Sustainability of biobased plastics

Analysis focusing on CO_2 for policies

CE Delft

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Content

Summary

In 2018, only 9% of new plastic on the market was recycled plastic and only 1% was biobased plastic. Due to the environmental benefits of biobased and recycled plastics over fossil plastics, several options to increase their uptake are under investigation and debated. Both financial and regulatory options are possible.

This analysis first focuses on determining and explaining the potential carbon footprint reductions achieved by biobased plastics compared to fossil plastics. Secondly, we propose a methodology, based on the EU's revised Renewable Energy Directive (RED II) calculations for renewable energy, to calculate the carbon footprint reduction of biobased plastics.

Context

CE Delft previously studied the effect of an obligation for the use of recycled or biobased material in new plastics for the Dutch ministry of Environment (CE Delft, 2022). This study concluded that it is possible to reach a maximum market share of 25 to 30% of recycled plastics with such an obligation, but that this is very ambitious. To reach a higher target (e.g. 50-60%) of biobased/recycled plastics, a considerable amount of biobased plastics is required.

If the government intends to stimulate the production and use of biobased plastics through policy, this support can be conditional on meeting sustainability criteria. As with renewable energy in the RED II, these criteria can include a minimum GHG emission reduction compared to a fossil alternative as well as rules on where/how the required biomass can be sourced. The purpose of the sustainability criteria is to only support those production chains that result in a GHG emission reduction and prevent negative environmental side-effects.

An RED-based approach for biobased plastic

Since a number of biobased plastics show promising carbon footprint reductions (i.e. larger than 1 kg CO_2-eq./kg plastic), it is relevant to consider what a potential government support policy could look like. Parts of the production chains for biobased plastics are comparable or identical to those of renewable energy sources, as they use similar biomass sources as biofuels. Therefore, governmental policy support policy for biobased plastics could align with the RED II where possible.

This report proposes such an RED-based approach for biobased plastic. The starting point is that biobased plastics must meet a carbon footprint reduction compared to fossil plastics to be eligible for (some form of) government policy support. As is the case for renewable energy in the RED II, default carbon footprint values can be used for well-established production chains for biobased plastics, while also giving companies the option of supplying case-specific carbon footprint calculations as a secondary option. The proposed method is further based on the following four principles:

1. Accuracy.
2. No risk that non sustainable biobased plastics will be stimulated.
3. A similar approach as for biofuels in the RED II.
4. Practicality, not too complex for companies and governments.

The calculation method is summarized in Table 1, which also compares it to the RED II and the methodology proposed by JRC. More details on the proposal are available in Chapter 5.

Table 1 - Overview of main characteristics of carbon footprint calculations

	JRC	RED II [1]	This report
Product	Plastic	Renewable energy	Plastic
Functional unit	The function of the studied product	The energy content of the studied product	Amount of plastic
Comparison with fossil alternative	Based on the function	Based on the energy content	For drop-in: Based on the mass. For others: Based on the mass and corrected with replacement factor
Reduction compared to fossil alternative	N/a	Percentage (depending on energy type and start op operations)	Absolute amount (e.g. 1 kg CO_2-eq./kg plastic)
System boundaries	Cradle-to-grave (includes EoL based on scenario)	Cradle-to-grave (includes emissions from use of fuel)	Cradle-to-gate (no EoL)
Biogenic CO_2	Biogenic CO_2 excluded	Biogenic CO_2 excluded	Biogenic CO_2 included
Allocation	Allocation avoided if possible by subdivision or system expansion, after this allocation based on physical property preferred	Energy allocation	Energy allocation
Direct LUC	dLUC included	dLUC included	dLUC incluced
Indirect LUC	iLUC excluded from calculation, but reported	iLUC excluded (high iLUC crops not allowed)	Multiple options, to be determined by policy makers
Impact categories	GHG + other PEF categories	GHG	GHG

Discussion and next steps

The RED-based approach proposed here for biobased plastics can be used as a starting point for governmental support for biobased plastics. However, there are a number of topics that can be debated or still need to be decided upon:

— Details of the **proposed calculation method**. Two methodological topics that should be considered in this discussion are how to deal with the end-of-life (EOL) treatment of biobased plastics (see discussion in Section 4.1) and emissions related to land use change (LUC). Including indirect LUC emissions is reasonable and the factors developed in the RED (1) period can be used. Later on, these factors should be updated.

[1] Only the part of RED II that is focussed on biofuels, bioliquids and biomass fuels is included in this overview.

- The **required carbon footprint reduction**, e.g. 1 kg CO_2-eq./kg biobased plastic, or another value. At 1 to 2 kg CO_2-eq./kg biobased plastics, the reductions are comparable to those of mechanical recycling of plastics. Over the entire life cycle of plastics, 1 kg CO_2 target corresponds to between 20 to 50% reduction (depending on the plastic type). At 2 kg CO_2, reductions lie in the range of 40 to 70%.

- The **type of policy support given to biobased plastics** that meet the carbon footprint reduction threshold. The approach suggested here can be implemented in different types of support schemes for biobased plastics, such as subsidies or a mandatory share of biobased content in new plastic products. These options can be combined with support for the use of recycled plastics. For example, a combined mandatory share of biobased and/or recycled content in new plastics products can be implemented. This would enable more ambitious targets on the share of 'sustainably produced' plastics and also provide plastics producers with a choice to use biobased plastics, recycled plastics, or both in their products. This can stimulate the use of biobased plastics in products where it is difficult to use recycled material (e.g. using bio-PE for foils), while using recycled plastic in products where a biobased alternative is more challenging (e.g. using mechanically or chemically recycled PET instead of 30% bio-PET).

Samenvatting

In 2018 was het marktaandeel van gerecycled kunststof slechts 9% en dat van biobased kunststof slechts 1%. Vanwege de milieuvoordelen van biobased en gerecycled kunststof ten opzichte van fossiel plastic worden verschillende beleidsopties om hun toepassing te stimuleren bestudeerd en besproken. Zowel financiële als regulerende opties zijn mogelijk.

Deze analyse richt zich ten eerste op het vaststellen en verklaren van de mogelijke klimaatvoordelen die biobased kunststoffen kunnen realiseren ten opzichte van fossiele plastics. Ten tweede stellen we een methodologie voor waarmee de reducties in klimaatimpact van biobased kunststoffen bepaald kunnen worden, in lijn met de berekeningen voor biobrandstoffen uit de Europese richtlijn voor hernieuwbare energie (RED II).

Aanleiding

Eerder heeft CE Delft het effect onderzocht van een verplichting op het gebruik van gerecycled of biobased kunststof voor het ministerie van Infrastructuur en Waterstaat (CE Delft, 2022). Die studie stelde vast dat het mogelijk is om een aandeel van 25 tot 30% gerecyclede kunststoffen te bereiken met een verplichting, maar dat dit zeer ambitieus is. Om een hoger aandeel (50 à 60%) van biobased/gerecyclede kunststoffen te bereiken, zou daarom een aanzienlijke hoeveelheid biobased kunststof ingezet moeten worden.

Als de overheid de productie en het gebruik van biobased kunststoffen beleidsmatig wil stimuleren, kan deze steun gekoppeld worden aan het voldoen aan duurzaamheidscriteria. Net als bij hernieuwbare energie in de RED II kunnen voor biobased kunststoffen criteria gebruikt worden waarin zowel een minimale reductie in klimaatimpact als toegestane biomassabronnen worden vastgelegd. Het doel van de duurzaamheidscriteria is om alleen die productieketens te steunen die zorgen voor een reductie in de klimaatimpact en negatieve neveneffecten voorkomen.

Een rekenmethode voor biobased kunststof gebaseerd op de RED II

Aangezien sommige biobased kunststoffen veelbelovende reducties qua klimaatimpact laten zien (dat wil zeggen groter dan 1 kg CO_2-eq./kg plastic), is het relevant te bekijken hoe mogelijke overheidssteun vormgegeven kan worden. Onderdelen van de productieketen van biobased kunststof zijn vergelijkbaar of identiek aan die van biobrandstoffen, omdat ze dezelfde biomassabronnen gebruiken. Een regeling voor overheidssteun aan biobased plastics kan daarom waar mogelijk aansluiten bij de RED II.

Dit onderzoekt stelt een rekenmethode gebaseerd op de RED II voor biobased kunststof voor. Het startpunt hierbij dat biobased kunststoffen een minimale reductie in klimaatimpact moeten realiseren ten opzichte van fossiele kunststoffen om in aanmerking te komen voor (nader te bepalen) overheidssteun. Net als bij hernieuwbare energie in de RED II kunnen standaardwaarden voor de klimaatimpact gebruikt worden voor veelgebruikte productiestappen/-ketens voor biobased kunststof. Daarnaast kunnen bedrijven als tweede optie de mogelijkheid worden gegeven om hun eigen ketenspecifieke berekeningen van de klimaatimpact aan te leveren.

De voorgestelde methode is verder gebaseerd op de volgende vier uitgangspunten:
1. Nauwkeurigheid.
2. Vermijden van steun voor niet-duurzame biobased kunststoffen.
3. Een vergelijkbare benadering als voor biobrandstoffen in de RED II.
4. Een pragmatische aanpak, die niet te complex is voor bedrijven en overheden.

De voorgestelde rekenmethode is samengevat in Tabel 1, waarin ook een vergelijking met de methodes uit de RED II en die methodologie voorgesteld door de JRC is opgenomen. Verdere details over het voorstel zijn te vinden in Hoofdstuk 5.

Tabel 1 – Overzicht van de belangrijkste eigenschappen van rekenmethodes

	JRC	RED II [2]	Dit rapport
Product	Kunststoffen	Hernieuwbare energie	Kunststoffen
Functionele eenheid	De functie van product	De energie-inhoud van het product	De hoeveelheid product
Vergelijking met fossiel product	Op basis van functie product	Op basis van energie-inhoud	Voor 'drop-in': op basis van massa. Voor overige: Op basis van massa, gecorrigeerd voor een vervangingsfactor.
Benodigde reductie t.o.v. fossiele referentie	N.v.t.	Reductiepercentage, (afhankelijk van type energie en aanvang productie)	Absolute hoeveelheid (bijvoorbeeld 1 kg CO_2-eq./kg kunststof)
Systeemgrenzen	Cradle-to-grave ('End of Life' meegenomen voor scenarios)	Cradle-to-grave (emissies van gebruik brandstoffen meegenomen)	Cradle-to-gate ('End of Life' buiten beschouwing gelaten)
Biogene CO_2	Biogene CO_2 niet mee-genomen	Biogene CO_2 niet mee-genomen	Biogene CO_2 wel mee-genomen
Allocatie	Zo mogelijk allocatie vermijden door onder-verdeling of systeem-uitbreiding. Daarna voorkeur voor allocatie op basis van fysieke eigenschappen.	Allocatie op basis van energie	Allocatie op basis van energie
Directe verandering in landgebruik (dLUC)	dLUC meegenomen	dLUC meegenomen	dLUC meegenomen
Indirecte verandering in landgebruik (iLUC)	iLUC gerapporteerd, maar niet meegenomen in hoofdberekening	iLUC niet meegenomen in berekening (gewassen met hoge indirecte landgebruiksemissies niet toegestaan)	Meerdere opties mogelijk, wordt een beleidskeuze.
Impact categorieën	Klimaatimpact en andere PEF categorieën	Klimaatimpact	Klimaatimpact

2 Alleen het deel van de RED II dat zich richt op biobrandstoffen, vloeibare biomassa en biomassabrandstoffen is in dit overzicht meegenomen.

Discussie en volgende stappen

De rekenmethode die hier is voorgesteld voor biobased kunststoffen kan gebruikt worden als startpunt voor overheidssteun aan biobased kunststoffen. Er zijn echter nog een aantal onderwerpen waar verder overleg of keuzes nodig zijn:

- Details in **de voorgestelde rekenmethode**. Twee onderwerpen waar verdere discussie nodig is zijn hoe om te gaan met het modelleren van de eindelevensfase van biobased kunststoffen (zie ook Paragraaf 4.1) en emissies gerelateerd aan landgebruiks-verandering. Het is redelijk om indirecte landgebruiksemissies mee te nemen en hiervoor de factoren uit de RED (1) voor te gebruiken. Deze factoren kunnen later geüpdatet worden.

- **De benodigde reductie in klimaatimpact**, die op 1 kg CO_2-eq./kg biobased plastic of een andere waarde gezet kan worden. Waarden tussen de 1 tot 2 kg CO_2-eq./kg bio-based plastic zorgen voor vergelijkbare reducties als er met mechanische recycling van kunststoffen te behalen zijn. Over de hele levenscyclus van kunststoffen komt een reductie van 1 kg CO_2-eq. overeen met een besparing van 20 tot 50% (afhankelijk van het soort plastic). Bij 2 kg CO_2-eq. zijn de reducties rond de 40 tot 70%.

- Het **soort overheidssteun** dat gegeven wordt aan biobased kunststoffen die de eisen voor klimaatimpactreductie behalen. De rekenmethode die we hier voorstellen kan worden toegepast in verschillende beleidsopties, zoals subsidies of een verplicht aan-deel van biobased kunststof in nieuwe plastic producten. Deze opties kunnen ook gecombineerd worden met steun voor gerecyclede kunststoffen. Zo kan een gecombi-neerde verplichting voor het aandeel biobased en/of gerecycled kunststof in nieuwe producten worden toegepast. Dit zorgt ervoor dat hogere doelstellingen gesteld kunnen worden voor ‘duurzaam geproduceerde’ kunststoffen en geeft producenten naast de keuze om biobased, gerecyclede, of allebei de soorten kunststoffen toe te passen in hun producten. Dit kan ervoor zorgen dat biobased kunststof wordt toegepast in producten waar gerecycled kunststof minder geschikt is (zo kan bio-PE gebruikt worden voor folies), terwijl gerecyclede kunststoffen worden gebruikt in toepassingen waar een biobased alternatief uitdagender is (zo kan mechanisch of chemisch gerecycled PET gebruikt worden in plaats van bio-PET).

1 Introduction

In 2018, only 9% of new plastic on the market was recycled plastic and only 1% was biobased plastic. Due to their environmental benefits over fossil plastics, several options to increase the uptake of biobased and recycled plastics are under investigation and debated.
Both financial and regulation options are possible.

CE Delft previously studied the effect of an obligation for the use of recycled or biobased material in new plastics for the Dutch Ministry of Environment (CE Delft, 2022). In this study we concluded that reaching a maximum of 25 to 30% of recycled content in all plastic is very ambitious but possible with such an obligation. Only with a considerable amount of biobased plastics a higher target for biobased/recycled plastics is possible (total 50-60%).

However, carbon footprint calculations for biobased plastics are more complicated than those for recycled plastics. Some analyses indicate that the greenhouse gas (GHG) emissions of biobased plastics can be higher than those of fossil plastics. Stimulating these negative examples of biobased plastics is not the aim of policy makers.

This discussion on the carbon footprint of biobased plastics led to the question whether it is possible to develop a policy using sustainability criteria and a minimum GHG emission reduction target to stimulate biobased plastics that reach a considerable amount of GHG reduction. Ideally, it would be possible to identify biobased plastics that achieve comparable GHG emission reductions as recycled plastics, so that a combined stimulation policy can be considered.

Therefore, the goals of this report are to:
- assess GHG emission reductions of biobased plastic chains compared to fossil plastics;
- explain differences in findings where possible;
- for key polymer types, determine which biobased plastics are likely to meet a GHG emission reduction target per kg of plastic;
- evaluate whether a policy approach similar to the revised Renewable Energy Directive (RED II) for renewable energy can be envisioned for biobased plastics.

In Chapter 2, we provide an overview of carbon footprint results for important biobased plastics. The aim is to quantify the expected reductions compared to fossil-based plastics and to explain differences between studies. In Chapter 3, we discuss how the existing EU policy for renewable energy (the RED II) could be applied to biobased plastics. Chapter 4 discusses more detailed issues beyond RED II, namely dealing with novel biobased plastics and partly-biobased plastics. In Chapter 5, we summarise the findings and present a proposal for what an RED-based approach for biobased plastics could look like.

It should be noted that this analysis focus on the carbon footprint results of biobased plastics, and that other environmental impacts are out of scope.

Textbox 1 - This report and recent EC proposals for bioplastics

In November 2022 the European Commission (EC) published their 'Policy framework on biobased, biodegradable and compostable plastics' (see EC (2022)). Here we explain the relation between the EC proposal and this report.

Key elements in the EC policy framework:
1. Compostable plastics should especially be used for packaging applications (like tea bags, coffee pads) which can be composted together with food waste (coffee, tea, etcetera). The idea is to forbid the use of fossil plastics for these applications.
2. Communication about the sustainability of biobased plastics to the general public should be improved.
3. Sustainability criteria for biobased plastics should be further developed and used.
4. Environmental assessments of biobased plastics (LCA studies) should be improved and standardised.

Key elements that are not in the EC policy framework:
1. There are no proposals for a general support scheme for biobased plastics (such as the support schemes for biofuels and bio energy in the RED II system).
2. The framework has no general approach how to reduce the use of fossil plastics by a combination of recycling and biobased plastics.

This report has strong links with key elements 3 (sustainability criteria) and 4 (LCA) in the policy framework of the European Commission. We analyse the current LCAs and give suggestions how these could be used to ensure that biobased plastics will reduce CO_2-eq. emissions.

This report starts with a general approach how to lower the use of fossil plastics (key element 6, missing in the EC proposals). In earlier research for the Dutch Ministry of Environment (CE Delft, 2022)) about a mandatory percentage of recycled or bio-based plastic in the European Union we concluded that it will be very difficult to reach a higher recycled content than 25% to 30% in the EU in 2030. With the help of sustainable biobased plastics this renewable recycled content could be increased up to 50 to 60%.

Because biobased plastics are still more expensive than fossil plastics the use of them will not increase automatically. In addition, the energy policy in Europe (RED) that supports the use of crops suitable for biobased plastics for biofuels and bioenergy, does hinder the growth of biobased plastics in the market.

The Dutch Parliament has declared multiple times that they prefer the use of biomass and crops for materials over its use for energy and fuels (SER, 2020). This means that a support scheme for biobased plastics is necessary to reach a level playing field between biobased plastics and biofuels and bioenergy.

In this report we assume that a form of support policies (an obligation, an obligation together with recycling or subsidies) will be introduced. This support should only be given to biobased plastics which are sustainably produced and certain CO_2 reduction is reached.

The main issue analysed in this report is whether a substantial market share of biobased plastics is feasible if a certain CO_2 reduction minimum is included in the support policy. Furthermore, we describe how this CO_2 reduction minimum in the support policy can be introduced and organised.

2 Carbon footprints of biobased plastics

The goal of this section is threefold. First we will assess carbon footprint reductions of biobased plastics compared to fossil based plastics. Then we explain differences in findings where possible. Finally, for key polymer types, we determine which biobased plastics are likely to meet a GHG emission reduction target per kg of plastic.

In this chapter we look at different life-cycle assessment (LCA) case studies performed on biobased plastics. LCA is a standardized method to quantify the environmental impacts of products or services (ISO, 2006a, 2006b). In this report we focus on the carbon footprint results, i.e. the contribution to climate change through the emissions of greenhouse gases (GHGs).

This chapter analyses carbon footprint results for biobased polyethylene (PE), polypropylene (PP), polylactic acid (PLA) and polyethylene terephthalate plastics (PET). PLA is a potential candidate to replace fossil polystyrene (PS). Together, fossil PE, PP, PET and PS account for over 60% of the European plastics demand (Plastics Europe, 2022b). This means the four biobased plastics can, from a technical point of view, be used in a large share of European plastic products. Together, these four biobased plastic types account for about 37% of the current global production capacity for biobased (and biodegradable) plastics (European Bioplastics, 2021).

Carbon footprint estimates of different biobased plastics vary. For each biobased plastic type, LCA studies report different results due to variations in the value chain studied (i.e. 'real' differences) as well as methodological choices. The carbon footprints of biobased plastics are partly determined by direct land use change (dLUC) and indirect land use change (iLUC). The carbon footprint of dLUC occurs when cultivation of feedstock converts the land compared to the previous application, releasing CO_2 in the process. The increase or loss of soil and vegetation carbon stocks can be used to estimate the carbon footprint of direct land use change.
When crops are produced on land that was previously used for food production, iLUC can occur. As food production will have to take place at other land, there is the risk of expansion to land with a high carbon stock, such as rainforests.
If a crop causes dLUC because of transformation of unmanaged land, there should be no iLUC, as no arable land used for food/feed production is lost. Some studies include both dLUC and iLUC based on the assumption that part of the biomass is sourced from land is transformed to arable production. Compared to dLUC, iLUC impacts have a higher uncertainty.

An overview of reported carbon footprints of biobased and fossil plastics can be found in an overview study by Brizga et al. (2020). While the authors compare all alternatives at polymer level, as opposed to product level, the results have not been normalized for the different scopes and boundaries. As the results of the studies are converted to cradle-to-gate, the authors made the choice to include the biogenic carbon uptake. Based on this overview, it can be expected that, on average, the production of bio-PE, bio-PET and bio-PP leads to a reduction in carbon footprint. While these results are based on a small sample of reviewed and grey literature, they provide a further justification to focus on bio-PE, bio-PP, bio-PET, as well as PLA, in this report.

2.1 Harmonised literature comparison

In the following analysis we aim to explain the variability in carbon footprints of biobased plastics. In the analysis we include recent studies on bio-PE, bio-PET, bio-PP and PLA. Both studies commissioned by producers as well as scientific literature have been considered. Only case studies that give insight in the contribution of key elements to the overall carbon footprint are included, as the results of these can be interpreted in a more meaningful way. This analysis should therefore not be seen as an exhaustive literature review of these bio-polymers.

The results of the included studies have been harmonized to be cradle-to-gate of 1 kg polymer. We chose to include biogenic carbon uptake for biobased plastics. For drop-in biobased plastics, this allows for easy comparison with fossil-based plastics, as the end-of-life is identical. By removing as much methodological variability as possible, the results of different studies are more comparable. Since not all articles report results numerically, visual estimation from graphs was needed in some cases. In the following sections, we present the main characteristics and the results of the included studies with the goal of explaining the different results.

The structure of the text for the different biobased plastics is the same. First the plastic is introduced. Then LCA studies are introduced. Basic assumptions are presented in the table, when more insight is required, explanation is given in the text. Then the harmonized results of the analysis is presented in a figure and interpreted in text.

2.2 Polyethylene (PE)

Polyethylene is the most used plastic worldwide, mainly for the production of packaging. Biobased polyethylene can be produced from ethanol and is a drop-in for the fossil-based PE. For biobased polyethylene, a relatively large number of LCA studies is available. In many studies sugarcane is used as biomass feedstock, but maize, sugar beet and wheat are also reported.

Table 2 provides an overview of the included studies as well as basic assumptions. The following specific corrections and assumptions were made to further harmonise the methodologies of the LCA studies on bio-PE:

- For studies with a cradle-to-grave scope or that included further processing steps, only the production up until polymerization is taken into account.
- In the JRC report (Nessi et al., 2022), carbon uptake was not included in the calculations. We chose to include carbon uptake in our analysis for a fair comparison with other bio-PE and the fossil reference.
- As there is not one value for iLUC, but a range in Tsiropoulos et al. (2015), iLUC was left out of our analysis. Inclusion of the highest factor for iLUC would result in a carbon footprint of 1.8 kg CO_2-eq./kg polymer.
- As multiple options for dealing with allocation and substitution were evaluated in the article, we work with an average scenario.
- In the article by Belboom and Léonard (2016), a different value for carbon uptake is reported. We assume that this carbon uptake is emitted in the fermentation phase and is included in the polymer production step, since it cannot be physically present in the bio-PE at gate.

The fossil reference is from Plastics Europe data (Plastics Europe, 2022a).

Table 2 - Studies on Bio-PE carbon footprint included in this analysis

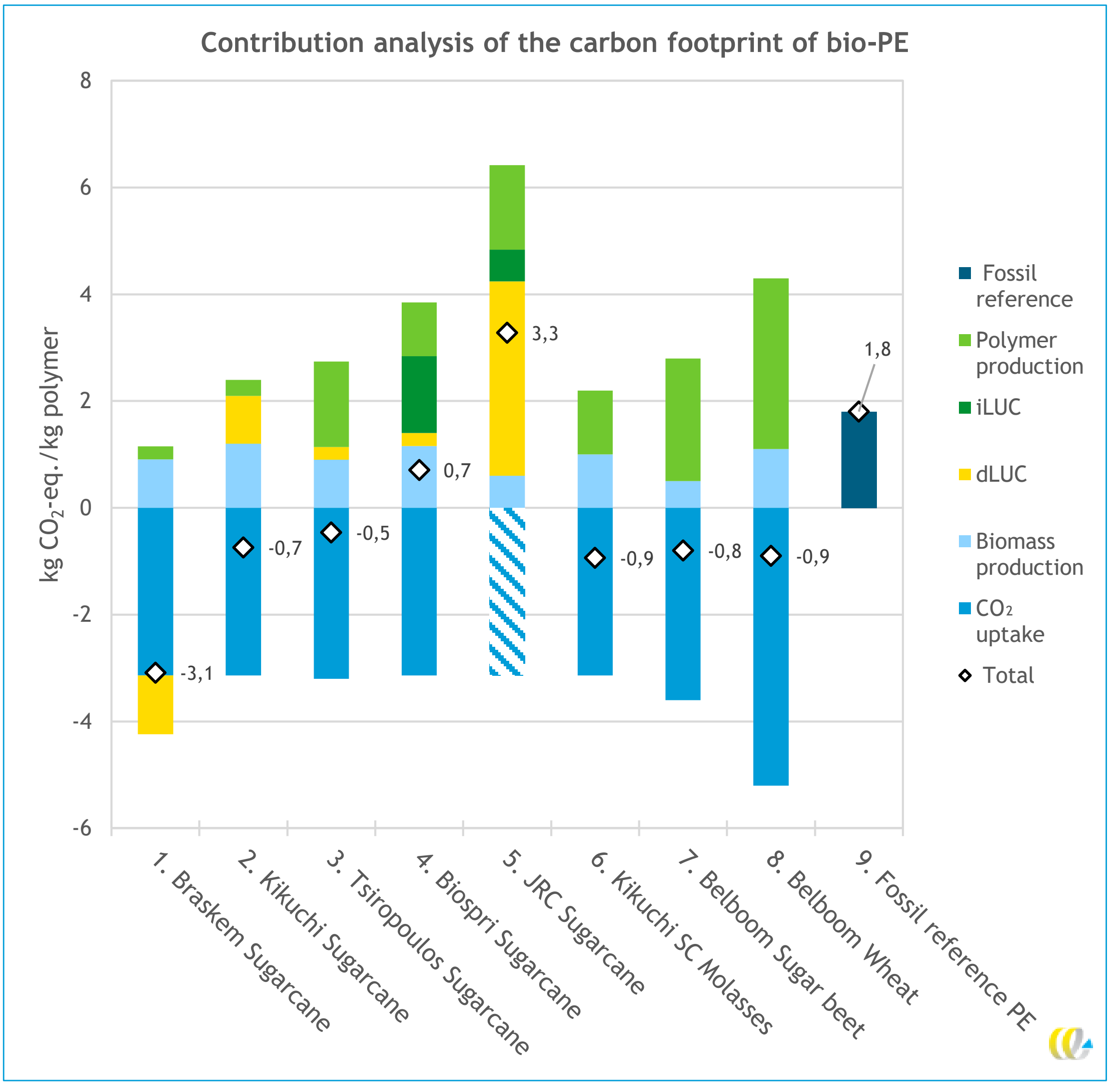
Name in Figure 1 (Author, year)	Feedstock	Original scope[a]	Energy mix	Allocation and substitution	LUC
1. Braskem Sugarcane (Braskem, n.d.)	Sugarcane (Brazil)	Polymer Cradle-to-gate	Bio-energy ethanol production + Brazil grid for other processing	No allocation, Substitution of fossil energy	dLUC credit
2. Kikuchi Sugarcane (Kikuchi et al., 2017)	Sugarcane (Brazil)	Polymer Cradle-to-grave	Unknown	Energy allocation	dLUC included
3. Tsiropoulos Sugarcane (Tsiropoulos et al., 2015)	Sugarcane (Brazil)	HDPE Polymer Cradle-to-gate	Electricity national grid, heat fossil	Different options explored	dLUC included, ranges of iLUC reported in article
4. Biospri Sugarcane (COWI & University of Utrecht, 2018)	Sugarcane (Brazil)	Bio-LDPE carrier bag Cradle-to-gate Cradle-to-grave	Unknown	Substitution marginal energy	iLUC and dLUC included
5. JRC Sugarcane (Nessi et al., 2022)	Sugarcane (Brazil)	HDPE bottles Cradle-to-grave	Grid energy	Substitution grid electricity	iLUC and dLUC included
6. Kikuchi SC Molasses (Kikuchi et al., 2017)	Sugarcane Molasses (Japan)	Polymer Cradle-to-grave	Unknown	Energy allocation	
7. Belboom Sugar beet (Belboom & Léonard, 2016)	Sugar beet (Belgium)	Polymer Cradle-to-grave	Unknown	Energy allocation, others in sensitivity	No LUC
8. Belboom Wheat (Belboom & Léonard, 2016)	Wheat BE (Belgium)	Polymer Cradle-to-grave	Unknown	Energy allocation, others in sensitivity	No LUC
9. Fossil reference PE (Plastics Europe, 2021)					

[a]: In this report the scopes have been harmonized to 1 kg polymer by leaving out further downstream processing.

Figure 1 provides the (harmonized) carbon footprint results for the included LCA studies on bio-PE. The comparison provides several insights that can explain the different carbon footprint results. The first large influential factor on the carbon footprint is land use change. dLUC is very scenario-specific. In the JRC study, dLUC is high because the previous land use is unknown. Within the JRC's method used for quantification of dLUC emissions, this leads to a high carbon footprint. dLUC can also be negative, if land with low carbon stocks is transformed cropland. The results of this assumption can be seen in the Braskem study.

Other methodological choices also influence the carbon footprint of biobased PE. Studies differ in the handling of co-products, of which the most influential is energy production. Using substitution to handle coproducts, such as energy, can bring down the carbon footprint. In the Braskem study, electricity production accounts for a carbon footprint reduction of 1.17 kg CO_2-eq. in the polymer production phase.

Figure 1 - Contribution analysis of bio-PE carbon footprints available in literature sources (see Table 2)



Conclusions carbon footprint bio-PE:

- the large differences in carbon footprint results can be explained by methodological differences and biomass source;
- when iLUC is accounted for a reduction of 1.1 kg CO_2-eq./kg bio-PE compared with fossil PE is possible;
- studies without iLUC generally show a reduction of 2.3 to 2.7 kg CO_2-eq./kg bio-PE compared to fossil PE.

2.3 Polypropylene (PP)

PP is the second most demanded plastic. PP is mostly used in packaging, but is also used in the automotive industry, household, leisure and sport items and other applications (Plastics Europe, 2022b).

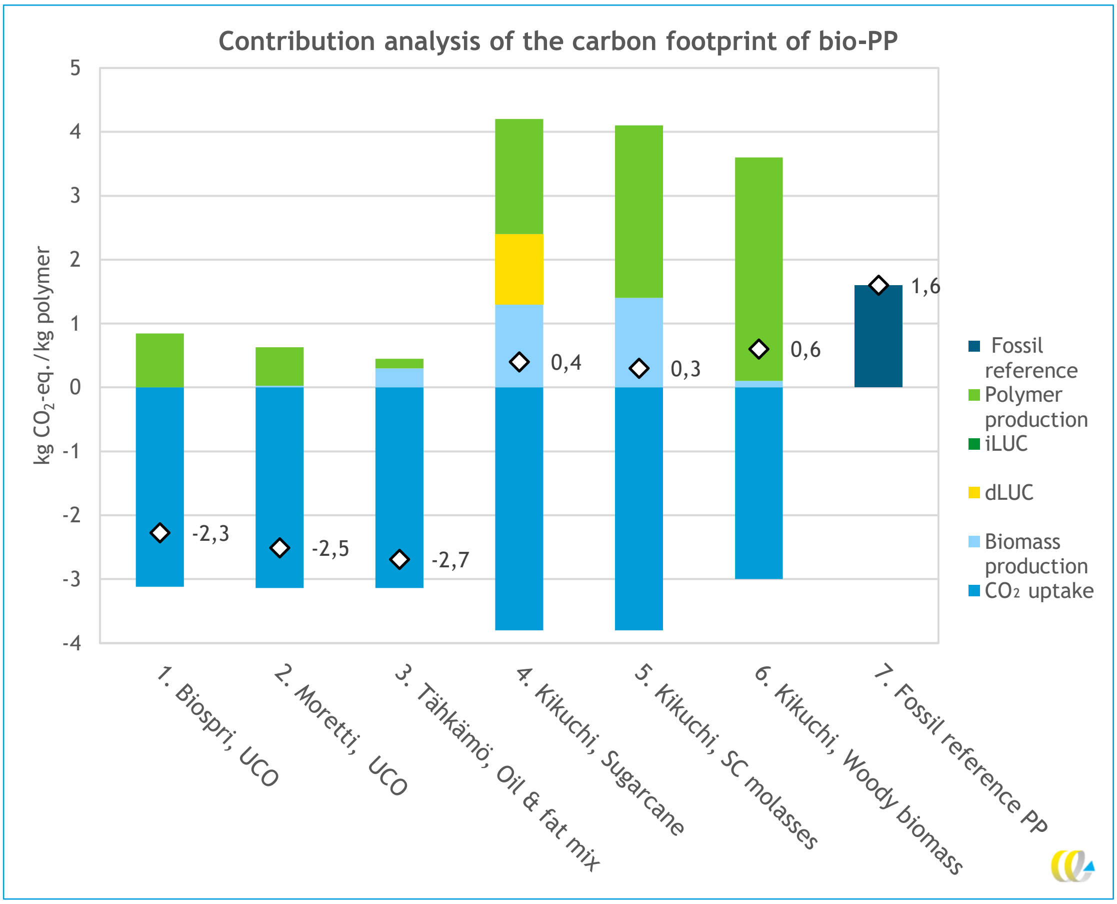
Table 3 provides an overview of LCA studies on bio-PP and their basic assumptions. The included studies use either used cooking oil (UCO), sugar cane products or woody biomass as feedstock. The different feedstocks are converted into bio-PP via different production routes. For the oil-based feedstocks, PP is produced in a cracker. Other options for the production of bio-PP are the production from sugar crops via ethanol or the production via syngas from woody biomass. None of the studies include iLUC. The exclusion of iLUC seems to be a methodological choice for the sugar cane-based routes.

Table 3 - Studies on bio-PP carbon footprint included in this analysis

Name in Figure 2 (Author, year)	Feedstock	Main inter-mediate	Original scope	Energy mix	Allocation and substitution	LUC
1. Biospri, UCO (COWI & University of Utrecht, 2018)	UCO (used cooking oil)	Bio-naphtha	Drinking cups Cradle-to-gate Cradle-to-grave	Unknown	Exergy allocation	N/a
2. Moretti, UCO (Moretti et al., 2021)	UCO	Bio-naphtha	Polymer Cradle-to-gate	Grid	Substitution and Energy allocation	N/a
3. Tähkämö, Oil & fat mix (Tähkämö et al., 2022)	33% UCO, 33% palm fatty acid distillate, 33% Animal fat, and 1% Fish Fat	Bio-naphtha	Polymer, Cradle-to-gate	Grid mixes for countries where processing steps take place	Mass and energy allocation	N/a
4. Kikuchi, Sugarcane (Kikuchi et al., 2017)	Sugar cane (Brazil)	Hydrous ethanol	Polymer Cradle-to-grave	Unknown	Energy allocation	dLUC included
5. Kikuchi, SC molasses (Kikuchi et al., 2017)	Sugar cane molasses (Japan)	Hydrous ethanol	Polymer Cradle-to-grave	Unknown	Energy allocation	N/a
6. Kikuchi, Woody biomass (Kikuchi et al., 2017)	Woody biomass (Japan)	Syngas/ methanol	Polymer Cradle-to-grave	Unknown	Energy allocation	N/a
7. Fossil reference PP (Plastics Europe, 2021)						

Figure 2 shows that for bio-PP produced from waste feedstocks (e.g., UCO), the carbon footprint is very low. This is because only the collection and preparation of waste is included in the biomass production phase. The polymer production also shows very diverse results between the waste route and other routes. The waste routes are all based on steam cracking, where propylene is one of the many outputs. In the sugar cane routes, polypropylene is produced via ethanol. For the woody biomass, syngas is the key intermediate. The choice of biomass feedstock not only influences the carbon footprint of the cultivation step, but the waste oil routes also show a lower contribution to the carbon footprint from polymer production. While it is apparent that the waste oil-based routes for bio-PP production have a low carbon footprint, the number of included studies is too low to draw general conclusions on preferable production routes.

