Alternative carbon sources for plastics: Is circular bio-based plastic a solution?
πλαστικός

“Easy to process, shape and form”
• Moulded: Animal horns, ivory
• Direct use: natural resin for coating, wood, fibres

Industrial revolution in the 1800s: the rise of wood-based chemistry (modified cellulose)
• Celluloid obsoleted ivory in the 1870s
• Viscose invented in the 1890s as cotton and silk replacement

Irish horn spoon
Ca. 1650
National Museum of Ireland

In the first half of the 20th century...

First plastics film: cellophane (1912)

Henry Ford’s project of producing car parts out of soybeans (1920s-1940s)

- Late 1930s: world-wide large scale oil extraction
- 1930-1950: invention and commercialisation of PVC, PS, PE, Nylons
- 1947: PET patented
- 1950s: commercialisation of PET, LLDPE, HIPS, PP, PUR and epoxy resin
- Global annual plastics production in 1950s: ca. 2 Mt
Every year, about 350-400 million metric tonnes of synthetic polymers are produced globally.

- Plastics are convenient.
- Plastics are problematic.
- Can we live without plastic?

Guidehouse, 2019
Can we live without plastic? ......for a day?

"I had made 164 violations, by my count."
If not, what now?

- Refuse, re-use: reduce demand, reduce waste
- **Make better plastics.....better?**

Part of the puzzle piece - alternative carbon sources:
1. Use biogenic carbon: “bio-based”: BIOSPRI
2. Recycle the biogenic carbon: “circular biobased”: biobased PEF vs PET
Are bio-based plastics a solution?

What is “bioplastic”?

<table>
<thead>
<tr>
<th>Biodegradable*</th>
<th>Yes</th>
<th>PBAT</th>
<th>PBS</th>
<th>PCL</th>
<th>PVOH</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>PE, PP, PET, PUR, ABS…</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No (fossil fuel-based)</td>
<td>Bio-based PET</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Partially</td>
<td></td>
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</tr>
</tbody>
</table>

Bio-based PET

Bio-based PE, PP

Bio-based PA, PUR, PEF...

PLA (polylactic acid)

Starch plastics

*certified as ‘biodegradable’
Global production capacity 2019: 2.11 million metric tonnes

- Partially bio-based and non-biodegradable: e.g. bio-based PET
- Fossil fuel-based and biodegradable: e.g. PBAT and PBS
- Fully bio-based and non-biodegradable: e.g. Bio-based PE
  - Fully bio-based and biodegradable: e.g. PLA, PHA
  - Partially bio-based and biodegradable: e.g. Starch plastics

Compiled based on European Bioplastics (2021)
LCA bio-based plastics (1/2)
What we learned from the “classical LCAs” for innovative biobased plastics:

Compared to their petrochemical counterparts *:
- The established biobased systems often have lower cradle-to-gate GHG emissions:
  - If biogenic carbon removals are accounted as a direct credit (e.g. as defined in PAS 2050).
  - (bio)chemical conversion processes can be carbon-intensive.
  - Sensitive to the choice of allocation/multifunctionalities
- Biobased systems often lead to a higher impact on land and water – the tradeoffs are not always fully understood

* See Broeren et al (2017) DOI: 10.1002/bbb
LCA bio-based plastics (2/2)
What we did not learn from the “classical LCAs”:

What are the environmental impacts of innovative biobased systems, if

- the impacts of indirect land use changes are accounted for?
- the end-of-life impacts are included in the scope?
BIO-SPRI (2017-2019)

“Support to Research and Innovation Policy for Bio-based Products”
Goal of the LCA: “Provide science-based evidence to support policy decisions”

- Identify the key environmental hotspots of innovative bio-based plastics
- Compare the environmental impacts with the fossil fuel-based counterparts
Selection of the case studies

5 Criteria, 16 sub-criteria
- Market potential
- Promise for deployment
- Available LCA data
- Innovation
- Potential sustainability benefits

Seven case studies:
- Beverage bottles
- Horticultural clips
- Single-use drinking cups
- Single-use carrier bags
- Food packaging films
- Single-use cutlery
- Agricultural mulch films
Life Cycle Assessment

“Best framework for assessing the potential environmental impacts of products” (COM (2003)302)

Take PEFCR as the guidance (v.6.3, 2018)

Cradle to grave
Geographical: products sold, consumed and disposed of in Europe
Technological: established technologies
Temporal: Status-quo (2018), very near future
16 Impact assessment categories
Normalisation: EU 27 NF for 2010 (ILCD)
Weighting: JRC-EF (2018)

Beyond:
- Effects of land use changes
## Overview of the case studies in BIO-SPRI

