Circular by design: taking control at end-of-life

Webinar Renewable Chemicals & Materials

Dr. Daan S. van Es, October 11th 2021

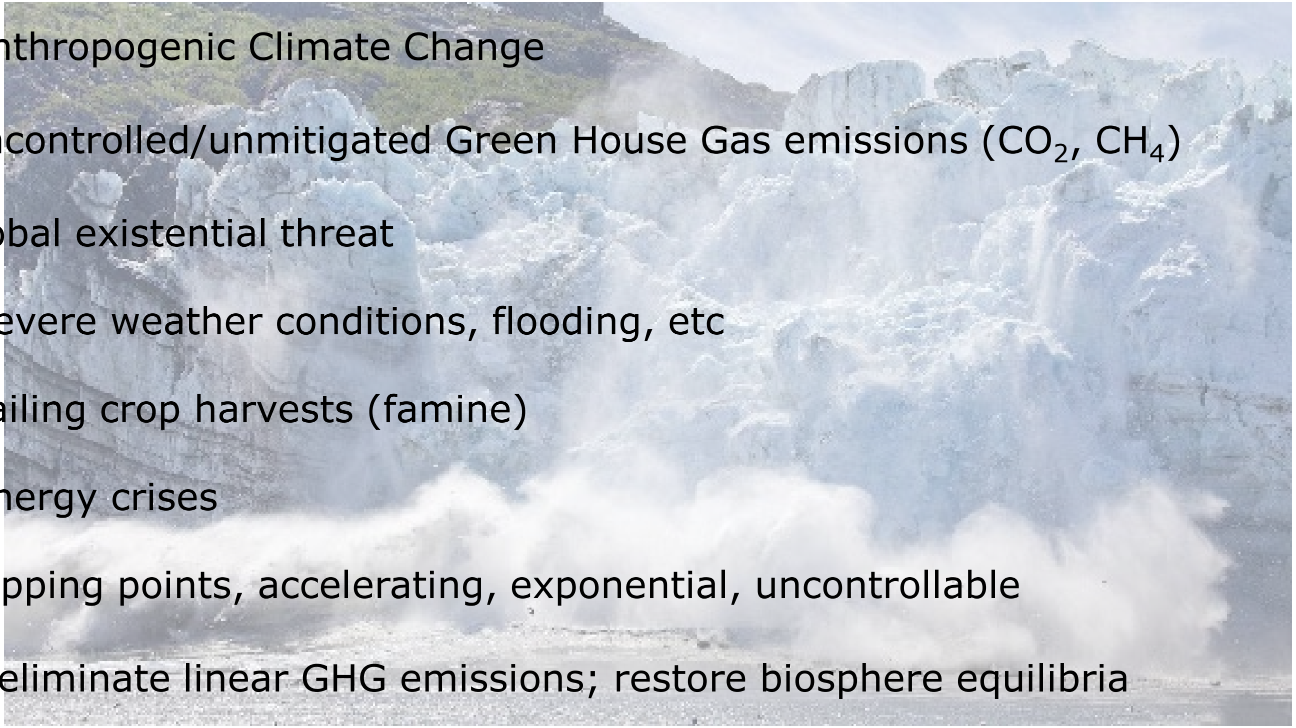
WAGENINGEN
UNIVERSITY & RESEARCH

Outline

- Current situation
- From linear to circular
- WUR model on circular chemicals & materials
- Examples for circular materials; PE vs PLA
- Conclusions

Current situation

Current situation



1. Crisis: Anthropogenic Climate Change

- Cause: uncontrolled/unmitigated Green House Gas emissions (CO_2, CH_4)
- Effect: global existential threat
  - Severe weather conditions, flooding, etc
  - Failing crop harvests (famine)
  - Energy crises
  - Tipping points, accelerating, exponential, uncontrollable
- Solution: eliminate linear GHG emissions; restore biosphere equilibria

Current situation

2. Crisis: Anthropogenic Persistent & Accumulating global pollution

- Cause: uncontrolled/unmitigated environmental emissions of persistent chemicals and materials (e.g. PFAS, HCFCs, nano-plastics, plastic soup)
- Effect: global existential threat, e.g.
    - (eco)Toxicity
    - Decreasing biodiversity
- Solution: phase out of ‘forever’ chemicals and materials; restore biosphere equilibria

From Linear to Circular

From linear to circular

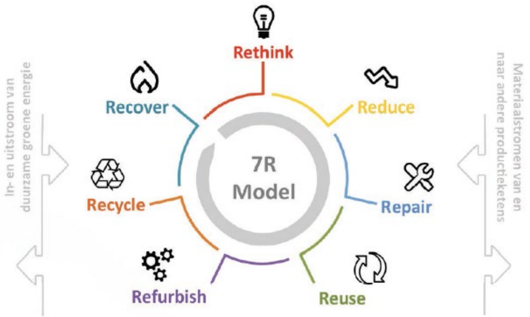
- Current production; cradle to gate/grave
    1. Low cost (cradle tot gate, costs non-inclusive)
    2. High performance (strength, durability, weight, etc) Now overdesigned?
    3. No/few concern(s) about End-of-Life scenarios
- Circular production; cradle to cradle
    1. EoL options should be clear; licence to produce
    2. Costs should include EoL, EPR
    3. Performance should be related to overall circularity
        - Sometimes less is better?

Designing a Circular Carbon Economy

Needed: A new sustainable, circular economy

1. Keep what works (time is running out) ☑
    - Condensation polymers vs polyolefins
    - Also consider inter-material exchange: paper vs plastic, wood vs steel, glass vs PET
2. Change what is needed
    - Linear non-renewable feedstock use (fossil feedstocks)
    - Linear waste generation (fossil based GHG, chemicals and materials emissions)
    - Close resource loops (reuse, repair, recycle, recover) ