and fossil-based plastics be compared to assess the climate change impact of these plastics?

To prevent confusion we advise to use a cradle-to-gate analysis to compare biobased and fossil-based plastics on a product level. In a cradle-to-gate analysis the biogenic carbon uptake into the biobased plastic is taken into account in the production phase. This approach has consequences for the carbon accounting of the waste treatment in cradle-to-grave analyses.
To prevent double counting of benefits, the incineration phase (gate-to-grave) of biobased plastics should not be counted as carbon neutral (Section 4.1).

8.9 Concluding: How do biobased plastics fit in a circular economy future?

Moving away from fossil resources towards biobased resources is essential for achieving a circular economy. Another important aspect of a circular economy is optimal recycling. Therefore, a circular economy will reach a high recycling rate for (bio)plastics. Because of the nature of plastics, which degrade after being recycled numerous times, and limits to use of recycled plastics (currently not allowed for food packaging, a source of virgin plastic will still be required. This input can be made more sustainable by using biobased plastic from sustainable sources produced from sustainable agriculture. With the right kind of recyclable biobased plastics (with a low carbon footprint and sustainable sourcing), a biobased economy can be linked to a circular economy.

Only for specific purposes (e.g. for agricultural purposes and to stimulate separate collection of food waste) biodegradability is an asset. For some applications with a plastic soup risk in the use phase, biobased plastics which biodegrade in nature can become a part of the solution.

9 Policy suggestions

This study elaborates on whether biobased plastics can contribute to three major policy goals for the Dutch government, as also included in the Dutch policy on the Circular Economy:
- lowering greenhouse gas emissions (CO_2-eq);
- lowering demand for fossil resources (oil, gas, coal);
- lowering the problem of microplastics in soil and water (plastic soup).

The main conclusions related to these policy goals are summarized in Section 9.1. In Section 9.2 our policy suggestions are elaborated on.

9.1 Main conclusions related to policy goals

Biobased plastics can contribute to lowering greenhouse gas emissions

The GHG balance (greenhouse gas balance) is influenced by the choice of raw materials for production and the end-of-life treatment of biobased plastics.

Production:
- The cradle-to-gate climate change impact is mostly influenced by the type of raw material being used:
  - For plastics that need fermentable sugars, sugar cane and sugar beet are preferable to cereal crops. Also the production of sugars from lignocellulose seems promising. The greenhouse gas emission savings in comparison to fossil-based plastics is not as high if maize starch is used.
  - By-products: use of by-products influences a product's sustainability; when by-products are used for other purposes, part of the environmental impact is allocated to those purposes (in LCA). Care should be taken that soil quality is maintained at a sustainable level.
- Biobased plastics made from sugar crops or (agricultural) waste have the lowest Indirect Land-use Change (ILUC) risk.

End-of-life treatment:
- **Mechanical recycling** influences the GHG balance positively, and means a lower demand for raw materials.
- **Incineration** with energy recovery has the same impact as incineration of a similar fossil plastic in the end-of-life phase, and contributes to energy production. The main difference is the emission of biogenic CO_2 instead of fossil CO_2. Care should be taken to avoid double counting (benefit in production phase as CO_2 is taken up in plant, and benefit in incineration phase as biogenic CO_2 is emitted).
- **Digestion** with biogas production also contributes to energy production and thus has a more advantageous GHG balance than composting.
- **Composting** biodegradable biobased plastics is CO_2 neutral, composting of biodegradable plastics does not produce compost. Composting of biobased plastics is only favourable when it has added value; when it has co-benefits such as increasing the amount of food waste collected to be composted and reducing the amount of fossil plastics ending up in the food and garden waste which is composted. If a biodegradable biobased plastic has co-benefits it can contribute to lowering greenhouse gas emissions indirectly.

Biobased plastics can contribute to lowering demand for fossil resources

Because the feedstock of biobased plastics are biobased resources there is no direct input of fossil resources necessary. The energy used for the production of biobased resources could, however, still be fossil-based energy. As this is also true for fossil-based plastics, biobased plastics can contribute to lowering demand for fossil resources.

Biobased plastics require use of natural resources

Production of biobased plastics requires natural resources, such as fertile land, fresh water and phosphate fertilizers. For raw materials, the order of preference based on environmental impact related to natural resource use is: waste materials, sugar crops (beet, cane) and starch crops (maize). Last on the list are oil crops.
Sustainable agricultural practices, focussing on e.g. water and nutrient management and maintaining soil quality, help lower the impact of the use of these natural resources.

Biobased plastics can contribute to lowering microplastics in soil and water, but are not a direct solution to the litter problem

Non-biodegradable biobased plastics do not contribute to lowering microplastics in soil and water but marine and soil biodegradable plastics can contribute to decreasing the plastic soup.

- Biodegradable materials are not a solution to the **litter problem**, the main cause for microplastics in soil and water. This issue should be addressed separately, by education of citizens. Before the material degrades (if it degrades completely, and does not create plastic soup), it has undesirable effects, such as messy streets and animals eating or getting stuck in the material. This is, of course, true for all materials that are littered and biobased plastics therefore do not have to be treated differently from other materials when it comes to litter.
- Biodegradability also is not a direct solution to the **plastic soup** problem: degradability depends on the environment, and a material which is biodegradable in an industrial installation may very well not be biodegradable in soil or water. Biodegradability could potentially positively reduce the **microplastics** problem, if soil and marine biodegradable materials are used for applications which have a high risk of creating **plastic soup** in the use phase. Examples of such applications are specific products in horticulture and agriculture, textiles through washing and consumer products that end up in the soil via the organic recycling.

9.2 Policy suggestions

The production capacity of biobased plastics was around 0.5% of the plastic market in 2014, and the volumes will increase significantly over the coming years (globally from around 1,700 ktonne in 2014 to around 4,865 ktonne in 2019).
This projected increase in production is uncertain, and in case of stimulation by European governments further increases in production can take place. For example, the market share of biofuels is much larger, which is mainly due to government intervention.

The resource base for biobased plastics and biofuels are overlapping. Sugar crops and corn and wheat can be used to produce both biofuels and biobased plastics. CO_2-eq reduction characteristics and other resource parameters are similar.

Lessons learnt from the introduction of biofuels should be incorporated into policy for other bio-products, such as biobased plastics. Also, from a level playing field perspective it would be interesting to consider introducing a similar policy framework for biobased plastics as for biofuels.

The products, applications, users and end-of-life options are more diverse for biobased plastics than for biofuels. Therefore, it is also important to incorporate into policy clear communication and stimulation or prohibition of certain undesired types for certain applications. For example, it is important to distinguish between litter and plastic soup, and find (different) solutions for both, because biodegradables are *not* the solution for either problem. Furthermore, to achieve a circular economy, the development of both sustainable input into the economy and optimized recycling is essential.

In general we recommend integrating biobased plastic stimulation policies in the current policy frameworks for waste (LAP 3) and the Circular Economy. The focus should be on prevention first, reuse second, recycling third and finally on biobased plastic as an interesting solution if the biobased plastic fulfils sustainability criteria.

Main policy suggestion: only stimulate biobased plastics that meet sustainability criteria
If the Dutch government would choose to stimulate biobased plastics, we propose to only support biobased plastics which meet sustainability criteria. A proposal for such sustainability criteria is elaborated on below, as well as ways in which stimulation could take place.

Sustainability criteria
1. Introduce a set of sustainability criteria and quality criteria for certification systems for biomass used for the production of biobased plastics, based on work that has been done in cooperation between government, industry and NGO's in this field (for instance the project group sustainable production of biomass (Cramer, Corbey), as part of the Energy Agreement and the Green Deal *Green Certificates*. Sustainability criteria could include:
   a. A minimum CO_2-eq reduction percentage including ILUC, and a minimum biobased content[4].
   b. A ban on direct land-use change (as in Green Deal Green Certificates).
   c. Mandatory rules for sustainable agricultural practices (as in Green Deal Green Certificates).

Elaboration on criterion a: Instead of a minimum CO_2-eq target, the stimulation could also depend on the CO_2-eq result (more than 60% CO_2-eq reduction results in a maximal stimulation, 40-60% in a moderate stimulation, 20-40% in a low stimulation). In this calculation a cradle-to-gate approach should be used which includes the uptake of CO_2 by plants.

[4] Additional to the CO_2 target a minimal biogenic carbon content should be determined. This can be proven by different methods, either physically (measured) or administratively (mass balance).

Also special attention could be payed to biobased plastic production from waste. The scheme should be simple, for example:

- Proxy values: agree on conservative standard figures for a number of biobased plastics. If desired, producers may use product specific values, based on reviewed LCA.
- Proxy comparison: since the difference in environmental impact between fossil plastics is currently small, as a proxy the comparison could be made with an averaged value. For a more specific comparison, the biobased plastic can be compared with the fossil plastic which is most similar, functionally (e.g. bio-PE with fossil PE).

These sustainability criteria could best be further developed in dialogue with the biobased plastic sector and environmental NGO's. The Green Deal Green Certificates has already set minimum requirements for the sustainability of biomass and transparency of trade and processing of biomass throughout the supply chain and quality criteria (for the certification systems). Several certification schemes for applying biomass in chemical products and plastics have been recognised by Green Deal Green Certificates as they could demonstrate that the required sustainability and quality criteria are fulfilled. This could be the starting point of discussion. A number of biobased plastics producers (e.g. Natureworks, Braskem and Corbion) currently have a recognised certification scheme in place. These were reviewed and found acceptable as part of the Green Deal Green Certificates in the Netherlands. Further development could include stimulation of international recognition of such a certification scheme.

Stimulation

There are numerous ways to stimulate biobased plastics *which meet the sustainability criteria*:

2. **Subsidies**: subsidize those biobased plastics which meet the sustainability criteria.
3. **Green procurement**: Include biobased (and also recycled) plastics in (governmental) green procurement.
4. **Financial instruments**: e.g. lower Dutch packaging Waste Funds Tariffs, and others as researched in a study about sustainable wood (CE Delft, 2015).
5. **Improve recycling systems for fossil plastics and biobased plastics**: we do not have a circular fossil economy now, so solely replacing fossil with biobased is not enough. Organize recycling for biobased plastics with growth potential, which are currently not sorted out in a mono stream (and are thus incinerated). Make a plan for recycling of biobased plastics together with all parties involved including market share estimations, growth potential analyses and introduction of separation of biobased plastics like PLA. Provide the plastic sorting and recycling sector with a compensation for consumer separation, post-consumer separation or recycling of biobased plastics with low but increasing market volumes (e.g. for PLA of PEF). Include issues such as that from a recycling viewpoint, it would be better if new products would be fairly uniform in quality and would be introduced rapidly, so that recyclers are able to adapt their processes accordingly. Broaden the scope of financial compensation of recycling to include products other than packaging. This is valid for both consumer waste as waste from companies.

Communication

6. **Arrange for an objective, periodically repeated campaign to stimulate proper recycling behaviour**. Inform consumers about the characteristics of biobased plastics and how to deal with them in the end-of-life phase. Suggestions:
   - clear logo's on packaging, as developed by KIDV;
   - disposing biodegradables with food and garden waste should only be promoted in the case of clear co-benefits.

Regulation

7. **Forbid to label (packaging) material as biodegradable**, to prevent increases in litter (already done in Belgium). Use the term 'industrially compostable' for compostable bags and packaging of food products whose contents may end up in the food and garden waste system and are subsequently composted.
8. **Adopt a (European) ban on oxo-degradable plastics**: these cannot be mechanically recycled and also do not biodegrade, causing all kinds of problems in the recycling treatment.
9. **Set specific standards regarding soil and marine biodegradability for products with a high risk of unintended disposal**.

9.1 Suggestions for further research and development

- Develop sustainability criteria for biobased plastics in combination with a stimulation system in dialogue with the biobased plastic sector and environmental NGO's.
- Come to a clear agreement on the way CO_2 figures for biobased plastics are calculated and presented (including the CO_2 uptake by plants and including the ILUC risk).
- Develop marine biodegradable biobased plastics for applications with plastic soup risks in the use phase (e.g. clothes). Integrate biobased plastics in the circular economy programme of the Dutch government for plastics (Rijksbrede programma Circulaire Economie).
- Compare the cost effectiveness of potential biobased plastic stimulation with the cost effectiveness of biofuel (€/ton CO_2 avoided) and biogas stimulation policies (RED+) and also the cost effectiveness of recycling schemes for plastic. These cost effectiveness calculations could show the most effective combination of recycling and biobased plastics.
- Explore the options for chemical recycling and its environmental impacts. Certain chemical recycling technologies may be environmentally attractive, but these are still under development.
- Work towards solutions to prevent the micro-plastics ending up in the environment.

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Annex A Biobased plastics characterics

A.1 Biobased biodegradable thermoplastics

The biobased plastics in this group are: PLA, PHA, TPS, Bio-PBS, PGA.

A.1.1 On market: PLA (polylactic acid)

Polylactic acid (PLCA) is a compostable, biodegradable thermoplastic made from renewable sources such as sugar cane, corn and beets. Due to its biocompatibility, biodegradability and suitable physicochemical properties, it has received much attention in recent years.

Applications

PLA is a transparent and brittle biomaterial. Potential for use is broad, and ranges from packaging materials (food grade) to medical applications.
The application categories that this plastic falls into are:
- flexible packaging (as foil);
- rigid packaging (as bottles and trays);
- textiles (Bolck, et al., 2012b);
- consumer goods (as disposable cups);
- electrics & electronics (van den Oever, Wagening UR).

Depending on the application category, PLA can replace different plastics, for example PET in bottles. PLA can also be used to make a type of foam, that can replace EPS (Molenveld & Oever, 2015).

Raw materials

PLA is made lactic acid. Lactic acid is made via fermentation of glucose (Chen & Patel, 2012) which can be obtained from several possible sources (raw materials) of which corn starch and sugar cane are the most common. Research focuses on the use of lignocellulosic crops and of wastes and residues. NatureWorks is investigating the production of lactic acid from methane (biogas).

Climate change impact

In Table 7 the climate change impact of different PLA production processes is summarized (Joint Research Centre, 2015). This is in line with the carbon footprint of the PLA produced by NatureWorks; the climate change result of their PLA is 0.62 kg CO_2-eq (Vink & Davies, 2015) from cradle-to-gate.
In Figure 20 the results of the production of PLA based on corn from NatureWorks is compared to the cradle-to-gate emissions for fossil-based PET. The JRC claims these data are cradle-to-gate, but it is unclear to what extent uptake of CO_2 is included in the figures.

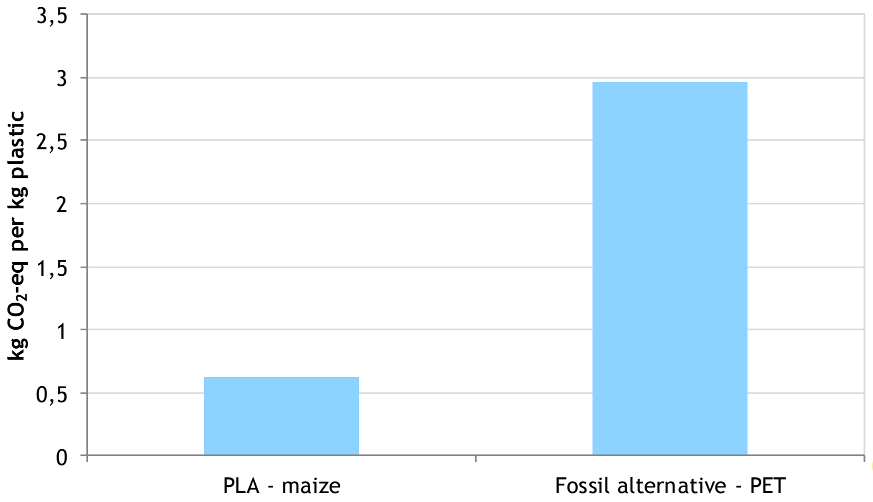
Table 7 Climate change LCA results for 1 kg of PLA in cradle-to-gate system

	Corn	Sugar cane	Corn stover
Geographical coverage	USA, Europe	Brazil, Thailand	USA, Europe
Climate change (kg CO_2-eq per kg PLA)	0.3/0.6-3.2	-0.1-1.0	0.5-1.5

Source: (Joint Research Centre, 2015).

In Figure 20 the cradle-to-gate impact of PLA and PET is shown, which does include the uptake of CO_2 in the agricultural phase.

Figure 20 Cradle-to-gate climate change impact - PLA vs fossil PET



Source: PLA based on (Vink & Davies, 2015) and PET based on (Ecoinvent, 2016).

End-of-Life

PLA is a biodegradable plastic, and can be composted in an industrial process (Tabone, et al., 2010).

PLA could also be sorted out at a plastic sorting facility if a product is made completely out of PLA, and could subsequently be recycled (Umweltbundesamt, 2013). To make this economically feasible it is necessary to have sufficiently large PLA waste streams. According to (Soroudi & Jakubowicz, 2013) the most environmental friendly End-of-life treatment for PLA is mechanical recycling. Other methods such as incineration, composting and anaerobic digestion are not as attractive from an environmental perspective. Difficulties with mechanical recycling of PLA include the necessity for a pure waste stream (Soroudi & Jakubowicz, 2013), but the resemblance of PLA and PET makes it difficult to separate the two (OVAM, 2015). The latter can lead to the contamination of PET-bottles significantly reducing the economic value (and possibilities for use) of the recycled PET. It is unclear whether or not PET can also contaminate PLA waste streams. It has proven to be possible to recycle PLA of drinking cups from festivals because this is a clean stream of PLA plastic (OVAM, 2015).

Another possibility at the end-of-life of PLA is chemical recycling (Soroudi & Jakubowicz, 2013). Chemical recycling of PLA entails hydrolysing the material back to lactic acid. The lactic acid can then be re-used as lactic acid and in the future possibly to produce new PLA. Whether or not this is environmentally preferable is unclear.

When PLA is incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 was first sequestered into the biobased plastic.

If PLA is used in combination with for example ABS or PBS (yielding a blend) the end-of-life options are more limited. Mechanical recycling in this case is possible but unlikely to happen. When a blend is used the biodegradability depends on the plastic with which PLA is combined.

Future developments

A few developments could decrease the environmental impact in the future such as the use of waste and residues and the use of lignocellulosic materials (Joint Research Centre, 2015). Also composites of PLA and natural fibres such as wood and hemp are being developed (Oever, 2010).

A.1.2 On market: PHA (Polyhydroxyalkanoate)

PHA denominates a group of polymers, polyhydroxyalkanoates. PHAs have various properties and applications, but are hardly used commercially (van den Oever, Wagening UR). If they are, they are mainly used in blends. They are biogenic polyesters that can be naturally accumulated in microbial cultures. PHAs are produced by bacteria (or, less common, yeast or plants). A highly studied type of PHA is PHBV, which is a potential replacement of PP due to its similar mechanical and thermal properties.

Applications

PHAs are biodegradable and biocompatible. PHAs can be used in coatings and packaging, and because of their biocompatibility also for medical purposes (Joint Research Centre, 2015). The application categories in which the different PHA's fall into at this moment are;

- flexible packaging such as PHBV (Molenveld & Oever, 2015);
- textiles;
- household/consumer products;
- medical compostable devices.

Raw materials

The substrates for PHA are glucose or fatty acids (Chen & Patel, 2012) which can be produced from a wide range of crops and biomass materials.
Common raw materials for the glucose are corn and sugar cane and common raw materials for oils (and thus fatty acids) are soybean and rapeseed.
The glucose or fatty acid is fermented by means of bacteria to produce PHA.

Climate change impact

In Table 8 the climate change impact of production of PHA from different raw materials is summarized (Joint Research Centre, 2015). It is unclear to what extent CO_2 uptake in the agricultural phase is included in the data in Table 8. In a review study of multiple biobased plastics, the climate change impact of PLA produced from primary material, which includes the CO_2 uptake in the agricultural phase, was found to be 1.7 kg per kg of PHA (Chen & Patel, 2012). This is approximately the average of all the PHA produced from primary materials as shown in Table 8.

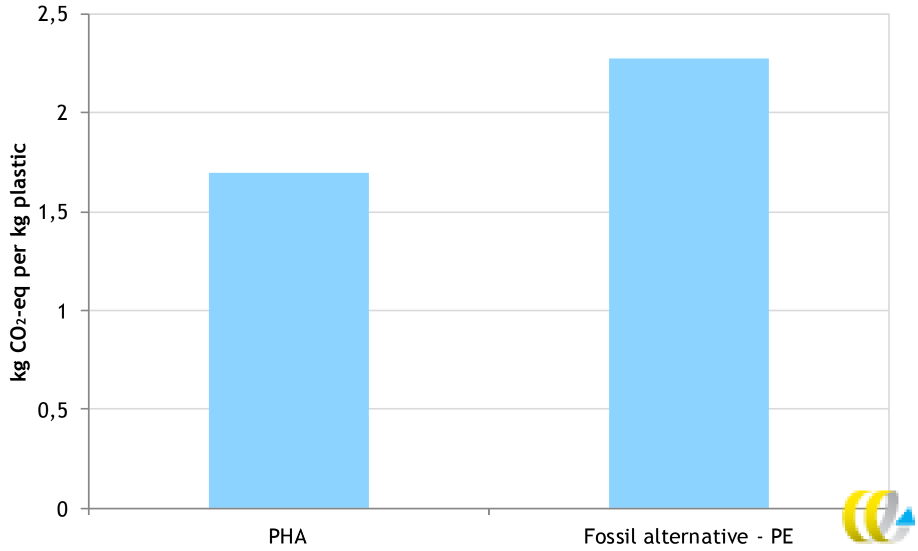
Table 8 Climate change LCA results for 1 kg of PHA in cradle-to-gate system

	Corn	Sugar cane	Lignocellulosic wastes	Soybean	Rapeseed
Geographical coverage	USA, Europe	South Africa, Brazil	USA, Europe	US	Europe
Climate change (kg CO_2-eq per kg PHA)	-2.3 - 0.45	0.1-1.1	1.3-5.1	0.26	5-6.9

Source: (Joint Research Centre, 2015).

Figure 21 shows the PHA in comparison with the fossil alternative LDPE based on Ecoinvent data (Ecoinvent, 2016).

Figure 21 Cradle-to-gate climate change impact - PHA vs fossil PE per kg



Source: **(Ecoinvent, 2016).**

End-of-Life
PHAs are biodegradable in professional treatment facilities including anaerobic digesters, and in home compost (Tabone, et al., 2010), as well as being biodegradable in both soil and water. PHA could also be sorted out at the plastic separator if a product is made completely out of PHA (Umweltbundesamt, 2013) and be mechanically recycled (Soroudi & Jakubowicz, 2013). Since production volumes are currently low, it is unclear whether PHA might cause problems in waste streams similar to PLA.

When PHAs are incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 was first sequestered into the biobased plastic.

Future developments
Research focuses on use of residues and wastes for production of PHAs. Examples of such developments are PHA production from switchgrass and the production of PHA from waste water (Joint Research Centre, 2015).

A.1.3 On market: TPS (Thermoplastic starch)

Applications
TPS can be produced to have different mechanical properties, which range from the mechanical properties of PE to PS (Bolck, et al., 2012b). It is mainly used as foam, for disposables such as trays and cutlery, and in blends.
The different application categories are therefore;
- rigid packaging (foams);
- consumer goods (disposables);
- compostable films and bags (retail, agriculture).

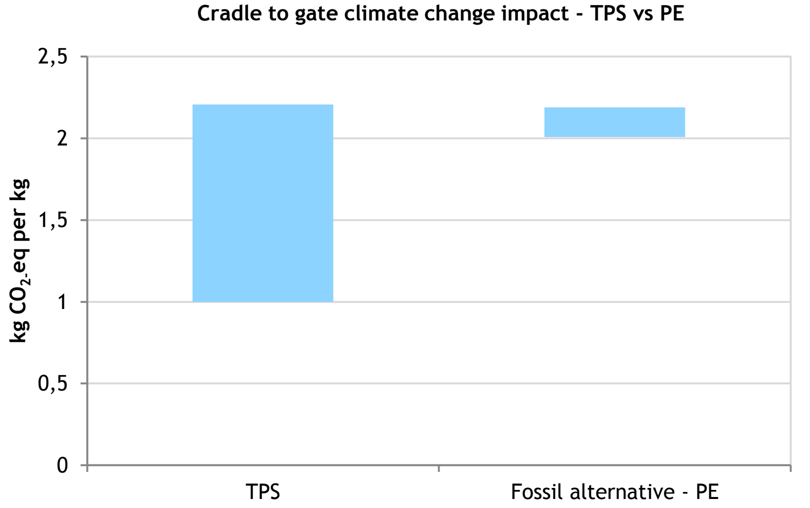
Raw materials

Thermoplastic starch is produced from pure starch and plasticizers. The most common plasticizer is glycerol (Combrzynski, 2012) which can be made from biobased oils. The main types of starch used for production of TPS are potato starch and corn starch.

Climate change impact

Figure 22 shows the cradle-to-gate climate change impact of TPS and PE. Ranges for the TPS case indicate maize sourced in different regions. For PE the lower value represents a value for average European production, the upper value a 'rest of world' average. Overall average values are closer to the lower value. Also (Momani, 2008) refers to a carbon footprint of 1.14 kg per kg TPS. This falls within the range as shown in Figure 22.

Figure 22 Cradle-to-gate climate change impact - TPS vs. PE



Source: Ecoinvent 3.3 Rec Cont.; lower value: European value, upper value: average 'rest of world value' (Ecoinvent, 2016).

End-of-Life

TPS is fully biodegradable, and it composts slightly faster than PLA (Sharma & Mudhoo, 2011). Since TPS is often used in blends, which degrade much slower, this property might not be relevant in practice (van den Oever, Wagening UR). If TPS is separated after use it can be recycled into new TPS.

When TPS is incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

If blends of TPS are used, for example TPS in combination with polyolefins, the end-of-life scenario is not known as of now. It is, however, unlikely that these plastics will be sorted in such a way that a pure waste stream can be produced. As with all biodegradable plastics, TPS might cause problems for waste treatment installations when the material is disposed incorrectly.

A.1.4 On market: Bio-PBS (polybutylenesuccinate)

Applications
Bio-PBS (Polybutylenesuccinate) is biodegradable and compostable. Currently, PBS is used in a fibre composite in car interiors. Future applications include food packaging materials (Holland Bioplastics, 2016). Not all grades of bio-PBS however have been FSA approved (van den Oever, Wagening UR). Characteristics are close to those of PP (Bolck, et al., 2012b).

Raw materials
PBS is made from glucose (Chen & Patel, 2012) which can be derived from a wide range of different biobased sources. The two intermediate chemicals for PBS are succinic acid and 1,4-butanediol. Succinic acid can be produced from fermentation of glucose (Bolck, et al., 2012b). 1,4-butanediol is currently made from fossil sources. The plastic can be both 50% made of biobased material (if only succinic acid is biobased – current situation) or 100% if both the ingredients are biobased (potential in future).

Climate change impact
In an LCA study (Sakamoto, 2012) the different stages of bio-PBS (or PBSC) are studied. According to Sakamoto the CO_2 emissions per ton of plastic are 3.8 tonne of CO_2 for the polymerization of the plastic (including the raw material acquisition in which CO_2 capture within plastics was assumed). (Chen & Patel, 2012) estimate the climate change impact of bio-PBS to be 2.3 to 3.9 kg of CO_2 per kg of plastic. No data was found on the climate change impact of conventional PBS and therefore no comparison can be made.

End-of-Life
PBS is biodegradable. It has a relatively slow rate of biodegradation; slower than PCL (Kunioka, et al., 2009). If PBS is separated after use it can be recycled into new PBS. As with all biodegradable plastics, PBS might cause problems for waste treatment installations when the material is disposed incorrectly

When bio-PBS is incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

When PBS is used in combination with PLA (a blend) the end-of-life options are more limited. Mechanical recycling in this case is possible, but unlikely and it is not yet known if this combined plastic is biodegradable.

A.1.5 PGA
Polyglycolide, or polyglycolic acid (PGA) is a biodegradable thermoplastic polymer. It has a relatively fast degradation rate, and is available under the trade name Kuredux. Generally, PGA is synthesized through the condensation of glycolic acid, while high-molecular weight PGA can also by synthesized by ring-opening polymerization of glycolide. There are multiple routes of synthesis of glycolic acid, but most is made through a catalysed reaction of formaldehyde with synthesis gas.

Applications
PGA is used in many medical and surgical applications, such as in sutures. Another example is its use as biodegradable synthetic materials for three-dimensional platforms in tissue engineering.

Although PGA is said to have better stiffness, mechanical strength and heat resistance than PLA, its high cost of production has limited widespread application (Yamane, et al., 2014). Another limitation to commercial uses is the compound's hydrolytic instability, causing rapid degradation and a loss of mechanical strength.

PGA does not fall within one of the application categories as defined in Chapter 3.

Raw materials
PGA is made from glycolic acid (GA). Glycolic acid can be produced from biobased material, but PGA is not currently commercially available based on biobased glycolic acid.

Climate change impact
Since no large-scale production of PGA is currently realized, no information on its climate change impact is available.

End-of-Life
PGA degrades more or less similarly to cellulose, with 100% being degraded after 30 days. This is tested under aerobic conditions maintained at 58°C in controlled compost (Yamane, et al., 2014). This means that the component is compostable according to Vinçotte's OK Compost standard, and can be composted in an industrial installation.

Due to its biodegradable nature, PGA might cause disturbances in plastic recycling streams when disposed incorrectly. When PGS is incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

Future development
PGA could be produced from biobased glycolic acid. Glycolic acid can be produced from sugars from renewable resources. GA is mostly extracted from sugarcane and sugar beets.

A.1.6 PBAT
Polybutyrate adipate terephthalate, or PBAT, can be produced as a partly biobased polyester. It can also be made fossil-based. It is a flexible polymer, which is fully biodegradable and compostable. It is marketed as a fully biodegradable alternative to low-density polyethylene, since it shares similar properties and uses.

Applications
Due to its inability to crystalize, PBAT is flexible and tough. Therefore, the plastic finds most of its applications as copolymer in PBAT/PLA blends, due to its high toughness and biodegradable properties. It is often used, in combination with starch and PLA, to produce films. Typical applications include packaging films, single use bags, and compost bags. In addition, PBAT based nanocomposites for medical and industrial applications have been investigated in literature. The applications can be summarized as follows:
- flexible packaging (films and single use bags);
- others (medical applications).

Raw materials
PBAT is mostly produced fossil-based. It is created from butylene adipate, dimethyl terephthalate (DMT) and 1,4-butandiol. Butylene adipate is a combination of 1,4-butandiol and adipic acid.

Novamont has developed a biobased 1,4-butandiol which is used to produce its fourth generation Mater-Bi (Novamont, 2016), which is a PBAT blended with starch. This means that the PBAT in the blend will be partly biobased.

Climate change impact
LCA's of PBAT often include their usage in blends with PLA or thermoplastic starch (TPS). For a mixture of TPS + 50% PBAT, GHG emissions of 0.92 kg CO_2-eq/kg of material are reported (Shen & Patel, 2008) (James & Grant, 2005). For a 50% starch + PBAT blend, used once, estimated GHG emissions are 2.88 kg CO_2-eq/kg of plastic. The types of waste treatment assumed in the calculation of both emissions are 70.5% landfill. + 10% composting + 0.5% litter + 19% reuse. These figures cannot be compared with a completely biobased plastic because the EOL (gate-to-grave) emissions of such blends will include the emission of fossil CO_2.

The climate change impact of biobased PBAT (such as Mater-Bi) is unknown.

End-of-Life
PBAT is degraded under soil conditions and composting conditions (Weng & Wang, 2013). PBAT biodegradation is mainly caused by microbial degradation and hydrolysis. One recent study compared degradation rates of PBAT to that of PLA, PHBV and PBS. After 75 days, PBAT showed the lowest of bio-degradation among the tested plastics: Only 9.3 ± 2.6% weight loss was shown under anaerobic conditions, and 15.6 ± 2.3% under oxygen limited conditions (Boonmee, et al., 2016). Another study found that the organic carbon content of PBAT decreases from 63.3% to 59.1% after 4 months of degradation under 'real soil conditions' (Weng & Wang, 2013). It is unclear what real soil conditions are.

Pure PBAT cannot be treated by means of anaerobic digestion (Hermann, et al., 2011). It is unclear whether or not this is the case for blends of PBAT.

As with all biodegradable plastics, PBAT might cause problems for waste treatment installations when the material is disposed incorrectly (possible contamination of mono streams). When PBAT is incinerated with energy recovery, the energy produced is (partly) fossil-based energy depending on the feedstock used.

Future developments
The production capacity of PBAT in Europe is expected to increase quite steeply, from around 0.4 million tons per year in 2015 to almost 0.9 million tons yearly in 2020 (Dammer, et al., 2013). Interestingly, it is expected that PBAT, which is currently most of the time produced fully fossil-based, will become increasingly biobased in the coming years. According to projections based on industry announcements and the capacity development in biobased adipic acid, one of the components used in the synthesis of PBAT, the biobased content of PBAT might reach 50% in 2020 (Dammer, et al., 2013).

A.2 Cellulose materials

The biobased plastics in this group are: regenerated-cellulose (RC) and cellulose acetates (CA).

A.2.1 Regenerated cellulose (RC)

Applications
Examples of regenerated cellulose are viscose (textile) and cellophane. This means that the main use of regenerated cellulose falls within the following application categories:
- flexible packaging (cellophane);
- textiles (viscose, lyocell).

Raw materials
Dissolving pulp is used to produce cellulose plastics. This pulp is mainly produced from wood and cotton (Bolck, et al., 2012b).

Climate change impact
According to (Shen, 2011) the climate change impact of viscose produced in Asia can be as high as 4.2 kg CO_2-eq per kg of viscose fibre, while that of viscose produced in Austria can be as low as -0.25 kg of CO_2-eq per kg of viscose fibre. The difference is mainly due to the different energy use, in the case of the production in Austria energy recovered from municipal solid waste incineration is used in the production. The production of lyocell ranges between -1 to 2 kg of CO_2-eq per kg of fibre (Shen, 2011). The cradle-to-gate climate change impact of viscose and lyocell in comparison to PET-fibre are shown in Table 9 and Figure 23.

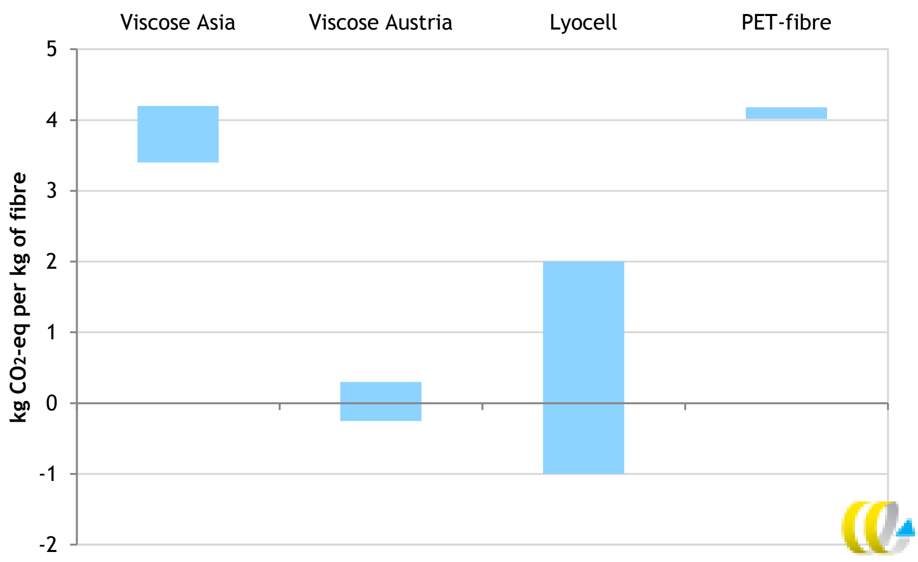
Table 9 Cradle-to-gate climate change impact of fibres

	Viscose, Eucalyptus	Viscose, Beech	Lyocell, Eucalyptus and Beech	PET-fibre
Geographical coverage	Asia	Austria	Austria	Western-Europe
Climate change (kg CO_2-eq per kg fibre)	3.4-4.2	-0.25-0.3	-1-2	4.1

Source: (Shen, 2011).

The ranges shown in Figure 23 show the maximum and minimum climate change impact per kg fibre as given in Table 9.

Figure 23 **Cradle-to-gate climate change impact of fibres**



Source: (Shen, 2011).

No LCA has been found for the production of cellophane.

End-of-Life

Viscose is biodegradable both in industrial processes as well as in nature (UNEP, 2015). It is not expected that a recycling system will be developed that only aims at multi-layer films such as cellophane (Umweltbundesamt, 2013).

When regenerated cellulose is incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

A.2.2 Thermoplastics cellulose (cellulose acetates)

Different types of cellulose acetates are; cellulose monoacetate, cellulose di-acetate and cellulose tri-acetate.

Applications

Because there are different types of cellulose acetates, thermoplastic cellulose can be used as hard plastics in moulds but also in the production of textiles. The use of thermoplastic cellulose falls within the following application categories:
- rigid packaging;
- textiles;
- consumer goods;
- automotive and transport (in decoration) (Bolck, et al., 2012b).

Raw materials

Wood pulp is used as a raw material for thermoplastic cellulose. The pulp is combined with acetic acid to produce cellulose acetates. Acetic acid can be produced from sugars and starch, but is mostly fossil-based (van den Oever, Wagening UR).

Climate change impact

No information has been found on the climate change impact of cellulose acetates.

End-of-Life

Currently cellulose acetates are not being recycled. There is however a process that can recycle cellulose acetates and chemically reduce it to a number of chemicals that could be used in different other processes (Soroudi & Jakubowicz, 2013).

Cellulose acetate is biodegradable, but the rate at which it biodegrades depends on its degree of substitution (van den Oever, Wagening UR). Compared to the degradation of cellulose an additional step is required to degrade cellulose acetates. The acetate needs to be removed by means of deacetylation. In nature the material is likely to biodegrade completely within a year (Puls, et al., 2011). It is unclear how and if the material would degrade in a composting installation.

When cellulose acetates are incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

A.3 Biobased non-biodegradable thermoplastics

The biobased plastics in this group are: PBT, PA, bio-PE, bio-PP, bio-PET, PEF, bio-PTT, bio-PVC.

A.3.1 On market: Bio-PE (polyethylene)

Polyethylene (PE) is the most commonly used plastic in the world, and is mainly known for its use in plastic bags and as a packaging material (Harmsen & Hackman, 2012c).

Applications

The chemical composition of bio-PE is the same as fossil-based PE. It can therefore also be used in both rigid and flexible packaging. The different application categories that bio-PE falls into are;

- rigid packaging (as bottles and bottle caps) (Molenveld & Oever, 2015);
- cosmetics and personal care (Shen, 2011);
- automotive and transport (Shen, 2011);
- agriculture and horticulture (Shen, 2011);
- consumer goods such as toys (Shen, 2011).

Raw materials

The substrate for bio-PE is glucose (Chen & Patel, 2012) which can be derived from a wide range of different types of biomass. The glucose is then transformed into bioethanol, and consequently into bioethylene. Bioethanol is currently mainly produced from corn and sugar cane.

Bio-PE can also be produced by means of animal or vegetable oils and fats, in combination with production from fossil sources. The oil or fat is transformed into biodiesel which is blended with naphta into the cracker. This is currently done by Sabic (Sabic, 2016).

Climate change impact

In Table 10 the climate change impact of different PE production processes is summarized. These figures include the uptake of CO_2 in the biomass.
In Figure 24 these results are compared to the cradle-to-gate emissions for fossil-based PE (HDPE-LDPE). According to (Braskem, 2016) its PE-resin has a climate change impact of -2.78 kg of CO_2 per kg of PE. PE-resin still needs to

be formed into PE so it is likely that the PE produced will end up in the same range as those given by (Chen & Patel, 2012).

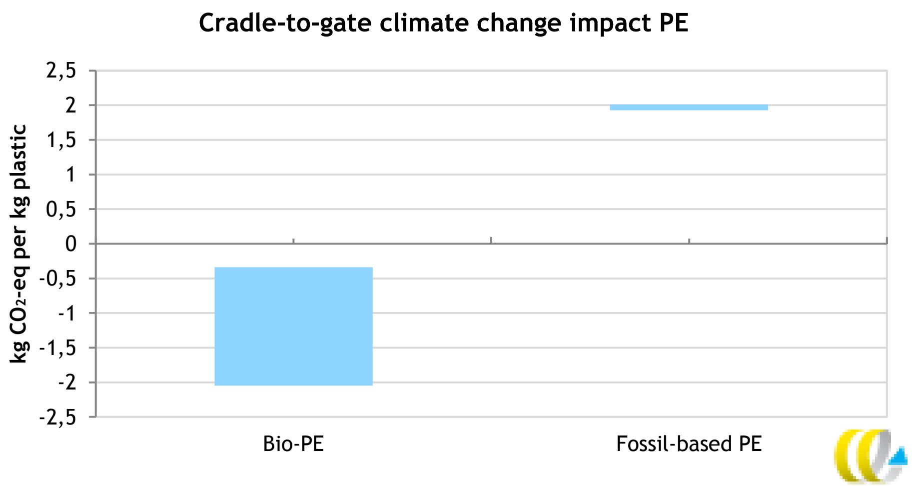
The production of bio-PE by means of animal or vegetable oils has a climate change impact of 4 kg of CO_2 less per kg of PE than for fossil-based PE according to Sabic (see Annex B.2). This means this form of bio-PE would have a climate change impact of approximately -2 kg CO_2 per kg of bio-PE.

Table 10 Climate change LCA results for 1 kg of Bio-PE in cradle-to-gate system

	Corn	Sugar cane
Climate change (kg CO_2-eq per kg bio-PET)	-0.34	-2.05

Source: (Chen & Patel, 2012).

Figure 24 Cradle-to-gate climate change impact of 1 kg of PE-plastic, cradle-to-gate



The range for bio-PE is based on the climate change impact from PE produced from sugar cane (the lower end of the range) and corn (the higher end of the range) from (Chen & Patel, 2012).

End-of-Life

The chemical composition of bio-PE is the same as fossil-based PE and can therefore be recycled in the same way as conventional PE.

When bio-PE is incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

Future developments

Currently bioethanol is mainly produced from glucose, either directly from glucose or from starch that is converted into glucose. Glucose can also be produced from cellulose. Cellulosic materials, such as waste plant material and grasses, are not widely used yet to produce bioethanol but might become attractive in the future.

A.3.2 On market: Bio-PET (polyethylene terephtalate)

Bio-PET is a (partly) biobased plastic that is non-biodegradable.

Applications

Bio-PET is mainly used for the production of bottles. Examples of use are bottles used for soft drinks (Coca-Cola) and ketchup (Heinz). However in principle in all applications in which conventional PET is used, bio-PET could be used instead. Which means that applications in clothing, manufacturing and combinations with glass fibre to form resins are also possible. Examples of this are the use of bio-PET as a resin in cars by Toyota (Toyota, 2012). This means that bio-PET can be used in the following applications:

- rigid packaging;
- flexible packaging;
- textiles;
- consumer goods;
- automotive and transport.

Raw materials

PET is produced from ethelyne glycol and terephthalic acid. The commercially available Bio-PET is a PET of which only the polyethylene is made from biobased materials while the terephthalate is still being produced from 'conventional' fossil-based materials, as is the case for 'PlantBottle™'. In this case the polyethylene is produced from ethylene glycol from bioethanol. The biobased content of bio-PET in this case is 30%.

The substrates that can be used for bio-PET are shown in Table 11.

Table 11 Building blocks and their substrates that can be used for bio-PET

Buidling blocks	Substrates
Ethylene glycol	Bioethanol made from sugar cane or corn starch.
Terephthalic acid	For 100% biobased PET: paraxylene from biobased sugars, bioethanol or biomass. For up-to 30% biobased PET: paraxylene from petroleum.

Climate change impact

The production of conventional PET has a cradle-to-gate climate change impact of 3.2 kg of CO_2-eq per kg of plastic (Ecoinvent, 2016). According Shen (Shen, 2011) the climate change impact of maize-based PET from the USA (30% biobased) is 1.36 kg CO_2-eq per kg of plastics and the climate change impact of sugar cane-based PET from Brazil (30% biobased) is 1.03 kg of CO_2-eq. In these cases the climate change impact of land-use change of maize and sugarcane production is not taken into account. (Chen & Patel, 2012) state that bio-PET made of biobased polyethylene made from maize has a cradle-to-gate climate change impact of 1.4 kg CO_2 per kg of bio-PET, and bio-PET made of sugar cane 1 kg CO_2 per kg of bio-PET.

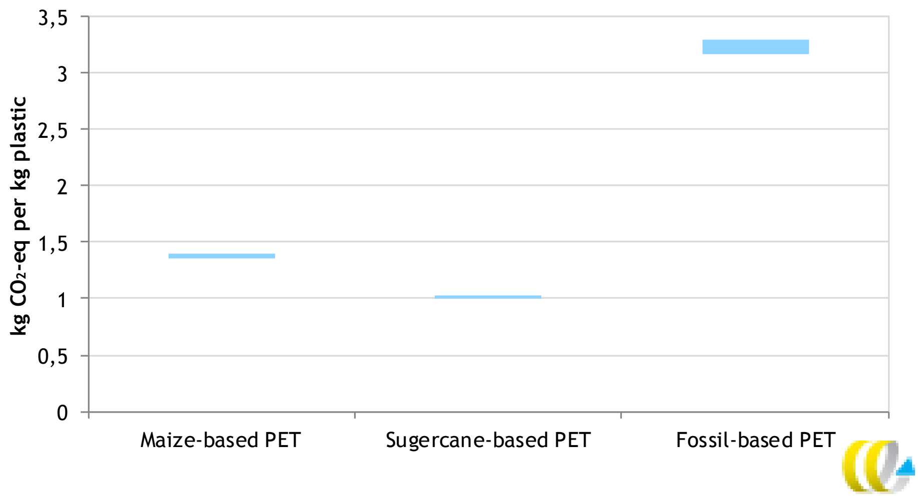
No data is available on the climate change impact of 100% biobased PET.

Table 12 Climate change LCA results for 1 kg of Bio-PET (30% biobased) in cradle-to-gate system

	Corn	Sugar cane
Climate change (kg CO_2-eq per kg bio-PET)	1.36-1.4	1.0-1.03

Source: (Shen, 2011). This excludes land-use change.

Figure 25 Cradle-to-gate climate change impact of 1 kg of PET-plastic, cradle-to-gate



Source: for 30% biobased PET (Shen, 2011) and for fossil-based PET (Ecoinvent, 2016).

End-of-Life

Bio-PET is chemically identical to fossil-based PET and can thus be recycled by means of the conventional recycling routes.

When bio-PET is incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

Future developments

A process has been developed in which also the terephthalate can be produced from biobased material. Cumapol and BioBTX has developed a method in which terephthalate can be produced from wood (Gemert van, 2015). The exact type of wood being used does not matter. The company Virent also produces paraxylene from plant-derived feedstock which can be used to produce terephthalatic acid and consequently bio-PET (Virent, 2015).

Figure 26 shows the production of bio-PET (the green boxes) as specified by Virent (Virent, 2014).

Figure 26 Process scheme for bio-PET

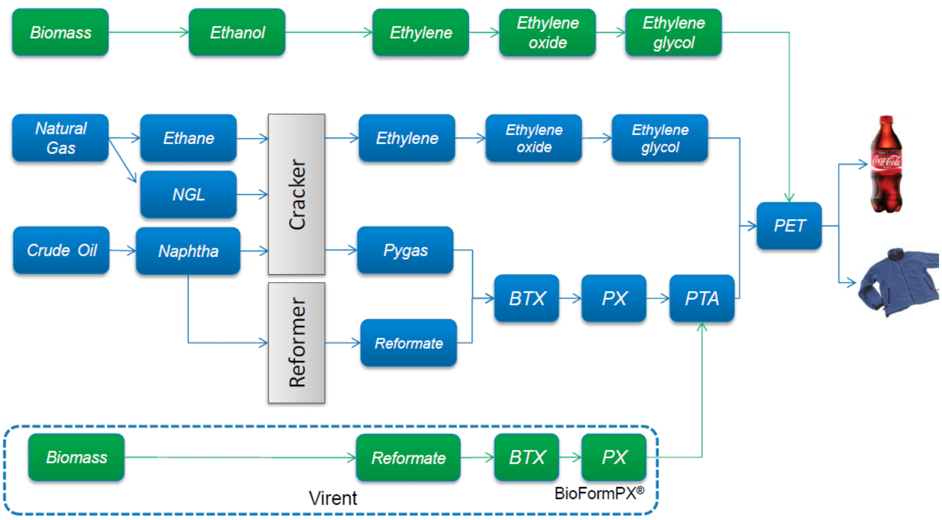


Figure from (Virent, 2014).

A.3.3 On market: Bio-PTT (polytrimethylene terephthalate)

Bio-Polytrimethylene Terephthalate (bio-PTT) is a semicrystalline polymer. PTT is very similar to PET, and is mainly used in carpet and textile fibres. According to (Shen, 2011), bio-PTT has the potential to replace PET, PA, PC and PBT.

Applications

Bio-PTT does not yet have a long list of applications. DuPont has developed Sorona, a bio-PTT with a biobased content of 37% renewable material. This material is marketed for fibre applications used in apparel and carpet industry. Another example of an application of bio-PTT is the interior of the Toyota Prius in Japan, in which biobased PTT from fermented plant sugar is used (PT Online, 2011).

- textile (apparel, carpets);
- automotive & transport (car interior).

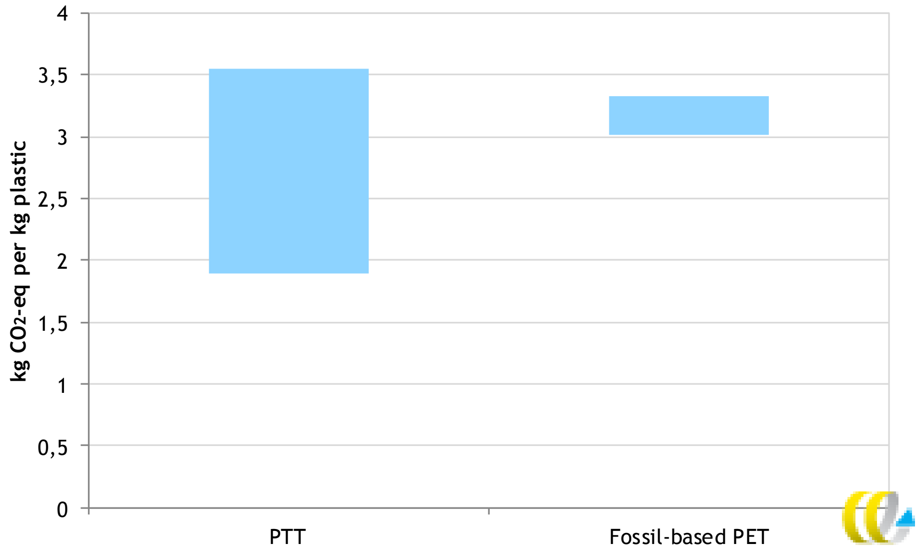
Raw materials

PTT is produced from 1,3-propanediol (PDO) and terephthalic acid. 1,3-propanediol is made from glycerol (Chen & Patel, 2012) or glucose (Joint Research Centre, 2015). It can be obtained from an industrial scale fermentation process: DuPont produces bio-PDO by aerobic fermentation of glucose from corn starch (Shen, et al., 2009). The terephthalate is currently still mainly produced from ‘conventional’ fossil-based materials.

Climate change impact

Based on an own analysis (Chen & Patel, 2012) states that the cradle-to-gate climate change impact of bio-PTT (where only the ethylene glycol is biobased) is between 1.9 and 3.2 kg CO_2 per kg of plastic. DuPont however, has stated a cradle-to-gate climate change impact of 3.17 to 3.55 kg CO_2 per kg of plastic (Chen & Patel, 2012). Figure 27 shows the range from the minimum climate change impact given by (Chen & Patel, 2012) and the maximum based on DuPont.

Figure 27 Cradle-to-gate climate change impact of PTT



Source: The fossil-based PET is based on data from (Ecoinvent, 2016).

End-of-Life

PTT is not compostable. The preferred end-of-life treatment of PBT is recycling. However, due to low production volumes, this is currently not feasible. When bio-PTT is incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

Future developments

A process has been developed in which the terephthalate used in PTT can be produced from biobased material, making a 100% biobased PTT possible. Cumapol and BioBTX has developed a method in which terephthalate can be produced from wood (Gemert van, 2015). The exact type of wood being used does not matter. The company Virent also produces paraxylene from plant-derived feedstock which can be used to produce terephthalic acid (Virent, 2015).

A.3.4 On market: Bio-PA (polyamide)

Polyamide (PA), better known as nylon, can be fabricated from both natural as well as artificial materials. PA is biobased if it is synthesized from biobased monomers. A number of different types of (partially) biobased polyamides (PA11, PA6, PA66, among others) are, and have been for long, commercially available on the market. PA11 has always been biobased, while the other types can be either completely or partially biobased (van den Oever, Wagening UR). Their different types stem from the different raw materials used for their production, and each type has slightly different properties.

Applications

Polyamide has many different applications, depending on its specific type. Each specific type also has a different biobased content, ranging from around 60% to 100%. Different types and their applications include:

- **PA11**: Pipelines for transport of gas, water, and oil mixtures.
  Many applications in the automotive industry such as fuel lines and pneumatic pipes. Also used in many types of cables and connectors, sports shoes and electronic device components.

- **PA12:** Production of biobased PA12 is in development by Evonik; applications will be similar to petrochemical PA12 (packing material in the food industry, and sterilized films and bags for medical uses).
- **PA6.10**: Key applications are in monofilaments (used in brushes and filter systems), and automotive applications.
- **PA4.10**: (contains ~70% biomass based on castor oil). Commercial applications include flexible packing materials in the food industry, as well as consumer electronics, furniture, and automotive interior and exterior.
- **PA10.12**: Is made from castor oil, and has characteristics similar to PA11 and PA12. It is used in automotive and industrial applications.

Other polyamides that could be produced from biobased material but are not (yet) commercially available are PA10.10, PA6, PA66, PA69, and PA5.10.