<table>
<thead>
<tr>
<th>Case studies</th>
<th>Bio-based baseline</th>
<th>Bio-based alternatives</th>
<th>Reference system(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beverage bottles</td>
<td>30% bio-based PET</td>
<td>30% PET from EU ethanol (fictional)</td>
<td>PChemPET</td>
</tr>
<tr>
<td>Single-use drinking cups</td>
<td>PLA</td>
<td>PLA from EU maize (fictional) Bio-based PP from UCO</td>
<td>PET PP</td>
</tr>
<tr>
<td>Single-use cutlery</td>
<td>PLA</td>
<td>n/a</td>
<td>PS</td>
</tr>
<tr>
<td>Food packaging</td>
<td>PLA from EU maize (fictional) Bio-based PP from UCO</td>
<td>PP</td>
<td></td>
</tr>
<tr>
<td>Horticulture</td>
<td>Starch plastics</td>
<td>Starch sourced from potato waste</td>
<td>PP</td>
</tr>
<tr>
<td>Agricultural</td>
<td>Starch plastics</td>
<td>n/a</td>
<td>LDPE</td>
</tr>
<tr>
<td>Single-use carrier bags</td>
<td>Bio-based LDPE</td>
<td></td>
<td>LDPE</td>
</tr>
</tbody>
</table>

Status-quo average technology mix; primary data from industry.

PET=polyethylene terephthalate; PLA=Polylactic acid, UCO=Used cooking oil, PP=polypropylene, PS=polystyrene, LDPE=low-density polyethylene
PChem=petrochemical
# End-of-life challenges

<table>
<thead>
<tr>
<th>Case studies (baseline vs. ref.)</th>
<th>(Est.) Current EOL for the bio-based (av. EU mix)</th>
<th>Intended EOL</th>
<th>Current EOL PChem reference (av. EU mix)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beverage bottles (bio-based vs. Pchem. PET)</td>
<td>Recycling, MSWI and landfilling</td>
<td>Recycling</td>
<td>Recycling, MSWI and landfilling *</td>
</tr>
<tr>
<td>Single-use drinking cups (PLA vs. PET, PP)</td>
<td>Recycling, Composting MSWI, landfilling</td>
<td>Recycling and composting</td>
<td></td>
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<tr>
<td>Single-use cutlery (PLA vs. PS)</td>
<td>Recycling, Composting mswi, landfilling</td>
<td>Recycling and composting</td>
<td></td>
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<tr>
<td>Food packaging films (PLA vs. PP)</td>
<td>In-situ soil biodegradation</td>
<td>In-situ soil biodegradation</td>
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<tr>
<td>Horticultural clips (Starch plastics vs. PP)</td>
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<tr>
<td>Agricultural mulch films (Starch plastics vs. LDPE)</td>
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<tr>
<td>Single-use carrier bags (Starch plastics vs. LDPE)</td>
<td>Composting, MSWI and landfilling</td>
<td>Composting</td>
<td></td>
</tr>
</tbody>
</table>

*Ratios are different based on different applications*
Land Use Changes

• DLUC Modelled in accordance with the PEFCR Guidance (v.6.3); consistent with PAS2050 requirements.
• ILUC modelled separately based on a *deterministic method* adapted for this study.
Indirect land use changes: a deterministic model

1. Establish plausible cause-effect chain events, understanding of service displaced and reacting supply.
2. Determine expansion/intensification based on past time-series data (e.g. FAO).
3. Calculate impacts resulted from expansion
4. Calculate impacts resulted from intensification

* GCB Bioenergy 8, 690–706. (2016); Slide credit Dr. Lorie Hamelin
Cradle-to-grave impacts of seven bio-based products, normalised and weighted results without LUC effects, comparing EoL EU mix with intended EoL

<table>
<thead>
<tr>
<th>Product</th>
<th>Normalised and Weighted Results (baseline with mix EoL = 100%)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Biomass production</td>
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<tr>
<td>Beverage bottles</td>
<td></td>
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<tr>
<td>With EoL EU mix</td>
<td></td>
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<tr>
<td>With Intended EoL</td>
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<tr>
<td>Clips*</td>
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<tr>
<td>With EoL EU mix</td>
<td></td>
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<tr>
<td>With Intended EoL</td>
<td></td>
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<tr>
<td>Single-use cups</td>
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<tr>
<td>With EoL EU mix</td>
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<tr>
<td>With Intended EoL</td>
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<td>Single-use cutlery</td>
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<tr>
<td>With EoL EU mix</td>
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<tr>
<td>With Intended EoL</td>
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<tr>
<td>Mulch films*</td>
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<tr>
<td>With EoL EU mix</td>
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<tr>
<td>With Intended EoL</td>
<td></td>
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<tr>
<td>Packaging films</td>
<td></td>
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<tr>
<td>With EoL EU mix</td>
<td></td>
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<tr>
<td>With Intended EoL</td>
<td></td>
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<tr>
<td>Carrier bags</td>
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</tbody>
</table>

* For case studies Clips and Mulch films, the EoL mix is assumed the same as the Intended EoL, which is in-situ soil biodegradation.
Comparing with the petrochemicals...