Figure 2 - Contribution analysis of bio-PP, for reference to used article, see Table 3



Conclusions carbon footprint of bio-PP:

- excluding iLUC, a reduction of 1 to 1.3 kg CO_2-eq./kg biobased plastic compared with fossil is possible;
- when produced from waste oils, a carbon footprint reduction over 3.5 kg CO_2-eq./kg biobased plastic is possible (when taking into account the biogenic carbon uptake).

2.4 Polylactic acid (PLA)

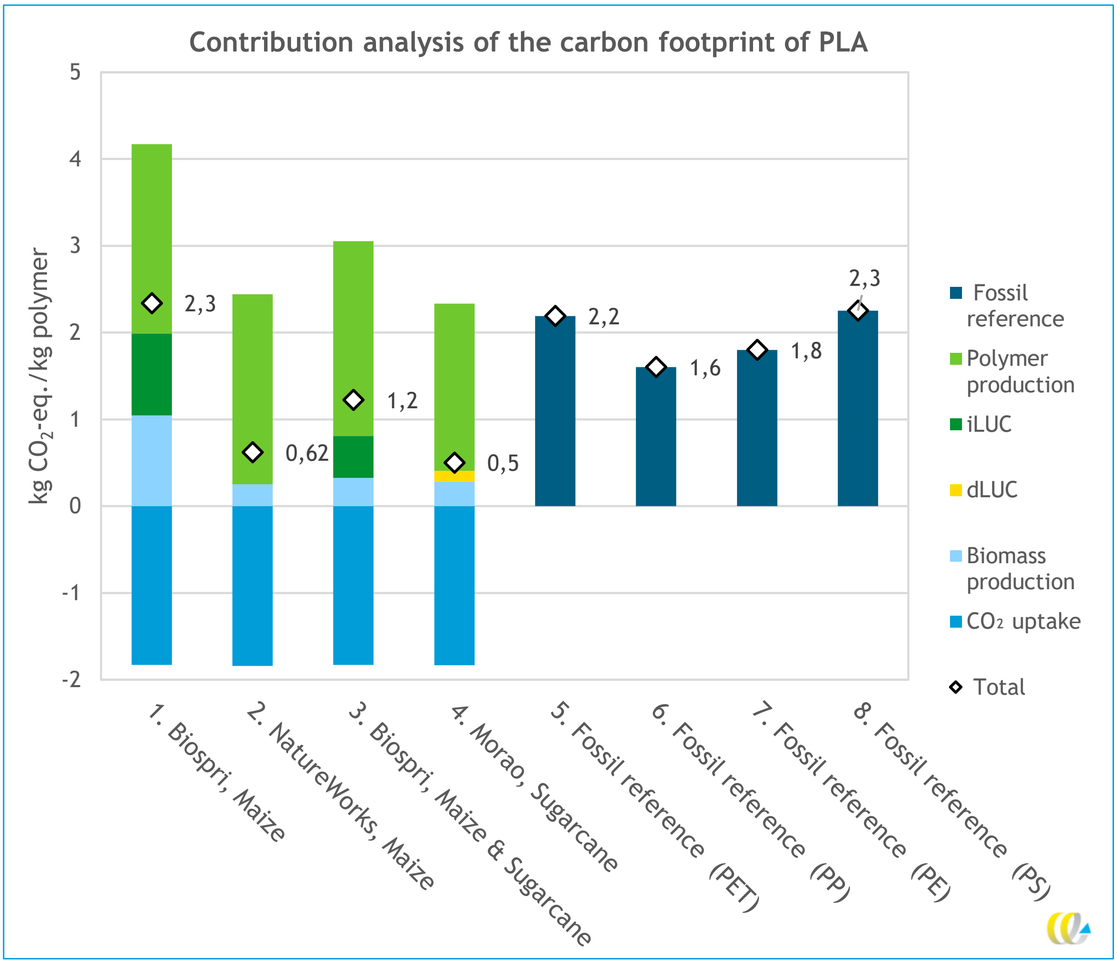
Table 4 shows an overview of the included PLA studies and their characteristics. All studies are based on the production of PLA from maize, sugarcane or a combination of the two. As specific company data is used in most cases, data is often confidential. This makes it harder to explain and interpret results. The studies included in this table give a contribution analysis of the carbon footprint; many other studies only report an aggregated end result.

Table 4 - Studies on PLA carbon footprint included in this analysis

Name in Figure 3 (Author, year)	Feedstock	Original scope	Energy mix	Allocation and substitution	LUC
1. Biospri, Maize (COWI & University of Utrecht, 2018)	Maize (EU)	Drinking cups Cradle-to-gate Cradle-to-grave	Unknown	Mass allocation, system expansion with substitution	iLUC
2. NatureWorks, Maize (Vink & Davies, 2015)	Maize (US	Polymer, cradle-to-gate	Unknown	Mostly mass allocation, substitution for gypsum	Left out
3. Biospri, Maize & Sugarcane (COWI & University of Utrecht, 2018)	Maize (US) and Sugarcane (TH)	Drinking cups Cradle-to-gate Cradle-to-grave	Partially bio-energy	Mass allocation, system expansion with substitution	iLUC
4. Morao, Sugarcane (Morão & de Bie, 2019)	Sugarcane (TH)	Polymer, Cradle to gate	Grid mix	System expansion with substitution,	dLUC
5. Fossil reference (PET) (Plastics Europe, 2021)					
6. Fossil reference (PP) (Plastics Europe, 2021)					
7. Fossil reference (PE) (Plastics Europe, 2021)					
8. Fossil reference (PS) (2021)					

The carbon footprint results for PLA are shown in Figure 3. Unlike bio-PE and bio-PP, PLA is not a drop-in biobased plastics but a so-called novel biobased plastic. This means it made up of different molecules than existing (fossil) plastics, and has different technical properties. Therefore, several fossil-based alternatives that PLA may replace are shown in Figure 3. It is important to note that 1 kg PLA does not necessarily replace one kg of another polymer. In Section 4.1, we will discuss replacement factors for novel biobased plastics such as PLA compared to other polymers and the implications of this.

Figure 3 - Contribution analysis of sugarcane PLA, for reference to used article, see Table 4



Conclusion carbon footprint of PLA:

- Including iLUC, reductions of 1 kg CO_2-eq./kg PLA are possible when compared with PS of PET.
- Excluding iLUC, the reduction of PLA compared with PS and PET can be 1.6 kg CO_2-eq. per kg.
- Excluding iLUC, the reduction of PLA compared with PP can be 1 kg CO_2/kg PLA.
- A replacement factor of 1.0 has been used. Monitoring of this replacement factor the years after the start of stimulation is advised and an update could be carried out after some years.

2.5 Polyethylene terephthalate (PET)

PET is a plastic that is mostly used for the packaging of liquids, such as bottles or other containers. The term bio-PET mostly refers to partly biobased PET. PET is the result of polymerization of two monomers, mono-ethylene glycol (MEG) and purified terephthalic acid (PTA). Currently only the MEG monomer is produced from biobased resources. When produced via this route, 27% of the mass of bio-PET is derived from biomass. When considering carbon instead of mass, bio-PET is about 20% biobased.

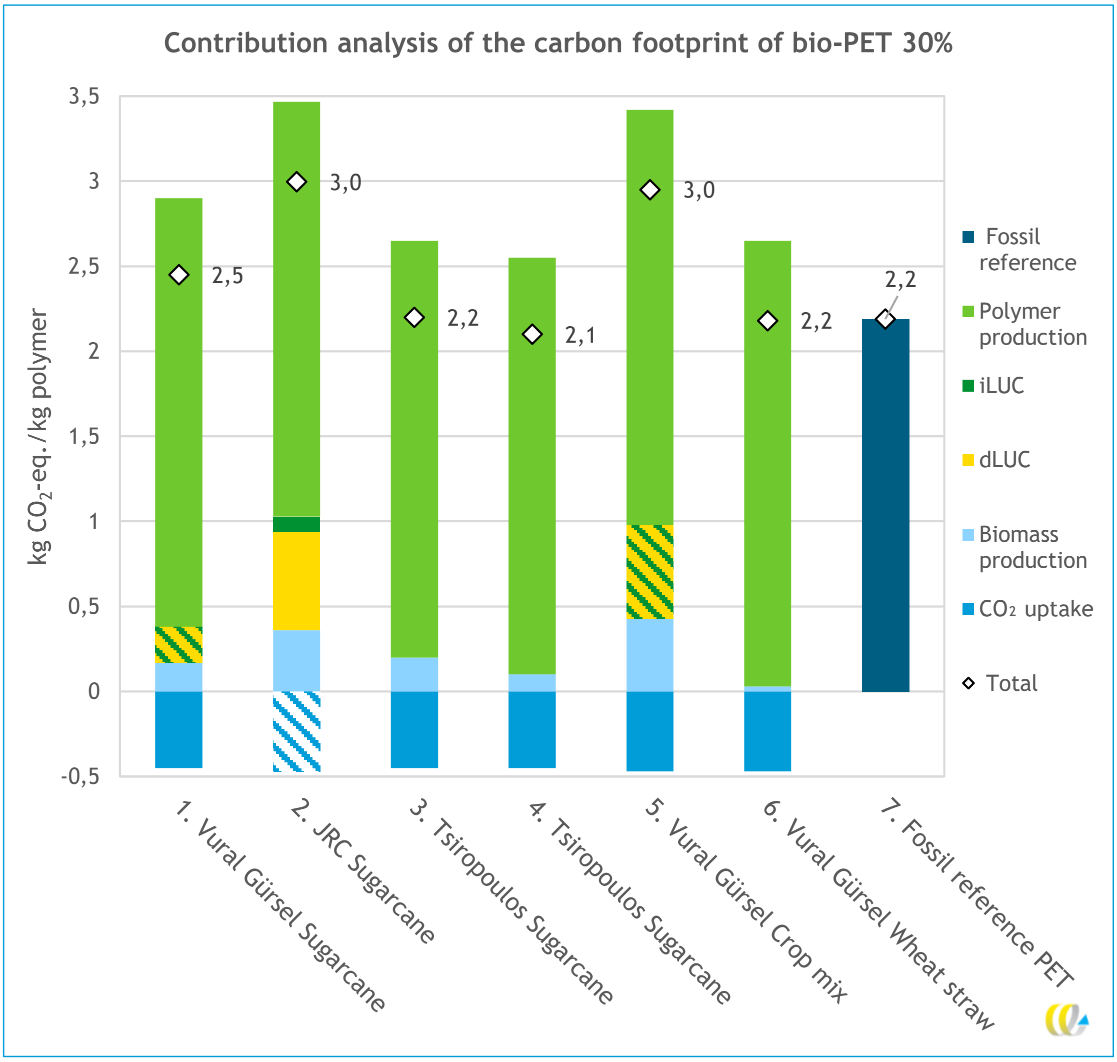
The studies included in this analysis thus all study partly biobased PET. Table 5 shows the main assumptions of the included studies on biobased PET.

Table 5 - Studies on bio-PET carbon footprint included in this analysis

Name in Figure 4 (Author, year)	Feedstock	Original scope	Energy mix	Allocation and substitution	LUC
1. Vural Gürsel Sugarcane Vural Gursel et al. (2021)	Sugarcane (Brazil)	PET bottles Cradle-to-grave	Unknown	Substitution of marginal energy and products	dLUC and iLUC
2. JRC Sugarcane (Nessi et al., 2022)	Sugarcane (Brazil)	PET bottles Cradle-to-grave	Grid energy	Grid electricity, fossil heat	dLUC and iLUC included
3. Tsiropoulos Sugarcane (Tsiropoulos et al., 2015)	Sugarcane (Brazil)	PET polymer Cradle-to-gate	Electricity national grid, heat fossil	Different options explored	dLUC and iLUC ranges reported in article.
4. Tsiropoulos Sugarcane (Tsiropoulos et al., 2015)	Sugarcane Molasses (India)	PET polymer Cradle-to-gate	Electricity national grid, heat fossil	Different options explored	N/a
5. Vural Gürsel Crop mix (Vural Gursel et al., 2021)	36% Maize (EU) 37% wheat (EU) 27% Sugar beet (EU)	PET bottles Cradle-to-grave	Unknown	Substitution of marginal energy and products	dLUC and iLUC
6. Vural Gürsel Wheat straw (Vural Gursel et al., 2021)	Wheat straw (EU)	PET bottles Cradle-to-grave	Unknown	Substitution of marginal energy and products	N/a
7. Fossil reference PET (Plastics Europe, 2021)					

In Figure 4 the contribution of the different life-cycle stages to the carbon footprint of bio-PET is shown. The polymer production stage includes the production of fossil-based PTA. Because only the MEG is bio-based in the included studies, the uptake of CO_2 is smaller than for the previous plastic types. Both dLUC and ilUC represent a substantial part of the carbon footprint in many studies. Tsiropoulos et al. (2015) reflect on the potential effect of dLUC and iLUC in the article. For the Brazilian sugarcane scenario, this would add up to 0.4 kg CO_2 to the carbon footprint.

Figure 4 - Contribution analysis of sugarcane bio-PET, for reference to used article, see Table 5



Conclusion carbon footprint of partly-biobased bio-PET:

— No substantial CO_2 reduction from bio-PET compared with fossil PET is expected with the current technologies.

2.6 Interpretation of carbon footprint findings

Based on the review of several studies we can identify main drivers to the carbon footprint as well as several promising production routes for biobased plastics. We will first present the main drivers of the carbon footprint. The differences in carbon footprint result scan be attributed to two types of differences. Firstly, there are (‘real’) differences in the value chain studied. Secondly, there are methodological differences in how the carbon footprint results are calculated.

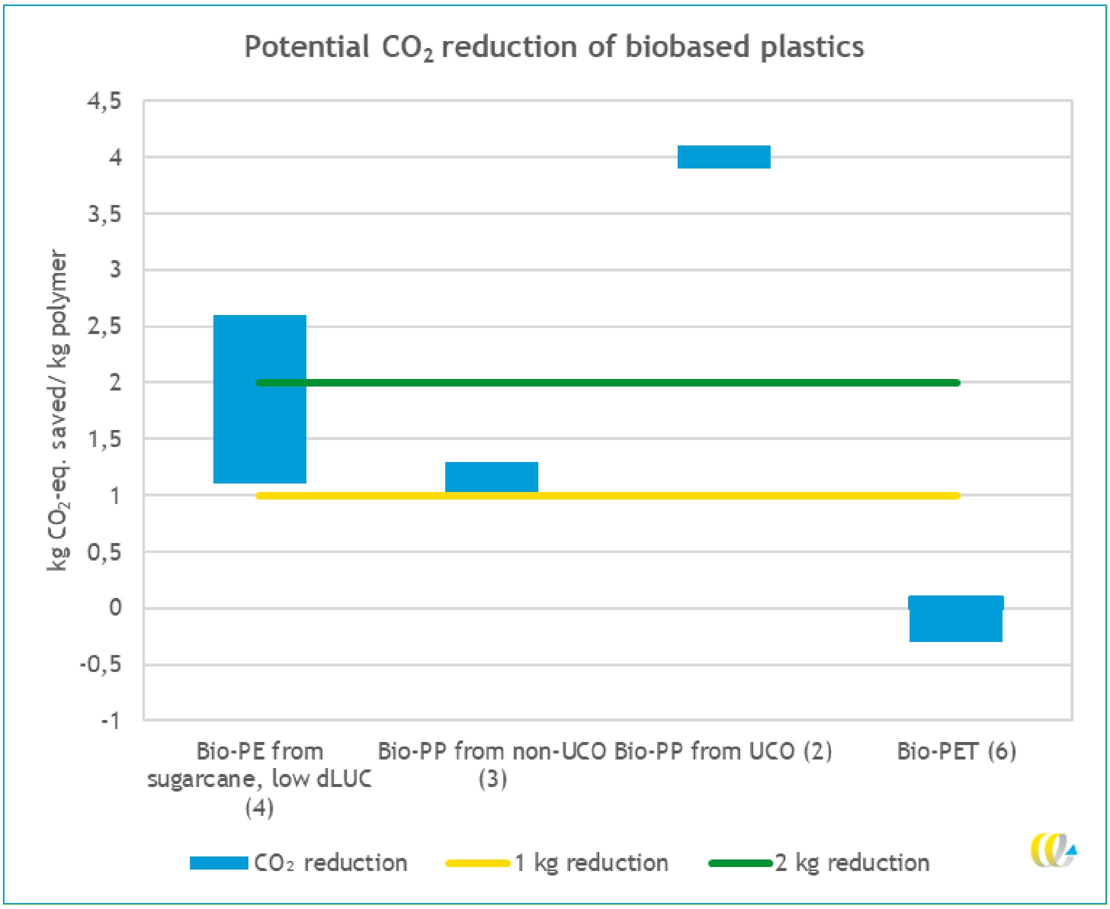
The main drivers of carbon footprints that stem from production design in biobased plastics are the conversion needed, the type of biomass used and the land use change associated with the biomass production. Between types of bioplastics, the carbon footprint of the conversion of biomass to biobased plastic differs. For example, the carbon footprint of the conversion of biomass is generally bigger for PLA than it is for bio-PE. For bio-PP, we see differences in the carbon footprint of the polymer production step based on type of biomass used. For the waste oil based routes, the carbon footprint of polymer production is lower than production via ethanol. The carbon footprint of polymer production is not always straightforward as there can be a negative carbon footprint caused by the utilization of by-products and coproducts. The choice of energy source can also have a large effect on the carbon footprint of the polymer production step. The feedstock used does not only influence carbon footprint of polymerization, but also emissions from cultivation. Linked to the impacts of cultivation, is the carbon footprint of direct and indirect land use change. This is connected to the choice of country and previous land use.

The other source of difference in LCA outcomes is methodological choices. Studies deal differently with coproducts and by-products, as both allocation and substitution are used in studies. When substitution is used for energy production, the choice for avoided energy can have a large effect on the results. A clear example of this is the LCA on bio-PE. Whether and how dLUC and iLUC are considered in the studies, can have a large influence on the results as well. Some studies ignore these, mostly citing the uncertainty of the calculation models or lack of consensus. Studies that do include land use change impacts, show that these can be very high. A consistent methodology should reduce the variability of results caused by methodological choices. This way actual environmental differences that stem from production process design, can be effectively compared.

Based on this review, some promising routes and overall conclusions can be identified:
- As shown in Figure 5, the highest carbon footprint reduction can be expected from bio-PP from UCO. The reduction is expected to be well above 2 kg CO_2 compared to fossil PP. For bio-PP from other feedstocks, a 1 kg reduction compared to fossil PP seems possible, but a 2 kg reduction is challenging.
- In general, bioplastics from waste can be expected to have a large carbon footprint reduction when carbon uptake is attributed to this feedstock. This also holds true for other applications, such as biofuels, but the availability of useable biomass waste is limited. It can therefore be expected that the demand for biobased plastics will not be met with only waste as feedstock.
- For bio-PE from sugarcane, if there is a low carbon footprint contribution from direct land use change, a carbon footprint reduction of 1 kg is likely. A reduction of 2 kg compared to fossil PE is possible.
- For bio-PET, the reduction of carbon footprint, if any, is currently expected to be small.
- For PLA we could not draw a robust conclusion, as the number of detailed LCA studies is limited and the fossil reference not straightforward (see also Section 4.1).

It should be noted that this overview is not exhaustive and reflects our understanding of the current situation which can change over time. Even if this overview does show a carbon footprint reduction for a specific production route, it does not mean that a specific biobased plastic cannot achieve a substantial carbon footprint reduction, either now or in the future. For some biobased plastics or production routes, insufficient information is available at the moment. In addition, existing and new production routes for biobased plastics are constantly being further developed, so environmental impacts can come down over time.

Figure 5 - Expected range of CO_2 reduction of biobased plastics (number of included studies shown in brackets)



3 RED applied to biobased plastics

When it comes to the policy side of biobased plastics, two issues are important. The first is that biofuels and bioenergy are supported in policy, while biobased plastics lack this support. The second issue is that there is a need for sustainability criteria to ensure that only those biobased plastics are promoted that reach a certain CO_2 reduction target and comply with sustainable agricultural practices.

Parts of the production chains for biobased plastics are comparable or identical to those of renewable energy sources. Therefore, it makes sense if potential biobased plastics support policy aligns with the revised EU Renewable Energy Directive (RED II) where possible. RED II uses a system of criteria to determine which renewable energy routes are considered sustainable and therefore count towards EU Member States' targets. Using a system aligned with RED II, could align support for biofuels and bioplastics, and provide sustainability criteria. In the following paragraphs we how RED II can be used for bioplastics.

In the Netherlands and most other EU members states there is no existing support policy for biobased plastics. For biofuels which use similar bio inputs as biobased plastics the RED with its obligations for fuels support biofuels and bioenergy receives subsidies in most European countries. In several reports and policy documents (SER, 2020, Ministerie van I&W, 2020, Ministerie van EZK & Ministerie van I&W, 2022) biomass for biobased plastics is preferred above bioenergy and biofuels. Inclusion of biobased plastics in an obligation for recycled or biobased plastics in the EU is an option for this policy change (CE Delft, 2022). Another option would be a tax for virgin plastics or a subsidy scheme for biobased plastics.

Biobased plastic are in most cases more expensive that fossil plastics. This is both due to a difference in scale and innovation time but also due to the fact that governments support the use of crops for biofuels which lifts the prices of the same crops which could also be used for biobased plastics, for example sugarcane. Without governmental support the market for biobased plastics will likely remain small, in 2021 the share of bioplastics was 2.3% in Europe (Plastics Europe, 2022b).

When support policy is introduced for biobased plastics this should be combined with sustainability criteria for biobased plastics according to the SER, the EC and the Dutch Government. In this chapter we check if the sustainability criteria which are already in place for biofuels are also useful for biobased plastics.

To ensure that greenhouse gas reductions are achieved with the use of biobased plastics, a system needs to be in place that allows for evaluation of the carbon footprint reductions of the biobased plastics. In parallel to this, there should be sustainability criteria that ensure other environmental impacts, like loss of biodiversity are limited. Although not developed for biobased plastics, the revised Renewable Energy Directive (RED II) gives handles on how such an evaluation system could be implemented (EU, 2018). In this section, the relevant aspects of RED II are introduced, and implementation of RED II for biobased plastics is discussed.

3.1 RED II sustainability criteria for biofuels

RED II is European legislation that sets targets for renewable energy use in member states. Renewable energy can only be included in the target if it follows the set requirements. For biofuels, a minimum carbon footprint reduction needs to be realised. Both the target for renewable energy and the required carbon footprint reduction are gradually increased over time. The target for carbon footprint reduction for transport biofuels started at a 35% reduction in the original Renewable Energy Directive (EC, 2009). The minimum reduction target is currently 50% for installations that came in use before October 2015. For installations that came in use between October 2015 and January 2021, the reduction target is 60%. For those coming in use after January 2021 the reduction is 65%.

To calculate the carbon footprint reduction the carbon footprint of the biobased fuel is calculated and compared to a reference value (the ‘fossil fuel comparator’). The calculation includes the emissions of cultivation, annualised direct land use change emissions, processing, transport, emissions of use of the fuel as well as emission savings from soil carbon accumulation via improved agricultural management, carbon capture and storage, and carbon capture and replacement. For the different elements, the calculation method is prescribed. For cultivation, processing, transport and distribution, standard values are given for the different pathways of several biofuels. These pathways are based on the type of biofuel, used crop, energy used and application of by-products. The standard values can be used for (some of) the production steps, or own calculations can be provided. For the other elements of the carbon footprint calculation, such as land use change impacts, no standard values are given and should be calculated. For the fossil fuels comparator, a carbon footprint is provided to calculate the GHG savings.

In addition to the required carbon footprint reduction, there are restrictions on the type and origin of biomass used. A selection of these restrictions will be highlighted. Transformation from land with high carbon stocks and large biodiversity for the production of biofuels is not allowed. An effect of this is that it leads to lower GHG emissions from direct land use change. There is now also a cap on the amount of biofuels from food and feed crops that contribute to the renewable energy target. RED II also prohibits the use of ‘high iLUC risk crops’. At the moment, only oil palm is considered a high iLUC risk crop (EU, 2019). In contrast to the earlier version of the RED, the use of biomass from food and feed crops is limited. Because of this, iLUC is not included in the RED II carbon footprint calculations.

3.2 Carbon footprint calculations biobased plastics

The RED II methodology for carbon footprint calculations can be implemented for biobased plastics, but small adjustments will need to be made. Using the carbon footprint calculation to determine emission savings compared to a fossil reference is more difficult with biobased plastics than with biofuels. For biofuels there is a clear property to compare biobased with fossil fuels, the energetic value. There is no common property to compare all biobased plastics with a fossil reference. For drop-in plastics like PE and PP, the comparison could be made on the basis of weight of the polymer. For novel plastics with no clear fossil counterpart, the comparison is less clear-cut. This is further discussed in Section 4.1.

A benefit of using the RED II methodology is that biobased plastics and biofuels are evaluated in a similar way. For some cases, both biobased plastics and biofuels are produced from one feedstock. For example, in the production of bio-PP via bio-naphtha, can produce biofuels as well (Tähkämö et al., 2022). Using a consistent methodology for allocation keeps the results of the carbon footprint comparable. As RED II prescribes how to deal with by-products and how to allocate emissions to coproducts, results will be more normalized than what we found in Chapter 2.

Table 6 - Overview of main characteristics of carbon footprint calculations

	JRC	RED II [3]	This report
Product	Plastic	Renewable energy	Plastic
Functional unit	The function of the studied product	The energy content of the studied product	Amount of plastic
Comparison with fossil alternative	Based on the function	Based on the energy content	For drop-in: Based on the mass. For others: Based on the mass and corrected with replacement factor.
Reduction compared to fossil alternative	N/a	Percentage (depending on energy type and start op operations)	Absolute amount (e.g. 1 kg CO_2-eq./kg plastic)
System boundaries	Cradle-to-grave (includes EoL based on scenario)	Cradle-to-grave (includes emissions from use of fuel)	Cradle-to-gate (no EoL)
Biogenic CO_2	Biogenic CO_2 excluded	Biogenic CO_2 excluded	Biogenic CO_2 included
Allocation	Allocation avoided if possible by subdivision or system expansion, after this allocation based on physical property preferred	Energy allocation	Energy allocation
Direct LUC	dLUC included	dLUC included	dLUC incluced
Indirect LUC	iLUC excluded from calculation, but reported	iLUC excluded (high iLUC crops not allowed)	Multiple options, to be determined by policy makers
Impact categories	GHG + other PEF categories	GHG	GHG

3.3 Additional sustainability criteria feedstock

The sustainability criteria in RED II aim to limit the negative side effects that can take place as a result of the increased demand for biomass. Following these sustainability criteria will on one hand lower the carbon footprint of biobased plastics, but also keep a level playing field for the different applications of biomass. Most sustainability criteria of RED II are similar to the sustainability criteria for biobased resources published by the Dutch Ministry of Infrastructure and Water Management in 2021 (Ministerie van I&W, 2021).

3.4 Land use change in biobased plastics

To calculate the GHG impacts of direct land use changes, RED II refers to the commission decision with guidelines on the calculation of land carbon stock changes (EU, 2010).
The carbon footprint of direct land use change can be positive (contributing to the carbon footprint) if land use changes for example from forest to agriculture, or negative if marginalized land is used for agriculture. As the choice of land where biomass for biobased plastics will be cultivated influences the carbon footprint, a larger required carbon footprint reduction offers more incentive to keep direct land use change low or negative.

[3] Only the part of RED II that is focussed on biofuels, bioliquids and biomass fuels is included in this overview.

While RED II limits the use of feed and food crops, the sustainability criteria for biobased resources in the Netherlands does not set a limit. The reason iLUC is excluded from the carbon footprint calculation in RED II is the limit on food and feed crops. If the sustainability criteria for biobased resources are followed, attention should then be given to indirect land use change impacts. The main cause of iLUC is the production on agricultural lands that were previously used for food and feed. As the demand for food and feed does not decrease, it can be expected that new agricultural land will be made, partially on land with high carbon stocks. At the moment, many of the feasible production routes use food and feed crops such as sugar cane, sugar beet, maize or wheat. One option is to include the estimated iLUC emission factors provided in Annex VIII of RED II. These factors give an expected carbon footprint due to iLUC, based on the type of crop used. It is important to realise that these iLUC emission factors are based on weighted mean values of modelling different feedstocks and therefore have a high degree of uncertainty. Another option is to limit the use of food and feed crops, this would however limit the use of biomass.

Textbox 2 - Overview of options for dealing with iLUC

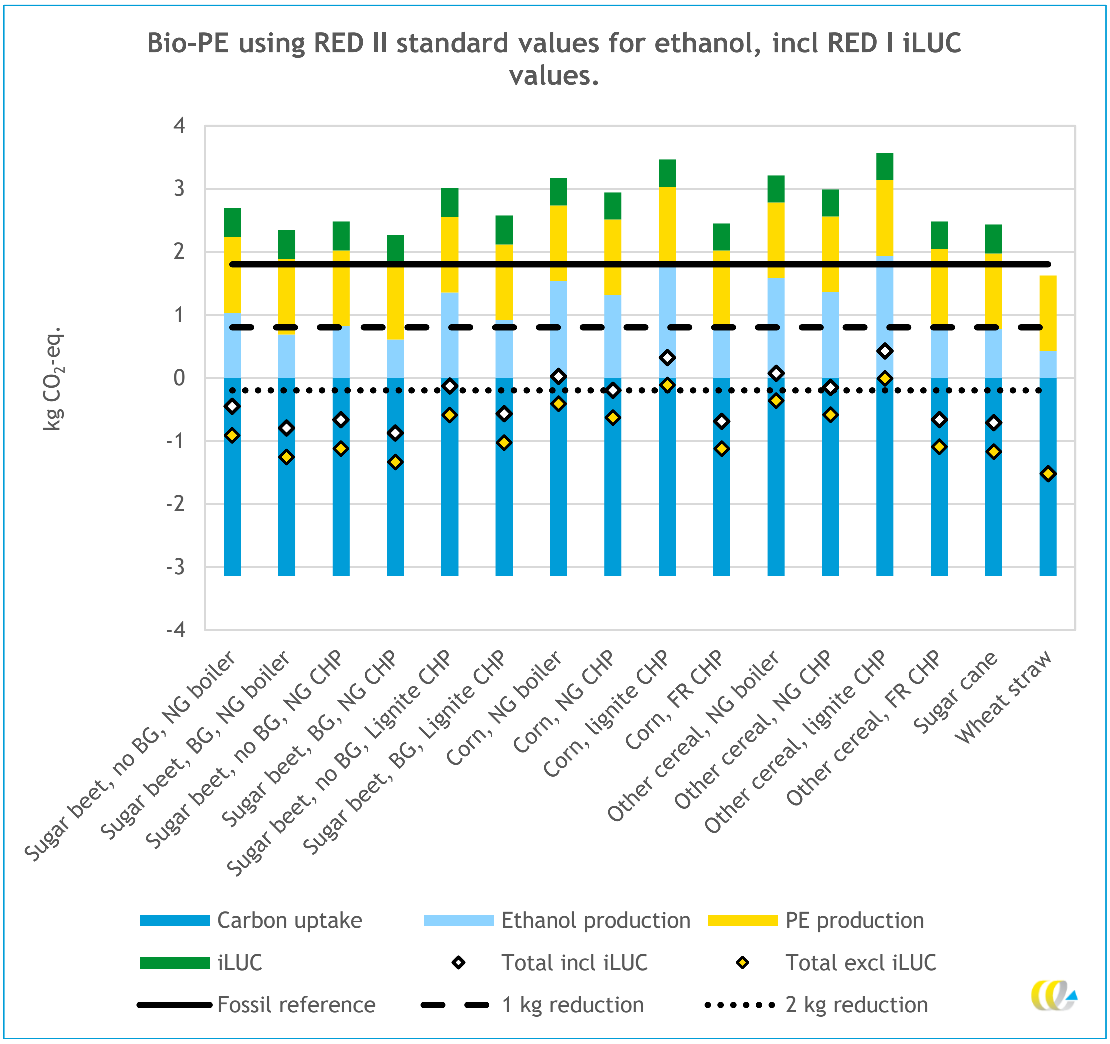
1. Limit the use of food and feed crops and do not account for iLUC:
   - this would be in line with RED II;
   - this would limit the production and use of bioplastics.
2. Do not limit the use of food and feed crops and account for iLUC:
   - this would avoid increase options for biobased plastics;
   - iLUC calculations are very uncertain as it is an indirect effect.
3. Do not limit the use of food and feed crops and do not account for iLUC:
   - it can be argued that the demand for biobased plastics is so low, that global iLUC effects will be small;
   - higher chance of promoting bioplastics that cause higher iLUC effects.

3.5 Example carbon footprint calculation bio-PE with RED II methodology/ values

It can be useful to know if a carbon footprint reduction could be expected when using the standard values given in RED II. As bio-PE is produced from ethanol and the RED II documentation provides carbon footprints of ethanol, we include a estimation of the carbon footprint of bio-PE using these values. The values given for ethanol differ per biomass feedstock. For most cases there is a further breakdown in source of heat for the type of process fuel used. For sugar beet ethanol, a distinction is made whether slop, which is a by-product from sugar production, is used to produce biogas. As a rough estimation for the carbon footprint of the conversion of ethanol into polyethylene 1.2 kg CO_2-eq./kg polymer is taken based on the values reported in Tsiropoulos et al. (2015). Direct land use change is assumed to be 0 for this comparison, which is the case when the previous land use is the same as in 2008. Indirect land use change (using the values of appendix VIII of RED II) is included in the analysis, but the results are presented both with and without iLUC.

Figure 6 shows the different carbon footprint results for the different feedstocks and processing options. If a carbon footprint reduction target of 1 kg is taken, all bio-PE options shown here can achieve this reduction. When the carbon footprint reduction target is set at 2 kg, some of the pathways will not achieve the target. Whether iLUC is included in the calculation or not, can be relevant for the conclusion whether certain pathways achieve the reduction or not.

Figure 6 - Carbon footprint of bio-PE when using RED II values for ethanol



Abbreviations used (no) BG = (no) biogas production from slop, NG = natural gas , CHP = Combined Heat and Power, FR = forest residue.

4 Additional discussion points

In addition to the topics directly linked to RED, biobased plastics present two additional, more complicated challenges for policymakers. Here we first discuss how to deal with novel biobased plastics (Section 4.1) and then focus on partly biobased plastics and blends (Section 4.2).

4.1 Novel biobased plastics

'Novel' biobased plastics are made of polymers that are not produced via a fossil route. This means they are made up of different molecules than the existing plastics, and have different technical properties. This distinguishes them from 'drop-in' biobased plastics, which are chemically identical to already-used fossil plastics.
Examples of novel biobased polymers include PLA, starch plastic blends, PEF and PHAs.