Raw materials
Many types of biobased polyamide are produced from castor oil. Other raw materials include palm oil. Both castor oil and palm oil are biobased materials. Putrescine is fossil-based and 1,6 hexanediamine could be produced biobased but is currently not being used in PA6.10.

Table 13 Raw materials for different types of polyamide

Type of PA	Raw material/intermediates
PA11 (100% biobased)	Castor oil
PA12 (100% biobased)	Lauric acid from palm oil
PA6.10 (60-100% biobased)	Castor oil and 1,6-hexanediamine
PA4.10 (70% biobased)	Castor oil and putrescine

Source: (Shen, et al., 2009).

Climate change impact
According to a cradle-to-gate assessment by Evonik, their product Vestamid Terra HS, which is based on PA6.10, has a global warming potential of 4.1 kg CO_2-eq per kg Vestamid Terra HS (Evonik, 2016). Table 10 shows the cradle-to-gate climate change impact of PA66 and PA6.

Table 12 Climate change impact (cradle-to-gate) of the production of 1 kg of PA66 and PA6

Type of PA	Kg CO_2-eq/kg material
PA66	8.26
PA6	9.25

Source: (Ecoinvent, 2016). It is unclear whether or not these are 100% biobased.

End-of-Life
According to (Soroudi & Jakubowicz, 2013) there are little examples of the recycling of bio-PA. The main issue with the recycling of PA according to them is the existence of so many different types of PA. They provide an example, however, of the recycling of PA11, by means of the recycling method that is already applied for PA66 because these two polyamides are compatible in the use as fibres.

When biobased PA is incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

Future developments

The production of biobased intermediates used in the synthesis of different polyamides is under development. Examples are biobased adipic acid and biobased hexamethylenediamine, which have been developed recently by Rennovia (de Guzman, 2013).

A.3.5 On market: Bio-PP (polypropylene)

Applications

Bio-PP has the same chemical composition of PP and can therefore be used in the same applications as PP. PP is generally used in the following applications:

- rigid packaging;
- flexible packaging;
- textiles;
- consumer goods;
- building and construction (mainly in piping systems).

Raw materials

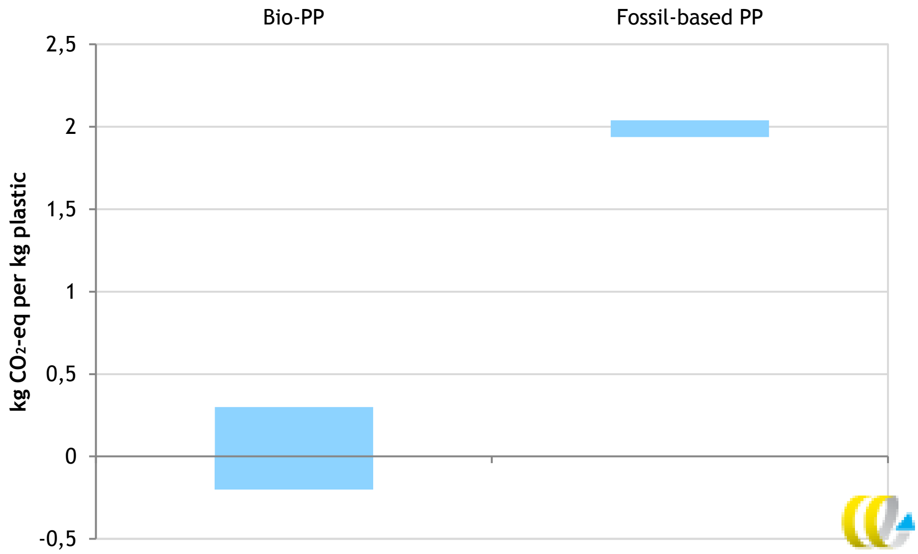
PP is produced from a synthesis between 2-butylene and ethylene (Chen & Patel, 2012). Both materials can be produced from glucose, which can be derived from a wide range of different types of biomass. To produce 2-butylene, the glucose is transformed into isobutanol and consequently to 2-butylene (Chen & Patel, 2012). Ethylene is produced from bioethanol which is derived from glucose. Biobased PP is not being produced commercially from glucose.

Bio-PP can also be produced by means of animal or vegetable oils and fats. The oil or fat is transformed into biodiesel which is blended with naphta into the cracker. This is done by Sabic (Sabic, 2016).

Climate change impact

(Chen & Patel, 2012) estimate that the cradle-to-gate climate change impact of bio-PP from glucose is -0.2 to - 0.3 kg CO_2 per kg of bio-PP. The climate change impact of bio-PP is compared to conventional PP in Figure 28.

Figure 28 Cradle-to-gate climate change impact of PP



Source: For bio-PP (Chen & Patel, 2012), source for fossil-based PP (Ecoinvent, 2016).

End-of-Life

Bio-PP has the same chemical composition of PP and can therefore be recycled in the same way that PP is recycled.

When bio-PP plastic is incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

Future developments

The production of bio-PP is possible, but is not yet commercially available. This might be the case in the future.

The production of isobutanol from cellulosic material might be possible in the future but more research will need to be done.

A.3.6 Soon to be on the market: PEF (polyethylene furanoate)

PEF can be viewed as a biobased competitor of PET. Terephthalic acid, the precursor to PET, can be replaced by FDCA (2,5-Furandicarboxylic acid) from renewable resources. FDCA can be polymerized into PEF, which is slightly different in chemical structure from PET but shares many characteristics. The US Department of Energy identified FDCA as one of the top 12 potential platform molecules likely to play an important role in establishing the green chemistry industry.

Applications

PEF is a competitive alternative to PET since it has good properties to keep water in or out, as well as oxygen and CO_2. It also has better tensile strength, but it is also brittle (van den Oever, Wagening UR). Its characteristics enable thinner PEF packaging, and extended product shelf life. It is therefore suitable for use in for example bottles. PEF can also be used in films and fibres (for carpets, home furnishing, and fabrics), as well as in other polyester applications.
The Dutch renewable chemistry company Avantium recently announced that it will build a plant in Antwerp with a capacity of up to 50,000 metric tons per year of FDCA as main building block for PEF. The applications of PEF therefore fall within the following categories:

- rigid packaging;
- flexible packaging;
- textile;
- consumer goods.

Raw materials

PEF is produced from ethelyne glycol and FDCA. The polyethelene is produced from ethylene glycol which can be produced from bioethanol via bioethylene. FDCA can be derived from sugars or bio-waste.

Climate change impact

Despite the fact that commercial scale production of PEF, and FDCA, is underway, little information about the climate change impact of both materials is available. According to (Harmsen & Hackman, 2012c) (referring to an LCA study presented during the 7th international conference on renewable resources and bio-refineries) a reduction of between 40 and 50% of CO_2 emissions is possible when using PEF instead of conventional PET.

End-of-Life
Tests show that PEF can be recycled and incorporated into the PET recycle with no effect on the recycled PET performance, as long as the PEF content remains below 5%. PEF is distinguishable from PET and could thus in principle with amended sorting facilities in the Netherlands be separated from PET.

When PEF is incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

Future developments
Recent developments in chemistry and increased attention from industry organizations, combined with the superior characteristics of the material as compared with PET, indicate the potential of PEF to become a competitive biobased alternative to PET.

Recent research shows potential in producing FDCA from inedible biomass such as furfural, in combination with usage of CO_2 (Banerjee, et al., 2016).

A.3.7 PBT (Polybutylene terephthalate)
PBT is a type of polyester: a thermoplastic (semi-)crystalline polymer, with applications in the electronics industry. Biobased PBT has physical properties equivalent to the petroleum based PBT. It is produced by a number of companies (e.g. Lanxess and Toray), and has seen substantial growth in commercial production volume over the past year.

Applications
Due to its high stiffness and good heat resistance, PBT is often used in engineering applications such as electronics. Examples are sockets, TV-parts and switches. The plastic is also used in automotive electronics, e.g. in connectors, sensors or control units. The application categories in which PBT falls are:
- consumer goods;
- electric and electronic equipment;
- automotive and transport.

Raw materials
PBT is produced from 1,4-butandiol and terephthalic acid. PBT has been produced with biobased 1,4-butandiol, but is currently not commercially available. A 100% biobased PBT is theoretically possible if also the terephtaic acid is produced from fossil-based resources.

Climate change impact
Preliminary life cycle analysis indicates that producing 1,4-butanediol from sugarcane-derived sucrose lowers the use of fossil energy by at least 86%. Carbon dioxide emissions are said to be lowered by 117% (Burk, 2010). Unfortunately, no detailed information about these results is available. Therefore, it is not possible to say whether the end-of-life phase has been taken into account in this analysis. No other LCA results are (publicly) available for PBT plastic.

End-of-Life
The preferred end-of-life treatment of PBT is recycling. However, due to low production volumes, this is currently not feasible. When PBT is incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

Future developments

In the future PBT could be produced from both biobased 1,4-butanediol and biobased terephtalic acid.

Terephtalic acid can be produced from wood (Gemert van, 2015). The exact type of wood being used does not matter. The company Virent also produces paraxylene from plant-derived feedstock which can be used to produce terephthalic acid (Virent, 2015).

A.3.8 Bio-PVC

Polyvinylchloride (PVC) is one of the largest commodity thermoplastics. It is a rigid, non-flexible lightweight plastic, which is often used in construction applications. PVC can be made flexible by adding plasticizers, such as phthalates. This flexible PVC is used in many applications to replace rubber. Biobased plasticizers from renewable resources have been developed.
Also, the monomer of PVC, ethylene, can be obtained by dehydration of bioethanol (Harmsen & Hackman, 2012c).

Applications

Rigid biobased PVC can be used in building applications such as pipes and window frames. This is the largest application of PVC, accounting for 55% of PVC use. PVC has a long lifetime, making the material appropriate for construction uses: frames last over 40 years, and sewage pipes around 100 years (Harmsen & Hackman, 2012c). Flexible PVC is, amongst others, used in packaging and household appliances. Bio-PVC that has been made flexible with biobased plasticizers can be used in applications such as floors, electricity cables and shower curtains. Biobased PVC is not (yet) available on the market.

- building & construction (pipes, window frames, floors, electricity cables);
- rigid packaging (rigid film);
- flexible packaging (cling film);
- consumer goods (household appliances, shower curtains).

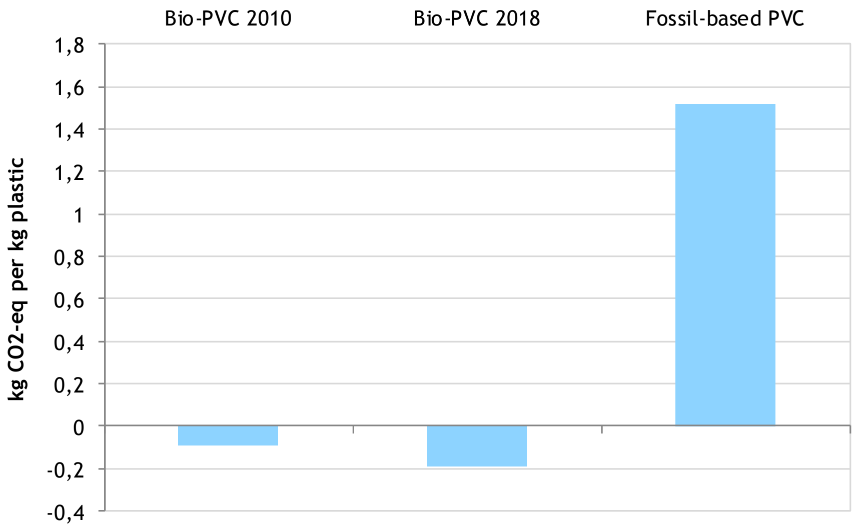
Raw materials

Biobased PVC has ethylene as its monomer. Ethylene can be obtained by de-hydration of bioethanol. Bioethanol can be obtained through two production routes: by fermenting virtually any source of sugar or starch (e.g. sugar cane, corn, wheat, sugar beet, etc.), and by hydrolysis of starchy biomass followed by fermentation (IRENA, 2013). The ethylene used in the production of biobased PVC is converted into 1,2-dichlorethane, which results in vinyl chloride after dehydrochlorination. Vinyl chloride can subsequently be polymerized, and biobased PVC is obtained (Harmsen & Hackman, 2012c).

Climate change impact

A cradle-to-gate life cycle assessment by (Alvaranga, et al., 2013) used two scenarios for bioethanol-based PVC (2010 and 2018) to compare its environmental impact to that of fossil-based PVC. Biobased PVC from 2010 has a climate impact of -0.09 kg CO_2-eq/kg of PVC resin, while biobased PVC from 2018 is estimated to have a climate impact of -0.19 kg CO_2-eq/kg of PVC resin. For fossil-based PVC resin, this figure is much higher: 1.52 kg CO_2-eq/kg of PVC resin. These are shown in Figure 29.

Figure 29 Cradle-to-gate climate change impact of PVC



Source: (Alvaranga, et al., 2013).

End-of-Life

PVC from biobased ethylene is non-biodegradable. It is expected that biobased PVC can be recycled in processing plants designed for fossil-based PVC. However, since no large-scale recycling has taken place, this is still uncertain.

When bio-PVC is incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

Future developments

Market forecasts predict that the production volume of biobased PVC will increase in the coming years, due to its wide range of applications and the general growing public interest for biobased plastics. Uncertain crude oil prices in the Middle East also form a driver for an increasing commercial market of bio-PVC (Grand View Research, 2016).

For biobased plasticizers used to make flexible PVC, a number of potential renewable resources have been investigated. Examples are epoxidized vegetable oil, from soya beans and sunflowers, and cardonol, which is obtained from cashew nut shells (Lim, et al., 2015). Still, these alternatives have not yet been introduced on a widespread commercial scale.

A.4 Thermosets

Biobased thermosets have, in general, less well-developed commercial applications than their biobased thermoplastic counterparts. Therefore, information about their climate change impact, end-of-life and future development is often less readily available.

In the following sections the information found is summarized for bio-polyurethane, bio-epoxyresins, bio-unsaturated polyesters, furan-based polymers and bio-composites.

A.4.1 Bio-polyurethane

Polyurethanes are widely used plastics composed of organic units joined by urethane links. Although most polyurethanes are thermosetting, thermoplastic polyurethanes also exist. Many international producers are currently producing biobased polyols, which form, together with isocyanates, the building blocks of (bio)polyurethane. The bio-content of polyurethane ranges from 30 to 70%, depending on the type of feedstock used for the manufacturing of its polyols (Grand View Research, 2015).

Applications

Polyurethane has a variety of applications: its most important applications are in flexible and rigid foams (building insulation), coatings, medical devices, synthetic fibres, various hard plastic parts, and load-bearing wheels. Rigid and flexible polyurethane foams together constitute more than 75% of the total demand in 2013 (Grand View Research, 2015). The application categories in which bio-polyurethane fall are therefore:

- building & construction (insulation, coatings);
- textiles (synthetic fibres);
- consumer goods (wheels);
- others (medical devices, hard-plastic parts).

Raw materials

Polyethane is produced from polyols and isocyanates. Both of these ingredients are currently still being produced from fossil-based material.

Climate change impact

(Meesters, et al., 2012) conducted a life cycle study of polyol from vegetable oil, evaluating different environmental aspects for different feedstocks (soy and rapeseed). The production of polyol is subsequently compared to the production of diesel and resin.
The system boundaries of the study are from cradle-to-gate, and the uptake of CO_2 by vegetable products is included as a negative CO_2 emission in the analysis.

The results show that the production of polyol from soy has associated emissions of +/- -1.4 ton CO_2-eq/ton product. For the production of polyol from rapeseed, this number lies between -0.3 and -1.3 ton CO_2-eq/ton product, depending on different scenarios. The emissions for polyol produced from fossil resources are much higher: around 4.1 ton CO_2-eq/ton product. In other words: the avoided GHG emissions for the production of polyol from soy and rapeseed, as compared to polyol from fossil resources, are high: for different cases (soy and three rapeseed scenarios), between 4.5 and 5.5 ton CO_2-eq/ton product are avoided.

End-of-Life

Conventional PURs, and thus also their biobased counterparts, cannot be recycled into the same material because they are thermosets, unless they are chemically recycled. Chemical recycling is, however, at the moment not economically feasible (Soroudi & Jakubowicz, 2013), and the question is whether or not it would be environmentally feasible for bio-polyurethane. The most common method of PUR ‘recycling’ is the grinding of PUR and using it as filler in several applications (Soroudi & Jakubowicz, 2013).

When bio-polyurethane is incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

Future developments

Adipic acid is the most common aliphatic diacid used to make polyester polyols, succinic acid can be used instead (Bolck, et al., 2012b). Succinic acid can be produced from fermentation of glucose (Bolck, et al., 2012b). Also, vegetable oils can serve as a substitute for polyols in polyurethane foams (Meesters, et al., 2012). Castor oil, soybean oil, sunflower oil and rapeseed oil have been listed as the most-used resources for polyols (Grand View Research, 2015). Biobased adipic acid has also been developed recently by Rennovia (de Guzman, 2013).

A isocyanate drop-in is available from Covestro under the name Desmodur eco N 7300, and is 70% biobased.

A.4.2 On market: Bio-epoxyresins

Epoxies are thermosetting polymer resins. They are widely used and have multiple applications. 75% of all epoxy resins are liquid epoxy resins, which are derived from, among other chemicals, bisphenol A and epichlorohydrin (ECH).

Applications

Globally, 41% of fossil-based liquid epoxy resins that are produced are used for coatings. 31% are used as adhesives, while the remaining 28% is used in a variety of other applications (Baroncini, et al., 2016). Biobased resins that have properties tailored to these applications are currently in development.

Examples of applications that are typical for bio-epoxyresins are e.g. epoxidized soybean oil, for instance, which can potentially be used in water resistant paper composites and shape memory polymers, while epoxidized linseed oil can be applied in composites, adhesives, and laminates.
Generally, applications can be listed as follows:
- building & construction (coatings and adhesives, biocomposites, shape memory polymers);
- electrical & electronics.

Raw materials

Liquid epoxy resins are mainly produced from bisphenol A and epichlorohydrin (ECH). The latter used to be produced in a petrochemical process.
However, currently, it is mainly produced from biobased glycerol, due to the large availability of biobased glycerol as a by-product of biodiesel production (Shen, 2011).