Out of 16 PEFCR impact categories, only *five* are recommended to be used for comparison. Cradle to grave baseline results excluding LUC effects, environmental impact reduction on median values (with ranges)

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>Savings* with EoL EU mix</th>
<th>Savings* with intended EoL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate Change (GWP 100a)</td>
<td>-11% (‐81% to 38%)</td>
<td>-65% (‐87% to ‐14%)</td>
</tr>
<tr>
<td>Abiotic depletion (fossil fuels)</td>
<td>-45% (‐72% to ‐7%)</td>
<td>-46% (‐72% to ‐3%)</td>
</tr>
<tr>
<td>Particulate matter</td>
<td>94% (2% to 603%)</td>
<td>100% (‐2% to 597%)</td>
</tr>
<tr>
<td>Photochemical ozone formation</td>
<td>23% (±79%)</td>
<td>12% (‐79% to 58%)</td>
</tr>
<tr>
<td>Terrestrial eutrophication</td>
<td>70% (‐77% to 143%)</td>
<td>66% (‐77% to 129%)</td>
</tr>
</tbody>
</table>

*Median savings based on the eight comparisons of the seven case studies (two comparisons were made for single-use cups).
Land use change in BIOSPRI project

Land use change will lead to marginal increases in impacts:
• 14% for climate change
• 10% for photochemical ozone formation
• 0.01-2.4% for all other impact categories

Simplified: the shorter the production chain, the stronger effect observed from LUC
Land use impacts are more complex than the current LCIA models can offer: impact of “carbon removals”

For perennial crops and woody biomass, land use and land use changes disturb:

- Carbon balances
  - Direct carbon balance change: biomass growth
  - Indirect carbon balance change: soil organic carbon content
- Nitrogen balances
- Available fresh water
- Biodiversity

Spatial and temporal explicit models are urgently needed for LCA
If not, what now?

- Refuse, re-use: reduce demand, reduce waste
- Make better plastics.....better?

Part of the puzzle piece - alternative carbon sources:
1. Use biogenic carbon: “bio-based”
2. Recycle the biogenic carbon: “circular biobased”
In the NL, about 2 Mt of plastic waste was reported in 2017 (including import)

Domestic generated (70%) and Imported (30%)

Over 40% (ca. 842 kt) was sent for recycling, of which
- 648 kt was sent for recycling in the NL, and
- 194 kt sent to recycling outside of NL

About 30% (ca. 570 kt) was incinerated with energy recovery
- Excluding imported RDF

Leaked into the environment:
- 0.02-0.07 kt on the NL beaches and river banks
- 4-13 kt leaked foreign environment

Lobelle et al. Knowns and unknowns of plastic waste flows in the Netherlands (forthcoming)
In Europe, PET is the most recycled polymer

About 25% of the PET market demand is met by rPET in EU27+UK
- Established deposit return systems in many European countries: high collection rate (65-96%)
- Heavier than water
- Improved packaging design
- Polyester
One of the bio-based alternative of PET is PEF, polyethylene furanoate. Sugar-based. First commercial production in 2024. Compared to PET:

- Good gas barrier (esp. O2 and CO2)
- Can be recycled similarly to PET
- Published LCA shows potential GHG reduction compared to PET (33-55% reduction depending on the scope)

But:

- Little known about the differences between MR and CR.
- Does recycling of PEF offers environmental benefits?
- How circularity is assessed and can it be reflected by LCA for bio-based plastics with multiple recycling trips?
Circularity does not always lead to Sustainability.
Carbon balance of the plastic sector over the entire life cycle: the PLAIA model

The Plastic Integrated Assessment model (Stegmann et al. 2022):
- Combining LCA with IAM
- A CBE combining recycling with higher biomass use could ultimately turn the sector into a net carbon sink.
- However, this involves continued reliance on primary feedstock.

Stegmann et al. (2022) Nature. DOI: 10.1038/s41586-022-05422-5
Circular biobased plastics - Some reflections from LCA practitioner’s view (1/2)

- Align both circularity performance and environmental sustainability*
- Blurred system boundaries: using waste as input
- Consequential LCA needed to understand the full implications of biobased circular economy:
  - System expansion/enlargement in combination with high-resolution MFA: for both the challenges in land use/changes and recycling
  - Spatial and temporal explicit assessment for land use impacts
  - Do not limit to GHG emissions, focus on the environmental trade-offs
Circular biobased plastics: Some reflections from LCA practitioner’s view (2/2)

- Small quantity compared to the total produced, but the impact can be substantial
- Cause-effect models not yet established
- Lacking fundamental understanding:
  - The effects on ecosystem and human health.
  - Their fates in air, soil, water and in the ocean, e.g. microplastics and nanoplastics – and what can they carry?
  - In the ocean: climate change will in return affect how plastics will travel.
- Impacts of plastic additives are worrying.
Are we too technocentric?

- Refuse, re-use: reduce demand, reduce waste
- Make better plastics.....better?

Part of the puzzle piece - alternative carbon sources:
1. Use biogenic carbon: “bio-based”
2. Recycle the biogenic carbon: “circular biobased”

Do we fully understand circular bio-based systems?

![Diagram showing the circular bio-based system with CO₂ emissions to atmosphere and processes like extraction, materials production, processing, consumption, and waste management.](image)

CO₂ Emissions to Atmosphere

- Extraction
- Materials Production
- Processing
- Consumption
- Waste Management

Natural resources
- Recycling and reuse

Cement, lime, Ammonia, Plastics

Waste