Fossil reference and replacement factor

The carbon footprint of drop-in biobased plastics can be directly compared to their fossil counterparts. Since they have the same chemical structure, they can replace each other on a same weight-basis. This is analogous to biofuels (e.g. in RED II), where all comparisons are made on the basis of the same energy content.

For novel biobased plastics, no chemical counterparts with identical properties are available. They may replace one fossil plastic in specific products, and another in other applications. Furthermore, when using these new plastics, products may need to be (partly) redesigned to account for differences in technical properties. For example, if a novel biobased plastics is stiff and strong, it may be possible to reduce a product's weight by making it thinner (compared to a previously used fossil plastic). Conversely, if a plastic has weaker properties more material may be required to meet the product's requirements.

The fossil reference and replacement factor (i.e. how much material is required) will therefore differ from application to application. To illustrate: because of its technical properties PLA is viewed as a replacement for PS, PE, PP or PET in the limited number of studies available. Depending on the product type, a higher or lower weight is required when using PLA instead of these fossil products. This is discussed in the box below. For other novel biobased polymers, less information on replacement factors is available.

Textbox 3 - Replacement factors for PLA

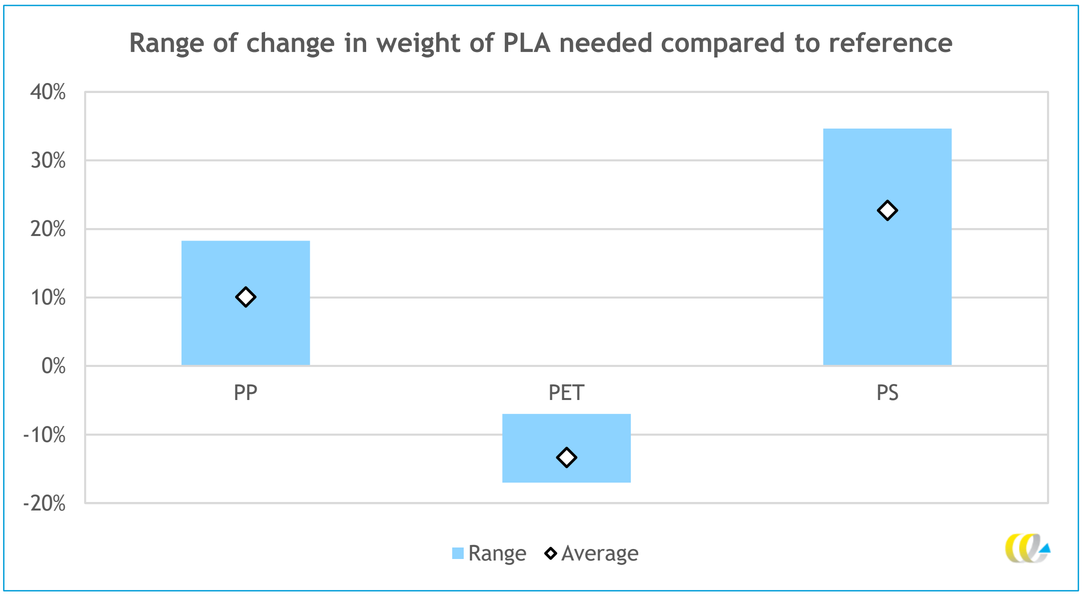
A range of different PLA replacement factors are reported in literature (i.e. indications of how much PLA is required to replace a fossil plastic in a given application):

- Compared to fossil PET, most cases show that less PLA is needed compared (COWI & University of Utrecht, 2018, Moretti et al., 2021, Americas, 2009, Nikoliae et al., 2015). The observed range is -17 to -7%.
- When PLA is used to replace fossil PP or PS, we see that a higher mass of polymer is needed. The range is 0 to +18% for PP (COWI & University of Utrecht, 2018, Moretti et al., 2021, Americas, 2009) and 0 to +35% for PS (COWI & University of Utrecht, 2018, Suwanmanee et al., 2010, Ingrao et al., 2015, Uihlein et al., 2008).

These replacement factors are shown in Figure 7. When interpreting the carbon footprint results of PLA, the replacement factors should be kept in mind. Figure 3 (carbon footprint of PLA and reference polymers per kg) shows that in three out of four studied cases, PLA has a carbon footprint between 0.5 and 1.2 kg CO_2-eq./kg, while the fossil references lie between 1.6 and 2.3 kg CO_2-eq./kg. If we assume the worst production route for PLA (the Biospri estimate at 1.2 kg CO_2-eq./kg) and the best reference for fossil plastics (1.6 kg CO_2-eq./kg for PP), the replacement factor would need to be >35% before the use of PLA would result in a higher carbon footprint than fossil plastics. Conversely, if less PLA is needed to replace a fossil plastic (as noted above: up to -17%), the carbon footprint benefits increase.

Nevertheless, it should be noted that the sample of studies with replacement factors is currently small and mostly focused on cups. Therefore, periodic review of replacement factors will be important for novel plastics.

Figure 7 - Observed range of weight of PLA compared to fossil PP, PET and PS



For PLA, a 1:1 replacement factor with fossil plastics represents a rough average of available information so far. It can be noted that other novel biobased plastics can have different replacement factors. For example, PEF plastic can offer better gas barrier properties than PET and could therefore be used to produce lighter bottles.

Different choices can also be made regarding which fossil reference to use for novel biobased plastics. For PLA, it is for instance possible to compare its carbon footprint to the average carbon footprint of PP, PET, PS and PE. Since the carbon footprints of these fossil products vary (see Figure 3), it is also possible to select a stricter benchmark by comparing the footprint of PLA only to PP.

To decrease these uncertainties, more information will need to be gathered from plastic producers/converters. It can be relevant to monitor trends in the market: in which products are novel biobased plastics applied, and which fossil plastics are they displacing?

Until such details are available, the effect of the uncertainties can be reduced by ensuring that a potential GHG emission reduction threshold applied to biobased plastics is sufficiently high. If biobased plastics need to achieve a GHG emission reduction of at least 1 kg CO_2-eq./kg compared to a fossil reference, we consider it unlikely that product weight variations will offset these benefits. For example, taking into account the carbon footprints of PLA and its fossil counterparts as well as their replacement factors (see box) shows that the expected GHG emission reduction can vary by about 35%. While the GHG emission benefit in some specific products may be smaller than 1 kg CO_2-eq./kg PLA, an overall carbon footprint reduction will likely be achieved.

End-of-life waste treatment options

For all plastics, the carbon footprint at end-of-life (EOL) strongly depends on the waste treatment route, e.g. incineration, landfilling or recycling. This is different from fuels which are combusted, releasing CO_2.

For all plastics, the optimal EOL scenario from a carbon footprint/circularity point of view is recycling. However, current recycling infrastructure is focused on the most-used fossil plastics and packaging applications. Novel biobased plastics are not yet sorted into separate fractions and recycled, because their market volumes are currently low. Nevertheless, prior research for PLA has shown that sorting and recycling can be economically viable if its market share increases, and that it results in lower GHG emissions (CE Delft, 2019).

This appears to be an 'environmental deadlock': novel biobased plastics need recycling infrastructure to enable the best environmental performance, but setting up recycling infrastructure requires sufficient market volume to become economical, but increasing market volume is most attractive if the plastics offer the best life-cycle environmental performance.

In the context of government support for biobased plastics based on their carbon footprint reductions, there are two available options:
1. Include the impact of the (current, average) EOL treatment in the carbon footprint calculations used to verify whether biobased plastics meet the GHG emission threshold. This adds complexity and creates a disadvantage for novel biobased plastics. However, it would result in more accurate carbon footprint reduction estimates for the current situation/recycling infrastructure.
2. Base GHG emission calculations on cradle-to-gate only, excluding the impact of EOL treatment. This option effectively assumes that there is no substantial GHG emission difference in the EOL treatment between the biobased option and its reference, representing a more optimised or future scenario. The biogenic carbon uptake in biobased plastics would need to be taken into account in the cradle-to-gate estimates to ensure fair comparisons.

In addition to the type of EOL treatment (e.g. incineration or recycling) that may be available to specific plastic types, it can be noted that the carbon content of novel biobased polymers also differs from their fossil counterparts, because they have a different chemical structure. If they are incinerated, different amounts of CO_2 may be released, depending on the biobased polymer and its fossil reference. However, this difference will decrease in importance as plastics recycling becomes more and more common.

Recommendations for novel biobased plastics

For novel biobased plastics, we consider the following approach appropriate:

- For all biobased plastics, including novel biobased plastics, the carbon footprint results should be compared to a specific petrochemical reference plastic. For drop-ins, this should be the fossil counterpart (i.e. the same polymer type). For each novel biobased plastic, evidence needs to be gathered on the most likely market substitutions.
- For PLA specifically, 1 kg PLA can, on average, be compared to 1 kg of fossil plastic (PS, PE, PET). Note however that the replacement factor will in practice differ per specific end-product. For other novel biobased plastics, more information needs to be gathered/evaluated as these are further developed and become eligible for government support.
- Leave out the end-of-life stage by making comparisons based on the cradle-to-gate scope (i.e. Option 2 above). Biogenic carbon uptake should be taken into account in this approach.

The recommendation to focus on the cradle-to-gate scope for biobased plastics deviates from the RED II, which uses a cradle-to-grave scope. Nevertheless, including the EOL for the carbon footprint calculations would increase the complexity of the calculations and may keep the environmental deadlock described above in place. In addition, the EOL of plastics (i.e. increasing recycling rates) can also be considered as part of broader policies on the circular economy, which can be viewed separately from policies aimed at supporting the market uptake of biobased plastics.

4.2 Partly-biobased plastics and blends

Some plastics can be partly biobased, meaning that a part of the carbon they contain is biogenic and a part is fossil. There are two potential causes for this situation:

1. Some plastics are made from two separate monomers, e.g. PET produced from PTA and EG. It is possible that one is made from biomass (e.g. ethanol → ethylene → EG) while the other is not.
2. Simpler plastics made from one monomer type can also be partly biobased. For example, bio-ethylene produced from ethanol can be mixed with fossil ethylene produced in steam crackers from crude oil.

In Case 1, the proportion between the monomers is fixed, since the polymer chain is always the same (EG-PTA-EG-PTA-EG-PTA-…). In Case 2, the proportion and thus the %bio-C can be varied on demand. Note that combinations of Case 1 and Case 2 are also possible. E.g. PET made with partly biobased EG made by blending bio-ethylene and fossil ethylene.

If Case 2 is allowed, there is an incentive to not use any more biobased monomers than necessary to meet the GHG emission reduction threshold.

If a mandatory target for the use of biobased and/or recycled plastics is implemented, only the biogenic part of partly-biobased plastics should be counted towards this target.

For partly biobased plastics, the GHG emission reduction threshold can be applied only to its biogenic part. This means that if 50% of a plastic's carbon is biogenic, that 50% should meet the GHG emission reduction target to be eligible for government support (e.g. 1 kg CO_2-eq./kg biobased plastic). Conversely, it can also be considered '50% eligible' for government support (counting for only 0.5 kg towards a mandatory target for using biobased

plastics, for instance). It can be noted that these calculations can also be done based on mass instead of carbon.
This solution can be applied to both types of partly-biobased plastics (Case 1 and Case 2 above). Plastic producers would be required to provide information on the share of biogenic carbon in their products, in line with the current reporting requirements for biofuels in the RED II.

5 Conclusions and recommendations

Biobased plastics that can substitute fossil-based plastics in the short to medium term include bio-PE, bio-PP, bio-PET and PLA. In a circular plastics system, biobased plastics can be a good supplement to recycled plastics, because the demand for plastic products exceeds the availability of recycled plastics. In addition, biobased plastics can have lower carbon footprints than fossil-based plastics.

If the government intends to stimulate the production and use of biobased plastics through policy, this support can be conditional on meeting sustainability criteria. As with renewable energy in the EU RED II, these criteria can include a minimum GHG emission reduction compared to a fossil alternative as well as rules on where/how the required biomass can be sourced. The purpose of the sustainability criteria is to only support those production chains that result in a GHG emission reduction and prevent negative environmental side-effects.