Climate change impact

Some studies show high savings (around 90% for both energy as well as GHG emissions) for epoxidized linseed oil as thickener for lacquers, as compared with conventional petrochemical thickeners (Patel, et al., 2005).

End-of-life

The biodegradability of bio-epoxyresins differs depending on the raw materials used. For karanja-oil-based bioepoxy, that was synthesized using citric acid, up to 82% was degraded in 69 days. Bioepoxy that was created using tartaric acid was degraded for 95% in 259 days (Kadam, et al., 2015).

Little information on the recycling of biobased epoxy resins is available. Because it is a thermosetting plastic, it is likely that very little (mechanical) recycling options are available for bio-epoxyresins.

When bio-epoxyresins are incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

Future developments
Bisphenol A is classified as reprotoxic; it has adverse effect on sexual function and fertility in male and female species (Baroncini, et al., 2016). Still, it is used as a basis for 85% of the world's production of epoxy resins. Biobased thermosetting resins, using non-toxic renewable natural resources as building block, are currently in development. The research on bio-epoxyresins with mechanical properties similar to their fossil-based counterparts is still somewhat limited (Liu, et al., 2012). Substituting bisphenol A based epoxy resins by materials from vegetable oil remains chemically challenging (Stemmelen, et al., 2011).

Much recent literature focuses on the synthesis of bio-epoxyresins from a variety of new organic materials. The usage of epoxidized linseed oil and epoxidized soybean oil to form bio-epoxy resins has been studied (Ding, 2015). Other raw materials include, among others: canola, karanja, natural rubber, eucalyptus, and bamboo (Baroncini, et al., 2016). As mentioned previously, challenges regarding mechanical properties still remain important.

A.4.3 Bio-unsaturated polyesters (UPEs)
Unsaturated polyesters (UPEs) are a large family of polymers with a wide range of applications stemming from their ability to undergo various post-polymerisation reactions. They are usually referred to as (thermosetting) polyester resins, or sometimes as UPE resins. Polyester resins are produced by dissolving a unsaturated polyester in a vinyl monomer, after which both elements are copolymerized and form a hard, durable plastic material.

Applications
Bio-UPE’s have various applications (Farmer, et al., 2015). They are also widely used as the matrix in commodity composite materials.
Most commercially available biobased resins are biobased up to a maximum of fifty per cent (WUR, 2016).
- building & construction (insulation, high-gloss coatings);
- others (medical uses: drug delivery systems, various biomedical applications).

Raw materials
100% biobased UPE’s are currently not commercially available. There is a UPE on the market under the name Palapreg Eko, which has been developed by DSM. It has a biobased content of 55% (DSM, 2010).

Climate change
No information on the climate change impact of the production of bio-UPE’s is available.

End-of-Life
Thermosetting plastics are generally hard to recycle. When bio-EPE’s are incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

Future developments

Bio-UPEs can be synthesized from bio-derived platform molecules, which can be obtained through thermal, chemical or biological treatment of biomass (Farmer, et al., 2015).

The bio-derived platform molecules used in the synthesis of unsaturated polyesters are usually obtained from plant oil. This can be, among others, corn oil, linseed oil, soybean oil and coconut oil. However, soybean oil seems to appear most frequently in the literature due to its large production volume (Mosiewicki & Aranguren, 2013).

A.4.4 On market: Furan-based polymers

Furan is a clear, colourless, flammable liquid cyclic ether. It is characterized by a ring structure composed of one oxygen atom and four carbon atoms. Furan resin is a biosynthetic thermoset, derived from extracts from carbohydrate components in sugar beet, wheat and corn, or from vegetable by-products such as corn cobs. Furan resin is an attractive alternative to phenolic resins, since they use furfural from agricultural by-products, instead of the toxic component formaldehyde (Rivero, et al., 2011).

Applications

Furan resin is used in natural fibre-reinforced plastic composites, which have applications in the construction- and automotive industry. Also, sand castings based on furan resins, which can be used in iron alloy casting, are becoming more widespread.
- building & construction;
- automotive & transport;
- others (sand castings).

Raw materials

Furan resins are produced from furfuryl alcohol, which is a compound that is obtained from furfural. This material can be derived from a variety of agricultural by-products such as corncobs, oat bran, wheat bran and other cellulosic waste materials.

Climate change impact

(Tumolva, et al., 2011) find that the production of 1 kg of 100% biobased furan resin results in 4.7 kg of fossil-based CO_2 production (cradle-to-gate).
The study mentions that the fixed CO_2 content of the material is 2.6 kg/kg of furan, which is, in other words, the CO_2 uptake of the material. Therefore, the net CO_2 emission of the production of 1 kg of furan resin is 2.1 kg.

End-of-Life

Thermosetting plastics are generally hard to recycle. When furan-based polymers are incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

A.5 Biocomposites

Composites are built up from at least two constituent materials: matrix (resin) and reinforcement (fibre). The resulting material has properties which are a mix of the individual materials. Composites are also called fibre reinforced plastics. In biocomposites at least one of the two constituent materials orginates from a biobased resource.

Applications
Composite plastic materials often possess mechanical and physical properties that make them better suited for a wide range of applications than the individual composite components (Petinakis, et al., 2013). They are among the most widely produced categories of plastics and have numerous applications such as in automobiles, construction materials, and household equipment (Duflou, et al., 2012). The quality of biobased composites has increased in the past years. The main applications are:
- construction materials;
- automotive sector;
- electronics (casings).

Because of the low densities of plant-based fibres, as compared to glass fibres, natural-fibre reinforced plastics are attractive in applications that require material weight reduction.

Raw materials
Examples of natural fibres for biocomposites are: Flax, hemp, kenaf, jute, sisal, ramie, abaca, cotton and coconut (Oever & Molenveld, 2012a). Sometimes, if both resin and fibre are biobased, the composite is 100% biobased, otherwise it is only partially biobased.

Climate change impact
One crade-to-gate LCA compares the production of one kg of flax/PLA biocomposite to one kg of glass/polyester composite (Le Duigou, et al., 2011). The functional unit is a flax mat/PLA biocomposite with mechanical properties in tension identical to those of glass mat/polyester.
The fibre volume content is fixed at 26.5% which is typical for marine applications. Le Duigou et al find that greenhouse gas emissions (gas/kg) for biocomposites are significantly lower.

Table 14 Greenhouse gas emissions in kg CO_2-eq associated with the production of one kg of flax/PLLA biocomposite, using a cradle-to-gate approach

Fibre content (volume)	Quantity of GHG emissions (CO_2-eq) per kg of flax/PLLA
0.0	1.55
16.5	1.33
26.5	1.29
40.1	1.15

Source: (Le Duigou, et al., 2011).

Table 15 Greenhouse gas emissions in kg. CO_2-eq associated with the production of one kg of glass/polyester composites, using a cradle-to-gate approach

Fibre content (volume)	Quantity of GHG emissions (CO_2-eq) per kg of glass/polyester
0.0	7.7
17.3	6.5
26.1	5.9
37.1	5.4
48.0	1.2

Source: (Le Duigou, et al., 2011).

End-of-Life

Because of the wide variety of biocomposites it is not possible to state what the end-of-life of all of the different composites could look like.
However, several types of biocomposites are likely to experience challenges during their recycling. These challenges include difficulties in separation of different parts of the different constituents of the composite, thermomechanical degradation, contaminations that result in inferior properties, and insufficient quantities of biopolymers (Soroudi & Jakubowicz, 2013). Therefore, it is generally difficult to recycle biocomposites.

If a biocomposite is completely biobased it could be compostable depending on the properties of the constituents (Soroudi & Jakubowicz, 2013).

When biocomposites are incinerated with energy recovery, the energy produced can be seen as carbon neutral (for the part of the composite that is biobased) because CO_2 has first been sequestered into the biobased plastic.

A.6 Elastomers/rubbers

Applications

Elastomers, or rubbers, have flexible properties, caused by their slightly crosslinked polymer structure. This means that the deformation of rubbers is reversible, while that of plastic is irreversible (RIVM, 2015).

For most applications the natural rubber is crosslinked by chemical modification. This process is called vulcanization. The natural rubber is heated in the presence of sulphur to make it better resistant to abrasion. Vulcanised natural rubber is used in vehicle tires and conveyor belts. The hard vulcanised rubber is used for pump housings and piping used in the handling of abrasive sludge. Compared to vulcanized rubber, uncured rubber has relatively few uses. It is used for cements; for adhesive, insulating, and friction tapes; and for crepe rubber used in insulating blankets and footwear.

Although this list is not exhaustive, general applications can be summarized as follows:
- automotive & transport (vehicle tires, inner tubes of tires);
- building and construction (piping, cements);
- consumer goods (insulating blankets, footwear);
- others (pump housings, conveyor belts, adhesive, insulating, and friction tapes).

Raw materials

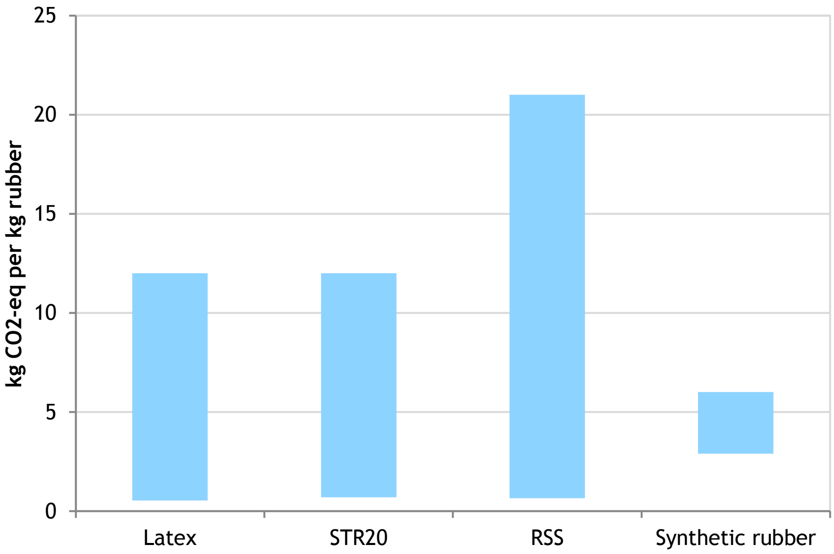
While most elastomers used to be derived from latex from the rubber tree, currently most are synthesized from petroleum oil. In 2012, natural rubber had a market share of approximately 30% (Harmsen & Hackman, 2012c).
It is predominantly produced in Southeast-Asia. Two other plant based sources that show promising results are the Guayule, a shrub native to the southwestern United States and northern Mexico, and the Kazakh dandelion (Bolck, et al., 2012b).

Bio-EPDM, a synthetic rubber, is produced by Lanxess (Lanxess, 2016).
This rubber can be produced with up to 70% biobased content, depending on the amount of biobased ethylene being used. Biobased ethylene is produced from bioethanol and thus from sugars derived from sugar cane, corn or sugar beet.

Climate change impact
Results of studies that estimate emissions associated with the production of natural rubber vary, depending on location of production and rubber type. In Thailand, one of the world's largest rubber producers, the production of concentrated latex results in 0.54 ton CO_2-eq/ton product. The production of block rubber (STR20) contributes emissions of 0.70 ton CO_2-eq/ton product, while ribbed smoked sheet rubber production emits an estimated 0.64 ton CO_2-eq/ton product (Jawjit, et al., 2010). In some cases, tropical forests have been converted to rubber plantations. Then, estimated emissions are considerably higher: 13, 13, and 21 ton CO_2-eq/ton product for concentrated latex, STR 20, and RSS, respectively. In Sri Lanka, the production of one kg of (natural) latex foam produced results in estimated emissions of 3.34 kg CO_2-eq per kg of product (Gunathilaka & Gunawardana, 2015).

In Figure 30 the climate change impact of these three natural rubbers are compared with fossil-based rubber.

Figure 30 Cradle-to-gate climate change impact of natural (biobased) rubber



The lowest climate change impact (best case) for natural rubbers is based on (Jawjit, et al., 2010). No land-use change has occurred for these rubbers. The highest climate change impact (worst case) for natural rubbers is based on (Gunathilaka & Gunawardana, 2015). In the worst case tropical forests are converted to rubber plantations for the production of natural rubber. For synthetic rubber the best case production is production in the EU and the worst case is production in the rest of the world. Both are based on (Ecoinvent, 2016).

End-of-Life
It is estimated that, every year, 17 kiloton of vehicle tire residues ends up in the environment in the Netherlands (Verschoor, 2014).

Elastomers do not allow reshaping, are therefore difficult to recycle. Current recycling practices, which consists of the blending of shredded scrap into virgin material, yields a product of lower quality. Therefore, the are developments towards devulcanization processes (PlasticsEurope, 2016).

One widespread application of end-of-life tires is the shredding of tires. Shredded tires in the Netherlands are used for artificial grass. Public attention regarding the supposed negative health effects of this materials rose in October 2016. While previous research indicated that the granulates were safe, the European Chemical Agency currently re-investigates the health risks of the use of rubber granulates on sport fields.

When natural elastomers are incinerated with energy recovery, the energy produced can be seen as carbon neutral because CO_2 has first been sequestered into the biobased plastic.

Future developments

The monomer of polyisoprene, isoprene, can be produced by different synthetic or natural pathways. One route is by fermentation of biomass that is rich in sugars. The monomer for polyisobutylene, isobutene can be produced from biomass from bioethanol. The monomer for polybutadiene is butadiene which can be produced from renewable resources: from biobased ethanol, by fermenting sugars into 1,4-butanediol combined with dehydration, and by fermentation of sugars (Harmsen & Hackman, 2012c).

A.7 Biodegradable, fossil-based thermoplastics

Fossil-based biodegradable plastics are used in blends, to improve a material’s characteristics, while maintaining or increasing biodegradability.
Partially biobased versions of these materials are being developed and will probably be available in the near future (European Bioplastics, 2016).

A.7.1 PCL

Polycaprolactone, or PCL, is a biodegradable thermoplastic polymer derived from the chemical synthesis of crude oil. It can be degraded by aerobic and anaerobic microorganisms that are widely distributed in various ecosystems (Tokiwa, et al., 2009). It is a hydrophobic and semi-crystalline polymer, with a melting point of around 60°C. PCL can easily be blended with various commercial (bio)polymers.

Applications

PCL degrades slowly. Reported degradation times are 2 to 4 years (Sant, et al., 2013) and up to 3-4 years (Woodruff & Hutmacher, 2010). The compound has high drug permeability, and good blend-compatibility. Therefore, it has a long history as a long-term implant delivery device and in various tissue engineering applications, mostly during the 1970s and 1980s. At present, more advanced and faster resorbable polymers have become popular.

PCL is also used as co-polymer for starch plastics, in PCL/starch blends. Here, it is able to compensate for pure starch materials’ characteristics such as low resilience and high moisture sensitivity. Some biodegradable plastic bags are made from PCL/starch blends (e.g. BioSak).

Raw materials

PCL is fossil-based, and derived from crude oil.

Climate change impact
PCL is reported to have a cradle-to-gate non-renewable energy use of between 77 and 88 MJ/kg. Its GHG emissions per kg of produced pellet are 3.1-5.7 kg CO_2-eq (Shen & Patel, 2008). However, LCA results that are available are subject to major uncertainties.

End-of-Life
PCL has been shown to be degraded by the action of aerobic and anaerobic microorganisms that are widely distributed in various ecosystems (Tokiwa, et al., 2009). PCL is however not biodegradable in human- or animal bodies.
In some experiments, certain strains of fungi or microorganisms isolated from soil (*Penicillium* and *Aspergillus*) were found to be able to fully degrade PCL within a very short time period: 12 days and 6 days respectively (Tokiwa, et al., 2009). These are however not the strains of fungi that occur in regular compost systems. Still, BioSak PCL-starch blend biodegradable bags are certified with the OK Compost HOME label.

When PCL is incinerated with energy recovery, the energy produced is fossil-based energy. Due to its biodegradable nature, PCL might cause disturbances in plastic recycling streams when disposed incorrectly.

Future developments
The number of publications about PCL in the field of biomaterials or tissue engineering has increased steeply between the period 1988-2010.
However, PCLs are currently not widely applied in medical clinics.
Future developments are mainly centred around the medical use of PCL in composite structures, with tailorable degradation properties (Woodruff & Hutmacher, 2010). Such PCL composites can be used as tissue engineering scaffolds for regenerating e.g. bone, skin, nerve and vascular tissues (Ulery, et al., 2011).

Annex B Interviews

To supplement literature data and the sustainability assessment, experts from various organisations and companies (e.g. waste treatment, recycling, producers) were interviewed. In the following sections these interviews are summarized.

B.1 Suez

Jeanette de Lange and Vincent Mooij
Suez Recycling and Recovery Netherlands
September 28, 2016

Biobased plastics and sorting

Sorting companies sort the plastic hero mixture in the following categories:

- pure PE;
- pure PP;
- pure PET;
- foils;
- mixed plastics.

These streams are sorted and baled per stream. These bales still contains some residue or other types of plastics that are removed by the recycling company that buys the bales, shredders and washes them before the bales are extruded to granulates to produce new plastics.

For sorting companies there are two types of biobased plastics:
The biobased plastics that are based on so-called drop-in chemicals and are chemically identical to widely used fossil-based alternatives. Examples of such plastics are the PET produced by Indorama and the poly ethylene (PE) produced by BRASKEM. This category is perfectly compatible with the current recycling system, in which PET and PE are large streams that are collected and sorted to be recycled. If bottles contain a mixture of PEF and PET they are most likely to be sorted in the PET-fraction. For 100% PEF-bottles we do not have the answer right now. All other biobased plastics (e.g. PLA) end up in the residue. Firstly because the system has not been asked to sort these fractions. Secondly these streams are far too small to recover them for recycling (<1%). Thirdly because there are no outlets to recycle these fractions at the moment.

If in the collected plastic wastes contain 5-10% of one type of biobased plastic, than it would be possible to sort this biobased plastic out in the same way that PE, PP, PET and foils are sorted out. However all biobased plastics together are still far less than 5% of all the plastic collected by plastic hero. Off course in that situation there should also be a client, but with a market share of 5-10% in the post-consumer waste stream it is likely that an application of the baled biobased plastic is found.

Biodegradable plastics

Apart from the interesting role that biodegradable plastics could play in the future they currently have a number of problematic aspects:

- The sorting equipment tends to regard for example PLA as organic matter and therefore classifies it as non-plastic material. Consequently it ends up in the stream that is used for energy recovery by incineration.

- Apart from the biobased plastics that are identical to the fossil-based alternatives biobased plastics tend to be hard to recycle and also hard to ferment or compost. Apart from the bin liners for kitchen wastes most applications with a seedling logo require 13 weeks of composting while in many composting installations there is only time for 8 weeks. Consequently these plastics are not (fully) composted after 6-8 weeks when the composting cycle is stopped. In addition some materials could be compostable in 13 weeks if offered under the right conditions, which may not be met in practice: for example stacked coffee cups will not compost in 13 weeks, cutlery made of biobased plastics with seedling logo can be made too thick and thus not compost in time, etc. The recycling and recovery specialists at - Suez therefore often find themselves in the position that they have to lower the expectations of customers. There is a strong push from government to promote biobased plastics, especially by means of biobased purchasing. However, the reality about the poor recyclability in the current situation for all biodegradable plastics is not well communicated. Off course these are starting problems, the only problem is that there is no indication that biodegradable biobased plastics will reach sufficient market share to solve these problems in the next five years.
- The narrow focus on (biodegradable) biobased plastics makes that people forget about the bigger picture of the circular economy. This is especially visible in the current trend towards biobased disposables in hospitals. This trend is based on the idea that disposing of as much material streams as possible and fermentation of the resulting brew to produce biogas is the solution. However in this way a lot of valuable stock material is destroyed in the process. While at the level of a hospital it is possible to set up systems that have a higher material recycling rate. It is not easy, it requires a lot of change in human behaviour but it is possible.
- Using more mono-plastic materials of the known sorts (PE/PP/PET) either fossil or biobased will allow the market to significantly increase recycling rates over the use of all types of other/new plastics and composite plastics.

B.2 Sabic

Bert Bosman
Sabic Europe
September 29, 2016

SABIC is the second largest chemicals company in the world it has over 40.000 employees in more than 50 countries. In Europe SABIC has 5 major production locations, two of which are located in the Netherlands on the Chemelot industrial park in Geleen and in Bergen op Zoom. In Geleen SABIC operates 2 naphtha crackers and 7 polyolefin producing factories. Naphtha crackers produce traditionally on the basis of naphtha, a fraction of petroleum that is not used directly for gasoline or diesel production. The products of a naphtha cracker include ethylene, propylene, butadiene and aromatic compounds like benzene, toluene and xylenes. All of these products are considered compound chemicals that form the basis of the wide variety of chemicals that are used in modern life. Ethylene is globally the most produced chemical in the world, followed by propylene and aromatics.
Well known plastics based on ethylene and propylene are polyethylene (PE), including low and high density PE, respectively LDPE and HDPE and polypropylene (PP), the third most produced plastic is PVC that can be produced after (oxy)chlorination of ethylene.

The products of the naphtha crackers of SABIC in Geleen are partly converted to LDPE, HDPE and PP on site and partly send to other factories connected to the plant by rail, truck, ship or pipeline (the international ARG ethylene network).

Renewable polyolefin production from biobased feedstock at Sabic

Customers are increasingly interested in products produced from biobased feedstock. SABIC can feed the cracker with biodiesel, at the moment in a mixture with naphtha, when there is a demand for renewable materials.
The ISCC+ methodology is used to allocate the biomass to a specific product batch. The allocated biomass in this specific batch is typically higher than the actual biomass content since the biomass is strongly diluted in the complex system of logistics, cracker and polymer plants. However, due to the ISCC+ methodology, the total allocated biomass never exceeds the input of biomass corrected for losses in the fabrication process.
As an additional control of the amount of converted biomass SABIC started with C14 isotope measurements while the cracker runs on the naphtha-biodiesel mixture.
The actual production of renewable polyethylene, polypropylene, etc. fluctuates in time, depending on market demand. In total it adds up to several thousand tonnes per year.
The products resulting from the cracking process are the same as the products coming from regular naphtha cracking. Moreover, the renewable polyolefins are identical and have the same properties as the fossil equivalents.

Sustainability aspects of biobased production at SABIC

According to the LCA studies by SABIC (according to ISO 14040 through 14044 and using PAS 2050 for carbon accounting) the renewable PE produced by SABIC has a lower CO_2 footprint of 4 ton CO_2/ton PE compared to regular PE production from fossil derived feedstock (naphtha).

Demand limitations

Currently the demand for renewable LDPE, HDPE, or PP, as well as other products produced on the basis of biodiesel is limited because of the large price difference between fossil-based and biobased production.
Factors influencing the price difference are the following:

- The oil price, which is currently very low ($ 50/barrel).
- The regulation and support of biobased fuels in Europe and the Netherlands in particular, leading to a high demand and increased prices for biofuels (which fuel companies pass on to the final consumer).
  Note that the biodiesel used as a chemical feedstock by SABIC is the same as used to blend in automobile fuels.
- The scale of production in biorefineries today is significantly smaller than crude oil refineries), influencing the price.

B.3 Omrin

Aucke Bergsma
Omrin
September 23, 2016

Sorting and recycling

Which biobased plastics are present in household waste, and the amounts in which they occur, is unknown to us. We distinguish to types of biobased plastics: the 'traditional' which are chemically equal to their fossil counterparts, and the biodegradable ones. As the former (i.e. bio-PE, bio-PP, bio-PET) cannot be distinguished from their fossil counterparts, they are sorted out in mono streams and recycled if they end up in the sorting facility (either for consumer separated waste or post-consumer separated waste).

Currently, it is possible to sort out biodegradable (bio)plastics with NIR technology. The system is, however, currently not equipped or programmed to do so. The amount of biodegradable biobased plastics annually entering the waste stream is unknown, we assume the amounts are very small. As far as we know, the only biodegradable plastic used in the Netherlands is PLA.

Barriers to recycling

At the moment, sorting yields streams which are in accordance with the 'Raamovereenkomst Verpakkingen' (DKR quality). Biodegradable plastics do not qualify as a DKR-stream, and therefore end up in the residue. In our facility, all material < 5 cm goes to the digester, while the residue larger than >5 cm is incinerated (with energy recovery).

As far as we know, there are no facilities sorting out biodegradable plastics, partially because the amount is small, but also because the rules set by Nedvang do not include such material. Municipalities do not, therefore, receive a compensation for consumer separation, post-consumer separation or recycling of such material.

The presence of biodegradable (bio)plastics is undesirable in facilities currently sorting and treating recyclable plastics. The presence of biodegradable plastics influences the DKR quality of the outputs negatively. While separation is possible, this currently does not happen because of the barriers mentioned above (i.e. lack of volume, financial compensation).

Environmental impact and communication to consumers

How best to communicate to consumers how to dispose of their biobased plastics, starts with the question which route yield the largest environmental benefits. As stated by Milieu Centraal, the main environmental benefit of biodegradable plastics is the use of renewable resources. Environmentally, end-of-life treatment through incineration with energy recovery and composting hardly differs. I think only recycling can change this, creating additional environmental benefits. Non-biodegradable plastics which are equal to their fossil counterparts should be separated by consumers (as they are now), and should enter the recycling loop.

Future

To increase desirability of biobased plastics, for sorters and recyclers, it is necessary to:
- create a treatment route which yield environmental benefits;
- to increase the amount of biobased plastics to justify investments;

– include a financial compensation for sorting and recycling within the Raamovereenkomst Verpakkingen.

B.4 Holland Bioplastics/European Bioplastics

François de Bie
Holland Bioplastics/European Bioplastics
October 17, 2016

Benefits and applications of biobased plastics

There are two different types of biobased plastics, which both have their own benefits and consequently most promising applications; the biobased plastics and the biodegradable plastics.

The biobased plastics have the benefit that they are made from biobased material and have a lower carbon footprint and use less fossil resources than conventional plastics do. Biobased plastics can therefore provide added value in replacing plastics in applications where we want to lower the carbon footprint of plastics.

The biodegradable plastics can play a facilitating role in reaching a high level of composting of organic material. They lead to less plastic pollution in organic material. These plastics provide an added value in applications in which plastics come in contact with organic material. This is for example the case for food packaging.

Competitiveness of biobased plastics

Biobased plastics are currently (slightly) more expensive than conventional plastics. However they are likely to become more competitive in the future because of technological developments and process optimisation. Biobased plastics could also become more competitive if the incentives for fossil-based resources, such as subsidies, become less and/or if there would be more taxation on the emissions and carbon footprint of fossil-based plastics.

End-of-life

There are four different end-of-life strategies for biobased plastics:
– Re-using the product made of biobased plastics.
– Mechanical recycling of for example bio-PET or bio-PE.
– Composting in the case of biodegradable biobased plastics that are used with organic products. This is the case for applications where it is difficult to separate the plastic from the organic material. An example is the plastic used around cucumber, which might end up in the organic waste bin along with the remaining cucumber.
– Incineration of biobased plastics that end up in the residual waste bin or recycling bin but cannot be mechanically recycled. Examples of these are multi-layered foils and packaging which uses different types of biobased plastics. In this case the biobased plastics lead to the production of renewable energy at the end-of-life.

In the case of composting all biodegradable plastics that are in line with the EN 13432 standard can be composted by industrial composters in the Netherlands.

In principle a lot of plastics (including bio-plastics) can be mechanically recycled, but are not because of small amounts being present in the waste streams. These plastics will therefore end up being combusted. However this is no different than is the case with fossil-based plastics, which are also not all sorted out. Also there is a necessity to use these plastics to for example package our products.

Developments needed for increased production and use of biobased plastics

The current plastics industry is not necessarily very enthusiastic about biobased plastics. It would really help if the government were to take a stance and state that biobased plastics are the way to go concerning the circular economy and greenhouse gas emissions reduction. For example in France the government has put a ban on the use of conventional plastics in certain applications such as disposable cutlery.

Also currently all biobased plastics are seen as one type of plastic, while there are several types of biobased plastics – it's a family of different types of plastics. We should look at different types of biobased plastics more in the way that we look at different options for public transport in the Netherlands. The best public transport method is used for the set circumstances, and that is a train in one instance, and a metro in the other. Biobased plastics should also be applied in the place where they are best fit. So if you would like to reduce the carbon footprint of a PE shampoo bottle – a bio-PE biobased plastic is good solution. If you want to prevent organic waste in coffee capsules ending up in incineration or polluting the plastic recycle stream, a PLA biobased plastic coffee capsule can collected with the organic waste and composted.

Oxo-degradable plastics

Oxo-degradable plastics are often portrayed as biobased plastics.
These plastics should however be banned from use because they cannot be mechanically recycled and also do not biodegrade, causing all kinds of problems in the recycling streams.

Plastic soup

Biobased plastics are NOT the solution to the plastic soup. Often they are seen as solution, because they are said to degrade when they end up in the environment. Instead the plastic soup should be resolved by teaching citizens how to dispose of plastics.

B.5 Veolia Polymers

Gerrit Klein Nagelvoort
Veolia Polymers
October 19, 2016

Biobased plastics in recycling

Veolia Polymers does, at this moment, not encounter biobased plastics during recycling.

Biodegradable biobased plastics and recycling

Biodegradable biobased plastics are problematic plastics. They are not thermoplastic and can thus not be treated by means of mechanical recycling. It is important to prevent these biobased plastics from ending up in the conventional plastic recycling system.

A useful application for biodegradable biobased plastics is food packaging. This packaging will need to be designed in such a way that it can be composted (design for composting).

Non-biodegradable biobased plastics and recycling

Biobased polymers such as bio-PET are useful plastics. They can be recycled at the end-of-life in combination with polymers based on fossil raw materials.

Biobased polymers can be incinerated in the same was as polymers based on fossil raw materials. However, it is preferable to recycle these plastics at the end-of-life.

Developments of biobased plastics

An important future development is that it will be deemed normal to recycle non-biodegradable biobased plastics. This means that non-biodegradable biobased plastics will need to be designed for recycling.

B.6 Indorama

Wout Fornara
Indorama Ventures Europe B.V.
September 29, 2016

Indorama is world leader in PET production. PET is the most common thermoplastic polymer resin of the polyester family and is used in fibres for clothing, containers for liquids and foods, thermoforming for manufacturing, and in combination with glass fibre for engineering resins. The majority of the world's PET production is for synthetic fibres (in excess of 60%), with bottle production accounting for about 30% of global demand. In the context of textile applications, PET is referred to by its common name, polyester, whereas the acronym PET is generally used in relation to packaging. Polyester is one of the most produced polymers after polyethylene (PE) and polypropylene (PP).

Sustainability and PET

Indorama aims for a position on the Dow Jones Sustainability Index. Therefore, Indorama works systematically to reduce the CO_2 footprint of her production locations worldwide.
In the sustainability report 2015 CEO Aloke Lohia states that: "there are a number of ways that we can lower our impact on the environment, such as using renewable raw materials, as we do at our PET recycling facilities, to using more sustainable resources, such as solar energy."

In the production location in the Netherlands, Indorama reduces the footprint by producing partly biobased PET and by recycling PET that is partly used in the production of new PET bottles.
The biobased PET production is limited by the additional costs of biobased production compared to fossil-based production. As long as most brand owners are not willing to compensate for additional costs made in the production of bio-PET, the production of bio-PET may only increase if the oil price increases to at least $ 120/barrel.
The aim is to increase the recycled content of new bottles to 20% in 2020. That is significantly higher than today's recycled content in the production of PET bottles. The bottle neck is the availability of high quality recycled PET. Therefore, Indorama works with a number of technology start-ups on the

development of a new chemical recycling technology that will allow for qualitatively high PET production based on collected PET trays and coloured PET bottles, which are recycle streams that currently end up in the mixed plastics stream. This stream only has a low value application at considerable higher costs than other recycling streams.
Indorama does not aim for biodegradable plastics because that is not compatible with PET recycling.

Production numbers of PET, bio PET and recycled content

The worldwide production of PET is estimated to be around 60 million tonnes PET per year. About 15 million tonnes is used for packaging applications such as bottles. Most of the PET is used in textile applications, about 45 million tonnes.
Indorama produces 6 million tonnes worldwide. The worldwide recycling from Indorama of PET is estimated on 337,000 tonnes PET per year.

Indorama produces 1.6 million tonnes PET in Europe. Of this production of 1.6 million tonnes, 250,000 to 260,000 tonnes are applied in the production of bottles, the remaining 1.35 million tonnes are applied as fibres, staples and other applications. In Europe there are currently two PET recycling plants of Indorama: in Rotterdam, the Netherlands (70,000 tonnes per year of input bottle bales) and in Verdun, France (45,000 tonnes per year of bottle input per year).

The plan is to increase the recycling goal further. As described above Indorama plans to do this based on chemical recycling. The production mechanism to produce PET is a reversible reaction, thus using the right conditions and catalysts it may proof possible to reverse the reaction from PET to ethylene glycol and terephthalic acid (see information below on chemical aspects of PET production).
If this reverse reaction proofs to be possible it should be possible to increase the recycled content above the 20% per year. However, this will not be self-evident since that will require further alignment of PET collection and PET recycling. This is a tremendous logistical challenge since only in Europe large differences exist between countries and even regions in how PET is collected and what quality of PET selection can be offered by local collection and sorting organizations. Even if that hurdle is taken the collected PET has to be transported in an efficient and economical way to the chemical recycling plant. Potential solutions are that local collection organizations collect the PET, sort it, shredder and wash the material and ship it to Rotterdam. Another possible mechanism is that large companies selling products made of polyesters like sails, clothing or carpets invite customers to bring back their old material when they come shopping for new products.

The biobased PET production also occurs in Rotterdam and equals about 20.000 tonnes per year. This production is partly biobased (27% on mass basis): the ethylene glycol required for the PET production has a biological source. Because ethylene glycol is a by-product of biofuel production it is available in large quantities.
To produce a fully biobased PET molecule not only the ethylene glycol but also the terephthalic acid or its source p-xylene (p-X) should be biobased. Indorama has studied the options for the replacement of p-X. Biobased production of aromates like p-X is very much in development. However, the scale up that is required to come from the available pilot plants that are able to produce some tonnes of p-X per year, compared to the hundreds of tons per day required for the production of PET by Indorama, is a hurdle that proofs very difficult to take. In addition came the decrease in oil price, further reducing the likeliness

of a biobased alternative to p-X on the short term. Until these problems are solved Indorama produces PET based on p-X provided by one of the local refineries in Rotterdam.

Chemical aspects of PET production
Indorama uses the terephthalic acid process to produce PET in Rotterdam. This means that ethyleneglycol reacts with terephthalic acids to produce PET.

B.7 KIDV

Karen van der Stadt
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October 17, 2016

Sustainability of biobased plastics
If we want to achieve a circular economy it is essential to move away from fossil resources and towards biomass as a resource. Biobased plastics (plastics produced from biomass) can help achieve such a shift. There are, however, certain ethical questions and dilemma's which need to be addressed in order to create a sustainable circular economy: How much biomass can we source sustainably? Can agricultural product (or wastes) be used sustainably as a resource or does use interfere with other ecological processes (e.g. soil organic matter)? Does the 'Food-for-biobased economy' (Food-for-fuel) discussion also apply to biobased plastics? Current volumes of biobased plastics are relatively small, but this may change drastically in the future. Furthermore, an increase in demand is true for other biobased products. Therefore, scale of production/application as well as developments in other areas/products influence the potential sustainability and the fit of biobased plastics in the circular economy.

From the perspective of packaging, biodegradable plastics are most advantageous if there are co-benefits: added benefits such as an increase in consumer separated food waste.

Product quality
Currently functionality is the predominant reason for producers to choose a certain plastic. A number of biobased plastics cannot compete with fossil plastics yet, because of functionality issues (such as heat resistance, moisture permeability, ability to seal). For instance, starch-based biobased plastics are very sensitive to moisture. Furthermore, the price of biobased plastics is usually higher.
These issues make certain biobased plastics less attractive. Others seem to have more potential in the short term; those which are chemically identical to their fossil counterparts and therefore have the exact same functionalities. They have the added benefit that they do not contaminate the recycling system, because they are indistinguishable from their fossil counterparts.