5.1 GHG emission reductions of biobased plastics

Carbon footprint estimates of different biobased plastics in literature vary. For each biobased plastic type, LCA studies report different results due to variations in:
- the value chain studied (i.e. 'real' differences);
- methodological factors.

Key drivers in the first category are the biomass feedstock used, associated dLUC and iLUC, useful application of coproducts and energy use of conversion processes. Important methodological differences between studies lie in the accounting of coproducts and whether and how LUC carbon footprints are accounted for. The large influence of methodological differences indicate the need for uniform methodology when evaluating biobased plastics and comparing environmental performance to fossil-based counterparts.

By harmonising the methodological differences between LCA studies for biobased plastics as far as possible, we can identify at least four value chains for these polymers that can realise a GHG emission reduction of at least 1 kg CO_2-eq. per kg of plastic compared to their fossil counterparts: under the condition that dLUC is low, the reduction can be reached for bio-PE from sugarcane and several bio-PP crops. Also for bio-PP from UCO, and some PLA value chains the required reduction is possible. For other routes, more research and/or further development may be necessary to meet a 1 kg CO_2-eq./kg reduction.

It can be noted that the number of LCA studies on biobased plastics is relatively limited. Another limitation of this assessment is that the additives in plastics are typically not taken into account in LCA studies. Finally, it should be noted that this evaluation only considered the carbon footprint of biobased plastics. Other environmental impact types are not considered here.

In Textbox 4 we also calculated how much percent lower the GHG emissions of the plastics from cradle to grave are with the 1 kg CO_2 emission reduction targets. Depending on the EOL situation (no recycling, 50% recycling or 100% recycling), the reduction percentages vary between 20 and 63%. For the future with a proposed recycling percentage near 100%, the CO_2 reduction of bioplastics will be about 50% when a 1 kg cCO_2 emission reduction target is implemented. With the current recycling rate of about 50% for packaging the GHG emission reduction with a 1 kg limit is about 35% which was also the starting limit for the biofuels policy.

Textbox 4 - How ambitious is a 1 kg reduction for biobased plastics?

The calculations proposed here use an absolute reduction of the carbon footprint in the production of biobased plastics. The RED II uses a percentual reduction in carbon footprint of bioenergy during their production and use. The required reductions started at 35% and have been gradually increased, up to 65% for transportation fuels.

In Table 7, we show the expected carbon footprint reduction of biobased plastics as a percentage over their entire (cradle-to-grave) lifecycle. This comparison is based on the carbon footprint for fossil plastics gathered in Chapter 2 (cradle-to-gate). For incineration it is assumed that all carbon is released as CO_2 at end-of-life, without energy recovery. For recycling a cut-off approach is taken, where no burden or credit is assigned to the product. For recycling, no CO_2 is released at end-of-life.
This simple/theoretical exercise aims to show the level of ambition of a 1 kg CO_2 reduction target for biobased plastics and can be compared to the reduction targets of the RED II (see Section 3.1 for the development of reduction targets).

Table 7 – Carbon footprint reductions when using 1 kg CO_2 emission reduction targets (EOL plastic is incinerated, 50% recycled and 50% incinerated, or fully recycled)

Biobased plastic	Carbon footprint reduction with 100% incineration	Carbon footprint reduction with 50% incineration and 50% recycling	Carbon footprint reduction with 100% recycling
Bio-PE	20%	30%	56%
Bio-PP	21%	32%	63%
Bio-PET	22%	30%	45%
PLA[1] (compared to PE)	47%	49%	56%
PLA[1] (compared to PP)	49%	52%	63%
PLA[1] (compared to PET)	32%	37%	45%
PLA[1] (compared to PS)	45%	44%	43%

[1)] Note that these comparisons assume that 1 kg PLA replaces 1 kg fossil plastic.

For the drop-in plastics, the carbon footprint reduction, under the assumption of 100% incineration, is around 20% for a 1 kg carbon footprint reduction (for 2 kg all percentages are doubled). As the carbon content of PLA is lower than the fossil counterparts, the percentual carbon footprint reduction is larger (at low recycling percentages) than the drop-in plastics under the assumption that 1 kg PLA replaces 1 kg fossil plastics.

5.2 A RED-based approach for biobased plastic

Since a number of biobased plastics show promising carbon footprint reductions, it is relevant to consider what a potential government support policy could look like. Parts of the production chains for biobased plastics are comparable or identical to those of renewable energy sources, as they use similar biomass sources as biofuels. Therefore, governmental policy support policy for biobased plastics could align with the revised EU Renewable Energy Directive (RED II) where possible. RED II uses a system of sustainability

criteria to determine which renewable energy routes are eligible to count towards EU Member States' targets.
To evaluate the carbon footprint reduction of biobased plastics and ensure compliance with sustainability criteria, a system like RED II for biofuels can also be applied to biobased plastics. Based on the discussion in Chapters 3 and 4, we propose the following approach:

Goal: minimum carbon footprint reduction
- The **goal of the carbon footprint methodology** is to evaluate whether the use of a biobased plastic results in a minimum GHG emission reduction compared to a fossil plastic reference.
- While RED II uses 1 MJ as a unit of comparison for renewable energy, we suggest using **1 kg of plastic** to compare biobased and fossil plastics.
- The **fossil plastic reference** for drop-in biobased plastics is their direct fossil counterpart, i.e. bio-PE should be compared to fossil PE, etc. For novel biobased plastics, multiple fossil references can be used, taking into account realistic replacement factors. This is further discussed below.
- The **minimum GHG emissions** reduction to be achieved by biobased plastic to be eligible for support can be determined by policymakers and vary over time. We suggest an initial minimum carbon footprint reduction of 1 kg CO_2-eq./kg biobased plastic. This reduction is in the same range as GHG emission reductions achieved by mechanical recycling of plastics (thus making a combined policy for the use of biobased or recycled plastic possible). In addition, the value is sufficiently high to limit the likelihood of biobased plastics inadvertently increasing overall emissions due to uncertainties in the calculations. Finally, this value is achievable for various production chains of biobased plastics (see Section 5.1). It can be noted that this approach differs from RED II, which uses a percentage-based reduction.
- For **partly biobased plastics**, the GHG emission reduction threshold can be applied only to its biogenic part. This means that if 50% of a plastic's carbon is biogenic, that 50% should meet the GHG emission reduction target to be eligible for government support (e.g. 1 kg CO_2-eq./kg biobased plastic). Conversely, it can also be considered '50% eligible' for government support (counting for only 0.5 kg towards a mandatory target for using biobased plastics, for instance).

Carbon footprint calculations:
- A carbon footprint methodology based on **life-cycle assessment (LCA)** is used to determine the carbon footprint reduction of biobased plastics. Worldwide GHG emissions should be included.
- For the main biobased plastics and the main biomass sources **default values** can be calculated/gathered from literature and these factors can be used by companies and governments for reporting. If companies have better data they will be allowed to use their own data if they can be checked by the government.
- The carbon footprint methodology is applied to a **specific production route** for a biobased plastic to evaluate its GHG emission reduction potential. The calculations should be specific for a combination of a plastic (polymer) type and biomass feedstock[4].
- A **cradle-to-factory gate scope** can be used, meaning the calculations are conducted for 1 kg of plastic granulate produced, ready for downstream conversion into end-products. This does not affect the results for drop-in biobased plastics, since downstream steps ('from gate to grave') are identical to their fossil counterparts. For novel biobased

[4] Other properties, such as the geographical location of the biomass sourcing or details of the production route (e.g. distinguishing between a bio-ethanol route to bio-PE or a bio-naphtha route to bio-PE) can be relevant but would increase complexity.

plastics with a different chemical composition than fossil plastics, the environmental impact of their end-of-life is likely to differ. This is further discussed below.
- Given the proposed cradle-to-factory gate scope, the **uptake of biogenic carbon** into the plastic should be taken into account. This value can be calculated based on the polymer structure and should be reported separately.
- Default **carbon footprint values** can be provided for specific parts of the production chains for common biomass feedstocks. Where possible, these values should be identical to those in RED II for biofuels.
- In line with RED II, **waste biomass** is considered to be available free of environmental burdens.
- If standard values for iLUC are included in the carbon footprint calculation, **biomass from food and feed crops** can be used for the production of biobased plastics.
- For **other aspects** of the carbon footprint calculations (e.g. allocation of impacts to co-products, dLUC estimates, data sources and reporting, …), the existing calculations in the RED II can be followed for biobased plastics.

Novel biobased plastics

Assessing the carbon footprint reductions of novel biobased plastics is more complicated than those of drop-in biobased plastics, since there is not always an evident fossil-based counterpart and the replacement factor is uncertain.

- For PLA specifically, 1 kg PLA can, on average, be compared to 1 kg of fossil plastic (PS, PE, PET). Note however that the replacement factor will in practice differ per specific end-product. For other novel biobased plastics, more information needs to be gathered/ evaluated as these are further developed and become eligible for government support.
- It is relevant to monitor market developments for novel biobased plastics to estimate and validate replacement factors. If it becomes apparent that a replacement factor is too optimistic or too conservative, it can be refined.

5.3 Discussion and next steps

The RED-based approach to support biobased plastics as proposed in Section 5.2 can be considered a starting point for governmental support for biobased plastics. However, there are a number of topics that can be debated.

Organising collection and sorting of novel biobased plastic for recycling

Firstly, the RED-based approach proposes to calculate the carbon footprints using a cradle-to-gate scope, and leave out the EOL treatment of the biobased plastics. This may be considered a benefit for novel biobased plastics, given that the (recycling) infrastructure required for optimal EOL treatment is not yet in place for novel biobased plastics. However, the proposed approach limits the complexity of the required LCA calculations. Nevertheless, it is important to ensure that recycling infrastructure for novel biobased plastics is also installed if their market shares increase. This should be considered when developing circular economy policies covering the EOL of plastics.

iLUC

Secondly, there is a decision to be made regarding the inclusion of food and feed crops, which are most prone to causing iLUC. If biobased plastics made from food and feed crops are included in the support scheme, a method to include effects from iLUC in the carbon footprint calculation is reasonable. As iLUC is an indirect effect and the quantification is uncertain, this would however increase the uncertainty of the carbon footprint calculations. The first years the iLUC factors calculated in the RED (1) can be used. Later on, these factors should be updated in a iLUC study focussing on biobased plastics.

Update minimum reduction of 1 kg over time

Thirdly, the RED-based approach includes a minimum carbon footprint reduction of 1 kg CO_2 per kg of biobased plastics. Depending on the type of policy support given to biobased plastics, it can be argued that a more ambitious CO_2 reduction target is appropriate. Another option to consider is that the minimum carbon footprint reduction can be increased over time. For biofuels and bioenergy, the RED targets on minimum carbon footprint reduction have increased over time.

Determine default values in dialogue with industry

Fourthly, default values for the GHG emissions occurring during specific (parts of) value chains should be established and documented. This is line with the RED II approach for bioenergy, which also supplies conservative default values for specific biomass feedstocks (see also Section 0). The default values for biobased plastics can be used as a starting point to validate which specific biobased plastic production chains meet the set carbon footprint reduction target. For other production routes or other biobased plastics, companies can be allowed to supply their own carbon footprint LCA calculations following the methodology outlined above. To establish default values, input from industry and dialogue on the results is useful.

Sustainability criteria and a minimum CO_2 reduction as part of a support scheme

Lastly, it can be noted that the approach suggested here can be implemented in different types of support schemes for biobased plastics, such as subsidies or a mandatory share of biobased content in new plastic products. These options can be combined with support for the use of recycled plastics. For example, a combined mandatory share of biobased and/or recycled content in new plastics products can be implemented. This would enable more ambitious targets on the share of ‘sustainably produced’ plastics and also provide plastics producers with a choice to use biobased plastics, recycled plastics, or both in their products. This can stimulate the use of biobased plastics in products where it is difficult to use recycled material (e.g. using bio-PE for foils), while using recycled plastic in products where a biobased alternative is more challenging (e.g. using mechanically or chemically recycled PET instead of 30% bio-PET).

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