End-of-life treatment and communication
As said, the biobased plastics which have fossil counterparts can and should be recycled. There are, however, also non-degradable biobased plastics which technically can be recycled, but which currently are not recycled.
When volumes are too small (as is the case for these biobased plastics), costs are too high to justify the additional investments. Whether or not plastics are recycled may, however, influence decision makers to use them or not. We are not sure how such a barrier can be overcome.

Biodegradable biobased plastics should only be used in situations where there is a co-benefit; mainly the increase in consumer separated food waste. In this case the biodegradable biobased plastics should end up in the consumer separated food and garden waste, and are composted (possibly anaerobically digested first).
It is difficult to inform consumers to treat different (bio)plastics differently, and we still wonder whether it is desirable. We feel the agreement mentioned before, of only using biodegradables in case of co-benefits, helps create clarity. We would like to avoid the situation (like now) where consumers wonder how to dispose of their (bio)plastics. Disposal with food and garden waste has no environmental benefit (it degrades to CO_2 and water). When these plastics end up in the current plastic recycling system, it might reduce the quality of the DKR streams when they end up there.

B.8 OVAM

Annelies Scholaert
Public Waste Agency of Flanders
October 26, 2016

Current treatment in Belgium

At the moment, Belgium does not collect biobased or compostable plastics separately.

Part of the drop-ins, such as bio-PET or bio-PE, are consumer separated and treated with the regular PMD stream. PMD stands for Plastic bottles and flasks, Metals and Drink cartons. In Belgium, experiments run for the expansion of the regular PMD stream with other plastics. Biodegradable plastics are specifically excluded as they would interfere with a proper mechanical recycling of the plastics. In some communities however, other ‘soft’ and small ‘hard’ household plastics are already collected separately. This mixed stream is recycled altogether into new products. Here, no specific sorting instructions for biobased plastics apply. ‘Hard’ plastics can also be offered at the recycling parks, along with some other plastic streams (such as films, flower pots/trays, eps, etc.). Some intercommunales specifically mention that biodegradable plastics are not allowed in these separate streams, but not all do.

On the contrary, in Flanders, *all* plastics and packaging materials are banned from the food and garden waste, even when compostable. For OVAM, high quality food and garden waste separation and treatment is most important. Citizens are well informed, and subsequently consumer separation works well and impurities in the food and garden waste are relatively low. OVAM feels the addition of biobased plastics (compostables) could lead to an overall increase of non-compostable plastics (and other impurities) in food and garden waste. To avoid confusion, different labels are available (Seedling, and different compost/home compost labels from AIB Vinçotte and DIN Certco for example).

Communication is, however, complex. Rules should be uniform across Flanders. However, treatment units differ (e.g. digestion or not, removal of impurities before treatment) which could lead to different rules/advice in different regions. Furthermore, some composting facilities are making a shift to digestion with energy recovery. Some materials which can be composted, cannot be easily digested. Lastly, there is no evidence of biodegradable plastics adding value to the compost as an end product.

Therefore, OVAM does not recommend a general advice of adding biodegradable plastics to the food and garden waste. There are, however, some applications which deserve support. Examples are the combination of biodegradable material and moist food waste at events, or specific agriculture and horticulture applications, or aquaculture, or compostable bags that can be disposed in the food and garden waste stream.

Waste collectors and municipalities in different regions can, for instance, allow (and promote) the usage of home-compostable bags to collect food and kitchen waste. These bags facilitate the collection of food and garden waste. Allowing and promoting its use can be done in consultation with the collector, the intercommunale (union of two or more municipalities) and the waste processor. For home composting, awareness, communication and education are necessary instruments to ensure that peoples' compost heap will be maintained properly, offering the right conditions to compost these compostable materials at home.

At the end of October 2008, a definition and legal regulations for 'home compostability' was formulated in Belgium. Belgium was the first country in Europe to do so. In the Belgian Royal Decree that was concerned with this topic, also the legal regulations for the use of the terms 'compostability' and 'biodegradability' were formulated[5].

That is how in Belgium, it is forbidden by law to label packaging material as 'biodegradable' or 'biologically degradable'. This is done to prevent possible increases in litter. A widespread misconception in this context is that something either *is* or *is not* biodegradable. This is too simple.
The environment in which a product ends up as well as the character of a product (composition, thickness, shape), both play an important role.
The claim 'made from biodegradable material' therefore does not mean that the product altogether is biodegradable. This is the reason that biodegradable plastics do not offer a solution to the problem of litter. The idea that these plastics degrade in any environment, under any conditions, should not be propagated. In unfavourable conditions, the material will only break down to small pieces (microplastics). Hereby, the visible litter will become invisible pieces of plastic, actually worsening the problem of microplastics and the 'plastic soup'.

We have no overview on current amounts of biobased plastics and types of biobased plastics circulating in Flanders. On some events in Flanders PLA cups are used. These are separately collected and mechanically recycled into r-PLA for non-food applications.

Environment

The fact that biobased plastics are made from renewable resources does not mean they are inherently sustainable: production, processing, transport, etc. still have an environmental impact. The LCA methodology can be used to make an assessment of these impacts, and yields an environmental profile which shows the most important environmental impacts at different stages of the life cycle. These impacts can then be targeted specifically.

5 Royal Decree of 09/09/2008 establishing product standards for compostable and biodegradable materials.

Because carrying out an LCA is a complex task with high risk of misinterpretation or misuse, ISO norms were developed more than a decade ago. Now a more reliable methodology is developed at the European level with the 'Product Environmental Footprint' (PEF), which is tested by Europe. In the future, the PEF system will enable more complex analyses, while making them more reliable.

Future developments
It seems that biobased plastics have evolved and are not solely produced for their degradable properties anymore. Nowadays, the use of renewable resources, re-usability, functionality and added value are taken into account in the process of developing biobased plastics. These are important aspects that play a role in developing and unfolding the market.

Developing new polymers starts at the chemistry level. Renewable chemistry is therefore a field that will expand significantly. With regards to renewable chemicals, two categories of end products exist: the so-called 'drop-ins', and 'new' chemicals . Drop-ins are biobased versions of existing petrochemicals (bio-PET, bio-PE, etc.). They are chemically equivalent to their petrochemical counterparts. New chemicals, on the other hand, have chemical structures that are completely new, or have not been used previously in commercial markets. These new chemicals have similar or even better functionality than the petrochemicals they replace.

The search for new polymers with new or better functionality, technical characteristics and added value takes time. We expect that the volumes of drop-ins will therefore increase first, on the short term. The applications, collection and recycling methods and price-level are known, which contributes to their advancement.

As around 40% of chemicals is aromatic, a considerable share of R&D investments is reserved for finding ways to extract aromatics from organic (waste) materials. In this field, we might expect major developments.

Recently, a joint venture was established between BASF and Avantium, with the goal to produce and commercialize furandicarboxylic acid (FCDA). The new factory will be built on the site of BASF in Antwerp. FCDA is the main building block for PEF, which is similar to PET but biobased. In bottle applications, PEF is said to have better characteristics than PET. It is possible that a new market, based around this material, will be realized.

The costs are still a controversial issue. It is necessary to optimize production processes in order to decrease the costs of new polymers. Another example to decrease the costs is to search for better yeast strains, resulting in larger yields.

The abrogation of the sugar beet quota in 2017 will create a new source of resources used in the production of biobased plastics, and will therefore possibly influence the European market for biobased plastics. Furthermore, the extraction of resources from residue streams is being increasingly investigated. In Flanders, where it is not desirable to grow large monocultures of crops, the search for alternative renewable resources is very relevant.
In the same context, research increasingly focuses on Carbon Capture and Utilization (CCU), and more developments are expected.

Also short term developments are expected, for example as a result of the European Directive concerning measures to reduce the use of plastic bags. Several European member states (Italy, France) have mentioned the possible need for exceptions for biobased or compostable bags. In Belgium, it is still unclear how the Directive will be implemented in practice; the three regions and the federal government are currently working on proposals.

Role of the government

As mentioned previously, it is not possible to provide an absolute conclusion about the sustainability of biobased plastics in general. Perceptions often differ, and the multitude of different materials and development logically cause confusion about biobased plastics. We also see that, in practice, a number of different concepts are used interchangeably. This also causes confusion, and complicates communicating about biobased plastics.

Therefore, the government has a role relating to the communication about this topic. Clear definitions, such as formulated in Belgium's Royal Decree of 2008, and certification schemes, etc. are necessary.

R&D remains of crucial importance, and should be supported by establishing research programs, clusters, and roadmaps. Companies (mostly small enterprises and entrepreneurs) that wish to upscale their innovation projects often run into difficulties related to valorisation. When such issues arise, these companies might end up in the so-called 'valley of death'. Financial support from cooperatives or governments during this difficult step might form a helpful intermediary towards operating a healthy business.

Lastly, the government can play a stimulating role in the market development for biobased plastics through sustainable procurement. This might especially have a large impact for the construction sector and textile sector.

Obstacles to best practices in waste treatment

The main obstacles are: communication, recognisability of biobased plastics, incompatibility of some (i.e. biodegradable) biobased plastics with the current conventional processing systems, insufficient volumes for selective sorting and processing.

Biobased, non-biodegradable plastics, such as bio-PE and bio-PET, can follow the existing pathways of mechanical recycling. These co-called drop-in chemicals will be recognized and sorted by the same sorting installations that process PE and PET bottles and flasks from the PMD stream. Other materials will end up in the residue since the sorting equipment is not set up to recognize and sort out these materials.

Similarly, we expect that, even when the PMD system would expand and include additional plastic fractions, these drop-in plastics will not cause problems for mechanical recycling.

On the other hand, biodegradable plastics can in theory also be recycled. Looplife Polymers is an example of a company that does this. Due to their different melting points, however, these plastics cannot be processed along with other plastics. In the short term, investing in the material recycling of these plastics is therefore not feasible:

- The volumes are currently very small, which is why, at least in Flanders, no research into the recycling of biodegradable biobased plastics is conducted.

- A number of blends are currently on the market. These blends are generally very heterogenic, and therefore less suitable for polymer-specific sorting and material recycling processes.
- The lifetimes of biodegradable plastics are shortened, due to their biodegradability. Therefore, they are often not sufficiently stable to be recycled in multiple cycles.

For many packaging materials, it is difficult to communicate the appropriate sorting and treatment processes to the public. Therefore, as mentioned before, in Flanders, all packaging materials are banned from the food and garden waste route. This includes compostable packaging. Other issues regarding the disposal of biodegradable plastic are: whether the material has added value to the final compost, if the material can be recycled before ending up in the organic recycling system and in the case of home composting: what are the risks of microplastics?

The option to collect biodegradable biobased plastics in monostreams (e.g. fermentation/composting of selectively collected biobased plastics for instance at events) is, however, not ruled out.

Biobased plastics and a circular economy

When choosing a certain material for a certain product, it is important to think about its whole lifecycle: the design phase, the production phase, its usage and re-use, the collection and eventual waste processing. Solely replacing conventional fossil-based plastics by biobased plastics does not necessarily make a circular economy.

Moreover, the environmental impact of products is only one component in a complete sustainability assessment. Sustainability also includes an economic and social dimension. If we want to include biobased plastics in a sustainable policy for materials, these factors naturally play an important role as well.

Criteria to be met for biobased plastics to fit in a circular economy

As discussed previously, biobased plastics primarily need to be situated in the broad and global bio-technological evolution, in which they can possibly provide solutions to fundamental chain-related questions. Examples are: biobased plastics that can replace petrochemical plastics with hazardous flame retardants or REACH non-compliant plastics for example.

The development of new materials should be supported, e.g. when they are more sustainable then conventional plastics, have improved properties and improve raw material sourcing (including from bio-waste, remitting the feed vs. food discussion).

An ideal method to include biobased plastics in a sustainable circular economy is through a 'bio-refinery concept'. This concept integrates different biobased industrial processes into the production of both food as well as energy. Hereby, the resource will yield as much useful product as possible, and as little non-useful waste streams as possible. Bio-clusters, such as the current cluster between the Netherlands and Flanders, are in line with this concept. An adequate and stable supply of raw materials should however be ensured, making sure that the production concept is sufficiently scalable.

Plastics with biodegradable properties should only be incentivized if there is a proven environmental added-value and if accompanied by clear information for users/consumers. Therefore, clear definitions and commonly agreed criteria for 'biodegradability', 'compostability' and 'home-compostability' are needed at a European level. The sustainable use of biodegradable plastics should be ensured by a framework, also promoting the transparency on biodegradability claims. Referring to this, a European ban on oxo-degradable plastics should be adopted. Additives have been added to these plastics, after which certain parties claim that they can be broken down faster by light, oxygen or moisture. The breakdown however often consists only of the fragmentation (into microplastics) of the material (in some cases, fragmentation does not even occur). In Belgium, oxo-degradable plastics have been forbidden by the Royal Decree; this should also be the case in Europe.

Harmonized criteria will definitely increase market transparency and help to develop appropriate waste management practices.

Communication to consumers
If biobased plastics are introduced on a large scale, it is necessary that they are introduced on the market appropriately. Hereby, they are more likely to be disposed of appropriately. Currently, the situation around the disposal of biobased plastics is often not clear to consumers. A number of labels exists: AIB Vinçotte, DINCERTCO, etc. These labels do however not always correspond to the appropriate sorting message.

Previously, I referred to the communication role for governments (see our OVAM report and OVAM leaflets). Legislation also plays an important role in this respect: not only clearly defining and establishing rules, but also offering a comprehensive overview of all laws, norms and rules that influence the decision to introduce a product on the market. It is also important that, on a European scale, steps will be taken. An example is the realization of a European norm for home composting, for instance.

Furthermore, companies bear the responsibility to ensure that B2B communication is carried out in a clear and objective manner. It is of vital importance that industrial purchasers of biobased or biodegradable plastics understand what those terms mean, and which claims can be used to validate such statements (without greenwashing). Businesses have, for marketing purposes, their own focus and approach to communication. Some large retailers tend to attach more importance to home composting, while others are more focused on the renewable nature of plastic packaging. In this communication, they have the responsibility to deliver a right message by also bearing in mind the end-of-life stage of the product.

B.9 VA

Tim Brethouwer
Dutch Waste Management Association, department Bioconversion
November 4, 2016

Current treatment of biobased plastics
The department bioconversion (at the Dutch Waste Management Association), find it important to narrow the definition of biobased plastics to compostable biobased plastics. The members of the Dutch Waste Management Association have accepted compostable biobased plastics that comply with the EN 13432 standards for years. This is why the Seedling logo is accepted, and, if the occasion arises, the OK compost label. The members of the Dutch Waste Management Association are especially interested in compostable plastics that are used as carrier of food and garden waste. We are interested in the content of these bags more than in the material itself. The packaging is a facilitator

and should not result in significantly more residue, or in a disturbance of the process, or lead to a decrease in quality of the end product. Currently, the question whether our members should accept compostable biobased plastic food packaging is the subject of lively debate. Opinions are divided, and a definitive decision is possibly made on the 28th of November. Members of the bioconversion department expect four problems related to compostable packaging:

- Does accepting compostable packaging lead to more residue as a consequence of the introduction of fossil plastics? (plastic separation behaviour of consumers).
- Does accepting compostable packaging lead to more residue because biobased plastics degrade too slowly? (product characteristics).
- Does accepting compostable packaging lead to more residue because a share of the packaging materials is separated as a residue in an early stage? (routing).
- Does accepting compostable packaging lead to a decrease in the quality of compost because some plastics remain in the compost as visual pollution? (product characteristics).

The arguments listed above can be reduced to two important issues for the bioconversion department:

- Biodegradability (i.e.: is the norm representative for the practical situation?).
- Quantity of residue/pollution in the compost (direct/indirect).

Moreover, the waste management sector has the task to adequately process the extra quantities of food and garden waste that might be available due to the 'VANG' policy (From Waste to Resource). In the case that this policy leads to significantly larger quantities of food and garden waste, and compostable packaging can play a facilitating role in the collection of this waste, the issues as listed above will be less significant. Beside compostable biobased plastics, there are other packaging materials that can function as a carrier of food and garden waste (e.g. paper). An important aspect for the producers of biobased plastic bags is that they are functional: they have to be sufficiently strong to meet the expectations of the consumer (as described in EN 13592) while they must biodegrade rapidly enough to meet the demands of waste processors (as formulated in EN 13432).

Current situation – biobased plastics in waste treatment

The compostable biobased plastic bags that are currently available and function as a carrier of food and garden waste are thin and easily compostable. When they enter the treatment process, they have already been degraded partially. In general, we encounter many fossil plastics and little compostable biobased plastics, especially in our end product (compost). Compostable packaging such as trays are hardly available on the market. Compostable biobased plastics that are used as wrappers for magazines lead to unwanted pollution of the paper and carton waste fraction. Magazines are often disposed in the paper fraction without being opened. The sorter and traders in paper and carton waste consider fossil and compostable biobased plastics to be the same material. Therefore, both the magazine as well as its wrapper will be considered to be pollution.

Environmental benefits and concerns

Sometimes, we have the feeling that the waste phase is more important than the fact that biobased plastics are made from renewable resources. Therefore, we do not consider the claim that they are compostable to be very strong. A biobased plastic does not add anything to the composting process itself: it only functions as a carrier of food and garden waste. Biobased plastics that are easily degradable can contribute to the amount of methane in the fermentation process. The problem is often that compostable biobased plastics are already separated out before reaching the digester.

Biobased plastics will now disrupt the separation process of plastics. The consequences of this are not completely clear. The most important environmental benefit should be that the resources are renewable, although we do not know whether this is actually demonstrated in LCA's.

Future developments

We have some concerns about the transition period of fossil to renewable, and the diversity of (new) products. From a recycling viewpoint, it would be better if new products would be fairly uniform in quality and would be introduced rapidly, so that recyclers are able to adapt their processes accordingly.

We expect that fossil plastics will be phased out gradually, and will be replaced by alternatives such as secondary resources and biobased plastics.

The role of the government

We expect exemplary behavior from the government: sustainable purchasing and contracting, communication support, and stimulating and facilitating research. The government should definitely play a role in providing objective information to the public, since the average Dutch citizen is not able to differentiate between all different types of plastic, and is overwhelmed by the large diversity of claims and logos. Retail companies and producers of plastics have no interest in explaining the differences between the products. They only invest in positioning and promoting their product and packaging, which does not lead to better understanding among consumers.

Clear and unambiguous communication is essential, both in verbal expression as well as in other forms of communication (e.g. logo, colour, PR/marketing, etc.). Also, it is important to look at the entire chain of a product, from design to waste treatment.

In order to make pure waste separation (with an organic, a paper and a plastic fraction) an automatic procedure, we need consistent information and communication. An example could be a periodically repeated campaign that informs new households properly, and that spreads facts and debunks myths.

Within a circular economy, we want to create new raw materials from waste. This, of course, begins with the use of the appropriate raw materials that are suitable for re-use and recycling. Subsequently, only high-quality resources can be produced from the waste fractions if the introduction of pollution is prevented (examples are recycling of paper and plastics, and the production of compost). The introduction of pollution disrupts most recycling processes: therefore, stimulating proper separation behaviour which results in clean waste fractions is essential.

End-of-life treatment
As a general remark, end-of-life options should not become a goal in itself. From the concept of circularity, recycling would be the preferred option. The quantities of end-of-life material are however currently too limited to seriously put effort into recycling. Moreover, recycling also demands proper waste separation in clean plastic streams.

Composting is, in LAP3, placed on an equal footing with recycling.
As mentioned previously however, compostable packaging only has value because of its content.

Incineration is often negatively portrayed. If, however, biobased plastic is made from renewable resources and has a sufficient calorific value, it replaces fossil fuels and as such contributes to a better climate.

Biobased plastic in a circular economy
Biobased plastics perfectly fit in a biological cycle as a part of the circular economy. Of course, the familiar issues of land use, feed/food, etc. should be taken into account.

Perhaps the ‘ladder van Moerman’ can be used in reviewing the biological cycle, and the role of biobased plastics therein. Composting and digestion is, in accordance with LAP3, a form of recycling. Therefore, we consider this route to be completely circular.

B.10 BVOR

Arjen Brinkmann
Dutch Association of Biowaste Processors
September 26, 2016

Plastic and composting
Operators of composting installations find all types of plastics: fossil-based, biobased, biodegradable, compostable or a combination of these characteristics.
The only characteristic that is of importance to these operators is: is this material compostable at the temperature and residence time of the composting installation? If the plastics are certified with the Seedling logo this is the case in principle.

Figure 31: Seedling logo

However, process conditions in compost facilities may differ so that full degradation may not always be achievable. Also, if compostable materials come e.g. in a stacked form (e.g. a stack of compostable cups) degradation will be difficult.

If the plastics are not compostable they are contaminations and need to be removed. Removal usually occurs after the composting step. The remaining plastic clearly is not compostable and is removed together with other types of contaminations like glass, metal and ceramics by a combination of sieves, blowers, etc.

Such cleaning of the compost is very thorough since the clients of composters are very critical about the compost composition. The law accepts a maximum of 0.5% contamination per unit compost. Clients however, demand compliance to the norm of 0.1-0.05% contamination prescribed by 'Keurcompost' (Keurcompost requirements are based on food safety requirements). Currently, several composters are able to guarantee the norms of Keurcompost and are certified accordingly.

Ways to prevent non-compostable plastic in food and garden waste?

Very clear communication that only materials with the seedling logo are compostable and can be added to the food and garden waste. In case of doubt better add plastics to rest or plastic streams, so that energy or new raw material can be produced from it.

An interesting question is whether consumers are able to pick this message up as long as different types of plastics are used for different non-food and garden related applications like: covers of magazines or packaging of teabags. For example does the amount of non-compostable plastic in food and garden waste in an area increase if a producer of magazines introduces a compostable covers of magazines with a seedling sign. Which part of consumers differentiates and adds only the covers with seedling mark to the food and garden waste and which part of the consumers will add all plastic covers to the food and garden waste? This question is a key issue.

Figure 32: Keurcompost

When do compostable plastics have added value to compost producers?

Compostable plastics have an added value to compost installations in general and fermentation installations in specific applications, in particular if they are applied to collect food and garden wastes and specifically kitchen wastes (trash bags). Compostable plastics degrade to H_2O and CO_2, and so do not contribute to formation of compost.

Research shows that collection of kitchen wastes by means of compostable plastic bags (liners) significantly increases the collection of kitchen waste. This increase is especially beneficial for the yield of fermentation installations.

B.11 Morssinkhof Plastics

Matthijs Veerman
Morssinkhof Plastics
September 28, 2016

Biobased plastic and recycling

For recyclers there are two types of biobased plastics:
- The biobased plastics that are based on so-called drop-in chemicals and are chemically identical to widely used fossil-based alternatives. Examples of such plastics are the PET produced by Indorama and the poly ethylene (PE) produced by BRASKEM. This category is perfectly compatible with the current recycling system, in which PET and PE are large recycling streams.
- All other biobased plastics most of which are biodegradable. This stream is called the biodegradable plastic stream and has two drawbacks.

The first drawback of the biodegradable plastics in recycling is the size of these streams: these streams are still rather small, too small to have a recycling line of their own. So they have to be sorted out, and increase the already large stream of mixed and thus hard to recycle plastics. Since sorting out normally has an efficiency of 90-95%, part of these biodegradables end up contaminating the other streams and so reduce the quality and therefore the market value of the recycled plastics.

The second drawback is the biodegradability as such. For a material to be biodegradable it must degrade under certain conditions relating to moisture and temperature. These conditions vary per type of plastic. So it is possible that in the regular treatment of the washing and the extrusion the situation is such that the biodegradable plastics degrade while they are being extruded. This implies that the whole batch that is being extruded is off spec and cannot be sold.

The biodegradable plastics do not need to be problematic for recycling as long as they are offered as a pure and clean stream. Morssinkhoff has recycled PLA (a biodegradable plastic) from industrial parties that offered the PLA as a clean stream after a production fault, to make new granules so new production could be realized based on the same PLA.
The problem at the moment is that all biobased plastics together on the Dutch market have a very small market share (approximately 1%). Thus per type of material the market share is even smaller. This means that it is organizational and technical impossible to set up a recycling line as are in use for highly applied materials like: PE, PP, PET and foils.

Contaminations with biobased plastics occur in all four streams. Sometimes these contaminations can be easily removed in wash lines due to a difference in density. For example PLA/PET does not float while PE/PP floats. However, PET and PLA have similar densities and are difficult to separate. At the same time experience at Morssinkhof plastics shows that a low percentage of PLA can seriously degrade the quality of the PET granulate. This is especially problematic with the recycling of foils because of two specific circumstances:

1. Biobased plastics are relatively often applied in the form of foils, so the % of PLA is highest in this stream.
2. The separation based on differences in floating properties works not so well for foils due to the high surface compared to the weight of the foil.

Fortunately, currently the percentages of biodegradable plastics are still low. In addition, the sorting companies remove 90-95% of impurities from the streams that are offered for recycling. So most of the biodegradable biobased plastics end up in the mixed plastics streams, without contaminating other streams.

Limitations of the mixed plastic streams

Currently the use of biobased plastics based on drop-in chemicals like bio-PET by Indorama and bio-PE by BRASKEM do not end up in the mixed plastic stream. The bio-PET and the bio PE and the bio-PP are recycled as regular PET, PE and PP without causing problems.

The biodegradable plastics or (bio)plastics that are not pure PE, pure PP, or PET, end up in the mixed plastic stream. Maybe except for PEF (the alternative for PET that is being prepared by Avantium, there is not enough material on the market yet to know for sure how that will influence PET recycling).

Currently 40-50% of collected plastics from households end up in a mixed plastics stream. In the whole of Europe there are only a few companies that can mechanically process this stream. The processors that currently process the Dutch mixed plastic stream are located in Germany. They use the mixed plastic stream to produce concrete replacing materials. For example the white poles with reflectors attached to them standing alongside roads are held in place by means of a block of this material instead of a block of concrete.
The demand for such materials is limited. Furthermore the companies processing mixed plastics becoming increasingly critical on the components in the mixed plastic streams.

For example a relatively large part of the mixed plastic streams is formed by the PET trays. These trays consist for the largest part of PET, but are heavily printed and/or have additional layers of PE or EVOH.
These PET trays are currently refused by these mixed plastics processors resulting in large amounts of multilayer PET trays that can be mechanically recycled but without an application of the recyclate and thus higher costs. Therefore Veerman expects that also biodegradables finally will no longer be accepted in the mixed plastic streams since these plastics, like multilayer plastics, are considered a contamination of the plastic streams that have a value when recycled.

Costs of recycle streams

The cost of recycling plastics has two components: the costs of collection and sorting at one hand and the price of the sorted plastic at the other hand. Currently the municipalities receive a collection and sorting reward of approximately € 800 per tonne of plastic that is mechanically recycled, i.e. applied in such a way that the stock material is reused. So burning and energy recovery does not count in this system. So the municipalities want the material to be mechanically recycled, otherwise they will not be paid the € 800 per tonne. Therefore the processing fee for mechanical recycling lays above the processing fee of burning.
The price of the sorted plastic is determined by the oil price and the demand for a specific recycled plastic stream. Currently the price for sorted PET (including the bio-PET) is approximately € 50 per tonne, the price for PP (including bio-PP) approximately € 200 per tonne, and the price for HDPE (including bio-HDPE) is approximately € 250 per tonne. Meaning that for PET the net costs are € 800- approximately € 50 = approximately € 750 per tonne, for PP approximately € 600 per tonne, for HDPE approximately € 550 per tonne.

While the price for mixed plastics (including the biodegradable plastics) is approximately € -100 per tonne. Meaning that € 100 per tonne is to be paid to the processors to have the mixed plastic processes, resulting in a net price of approximately € 900 per tonne.
The price to be paid for the processing of the mixed stream may further increase since the German government is preparing a similar law as in the Netherlands that does not longer allow counting the burning of material as recycling. As soon as the law comes in to force the price for processing the mixed plastics is expected to raise.

System optimization

The current recycling system is perfectly compatible with biobased alternatives of PE, PP, PET as these biobased plastics react the same, chemically and physically, as fossil-based PE, PP and PET.

The best way to optimize the current recycling system is to decrease the number of plastics in the post-consumer waste. Currently there are so many different materials that none of these material streams is sufficiently large for a recycling line. The increase on biodegradable plastics and other biobased plastics that are not PE, PP or PET only further increase the mixed plastic stream.
It is fair to say that biobased plastics are only a very small part of the mixed recycle stream. Most of the mixed plastic stream consists of streams of fossil-based plastics that are not pure PE, PP, PET, or foil. This means that it includes small streams of pure plastic of a not very commonly used type like PVC or polystyrene, and a lot of different multilayer foils and composites, that are inherently not pure.

If there were new technologies that could unlimitedly sort very clean material streams, than much smaller streams could be recycled. However, it is not likely that such a technology will be available any time soon.

Another way to optimize the system is a check on recyclability of a new type of packaging. The evaluation should measure to what extend the packaging material supports recycling (for example by using recycled plastics using monolayers of PE, PP or PET,) and to what extend it frustrates recycling (use of materials that cannot be recycled yet like biodegradable plastics, multilayers, co-extrusion, heavily printed). The fee that is to be paid to the Waste fund (afvalfonds) should be related to the extent to which the packaging design supports/frustrates recycling, according to the principle that the waster should pay (de vervuiler betaalt).

B.12 Rodenburg bioplastics

Aaik Rodenburg
Rodenburg Biopolymers
October 31, 2016

Rodenburg biopolymers produces biobased plastics and biobased latex based on potato starch.

Environmental impact Rodenburg biopolymers

The biobased plastics and latex that are produced by Rodenburg Biopolymers are based on waste streams from the potato-processing industry. Therefore, the resources on which these materials are based have a very low environmental impact.

The biodegradability of the materials is tailored to the specific application. However, all materials can, in the long term, be broken down in a natural environment. Therefore, these materials do not contribute to the so-called plastic soup. When the materials enter the environment, they are degraded just like natural materials. Hereafter, they become part of the environmental food chain.

The digester which processes the production waste from Rodenburg Biopolymers shows that everything can be fermented. Currently, however, no certification scheme regarding fermentation exists. A fermentation statement of OWS in Gent does exist.

Research and Rodenburg Biopolymers

Due to the low environmental impact of the material that is produced by Rodenburg Biopolymers, there has been increasing attention for biopolymers during the past few years. Up until now, this has mainly lead to more development trajectories for new products.

In these trajectories, two characteristics of these biopolymers play a central role:

- high food security, which is important for e.g. food packaging;
- complete biodegradability in a natural environment, which means that no harm is done when plastics remain in the environment.

Some examples of biodegradable products are given below.

Completely bio-degradable Mars bar-wrappers

The technical tests regarding the material and its printability have been completed successfully. Currently, Mars performs consumer tests in France and Germany to test how consumers experience the new packaging (testing the feel of the wrapper, testing whether it opens in the same way, etc.).
After these tests, it will be decided on what scale the production will be started. This wrapper has been developed with Mars and a foil-producer in a FW7 project.

Terratube

WAVIN has developed the Terratube together with Rodenburg Biopolymers. This product ensures that temporary pipelines for electricity on construction sites, that need protection for e.g. the drilling of carpenters, are safely stored underground. After the construction work, the wires can be removed from the pipes.
The pipes can subsequently be kept in the ground, and, after a few years, will be degraded. This tube has been tested successfully Heijmans.
Currently, there is little demand for this product because there is no oversight of leaving cables in the ground.

Biobased protection grid for water plants

Biobased plastic structures protect young plants against being eaten by insects and other animals. This is necessary until the plant is strong and tall enough to protect itself. The water plant protection grid, also called Procrate, is developed in cooperation with Dutch Watertech and Omefa. A similar material for Ecosystem engineering is a biobased structure to which mussels can be attached. These mussel-structures are developed in cooperation with Rodenburg Biopolymers, Bureau Waardenburg and GEA 2H Water Technologies.

Self-dissolving plant pot

The self-dissolving plant pot is a new development. A plant is grown in the pot, and put in the garden together with this pot. After one year of growth, the pot has degraded completely. This product has been developed in an MIT trajectory, and will be commercially available from 2017.

Glue based on starch

For the Canadian company EcoSynthetix a type of glue based on starch has been developed. It is now in production, and can be used instead of formaldehyde in wood-fibre panels.

Biobased rails
These rails are based on roadside grass and Rodenburg Biopolymer. Conventional rails are made from galvanized steel, in which some zinc is gradually released into the environment. Therefore, Rijkswaterstaat has searched for alternatives to this material. Currently, the biobased rails are placed at the Grevelingendam, to see how the product behaves in a natural environment over the course of one year. After this period, crash tests will be performed. This research is undertaken in the framework of the Life project BG4US.

Food security and biodegradability
Rodenburg Biopolymers produces packaging materials for the food industry. In order to comply with food security demands, the biodegradability of these materials is limited: they are only degradable under industrial conditions.

Rodenburg Biopolymers often runs into limitations due to certain food security requirements. For legal reasons, the requirements are always assessed in a similar manner as for conventional plastics. Some examples for which these requirements could be adjusted are:
- Lettuce packaging has to undergo a 10-day test at 40 degrees Celsius, in which a 20% ethanol solution is used as simulation liquid. However, the lettuce that will be packed only remains fresh for a maximum of three days.
- A drinking nozzle on a 100-200 ml packaging is only exposed to moisture at the moment of opening and during drinking. This will be a maximum of 20 minutes. Still, similar tests and requirements (to those for lettuce packaging) are demanded for this product.

Demand for EcoSystem Engineering Elements
Ecosystem Engineering Elements are all plastic elements that are deliberately introduced into nature in order to strengthen nature or infrastructure in an environmentally friendly way. Examples are the biobased grid, the mussel structures, the Terratube and biobased rails. Another example is plastic used for strengthening e.g. newly installed dikes. This material can be used until the vegetation has become sufficiently strong to hold back eroded sand and clay.

For all examples, materials are deliberately added to the environment. This will lead to diffuse sources of microplastics, except when the material is completely biodegradable under natural circumstances. This is the case for biopolymers made by Rodenburg Biopolymers.

At the moment, unfortunately, the demand for such applications is small:
- Commercial parties are not held accountable when leaving cables in the ground instead of using Terratubes.
- Dikes are currently covered with non-biodegradable plastics, or not covered at all.
- Many governments are not up-to-date regarding the existence of current possibilities, and how these possibilities can help them in a cost-effective way to reduce their environmental goals.
- Many procurement processes offer possibilities for contractors to distinguish themselves with such details in the form of BREEAM points or CO_2 reduction requirements. However, an alternative and often cheaper product can still be applied, which does not have the same environmental benefits. Still, overall, these ‘details’ can have a large impact on the total environmental impact of a project.

Annex C Summary EU Conference on Plastics

At the EU Conference on Plastics, 8-9 December 2016, the results from this study were presented and discussed with participants. A number of interesting suggestions were made.

Supporting the general conclusions:
- in the long term recycling of biobased plastics is more important (in a circular economy) than biodegradability;
- biodegradability is only suitable if this is functional, or if there are co-benefits;
- good conclusion: the combination of a high recycling rate for plastics and biomass as a source for new plastic.

Policy suggestions (inspired by or as addition to the draft policy suggestions):
- do not present biobased plastics as a simple solution for more and more plastics. First prevention, than reuse, than recycling and then biobased plastic instead of fossil plastics;
- it is logical that European governments only stimulate biobased plastics with a good environmental performance and that somehow they can proof this;
- in the discussion the idea was formulated that a stimulation scheme could have a strong stimulation for biobased plastics with more than 60% CO_2 reduction, an average stimulation if 40% CO_2 reduction is reached and a weak stimulation if 20% CO_2 reduction is reached;
- it would be wise to determine sustainability criteria in dialogue with NGO's;
- some NGO's suggest to exclude biobased plastics made from food crops from governmental stimulation, others suggest that biobased plastics from waste should get a higher stimulation;
- some participants suggested to ban biodegradable plastics because recycling is favourable;
- it would be wise to organise a common system for LCA studies of biobased plastics (especially how to deal with CO_2 uptake by plants);
- is a general CO_2 tax not the best way to stimulate biobased plastics?

Suggestions for further research:
- support for biobased plastics would be interesting if the cost effectiveness of biobased plastics (ton CO_2 avoided/€) is higher than that of biofuels;
- if you take into account that biobased plastics need fertile land and include that in a complete LCA calculation are most biobased plastics still better than fossil plastics?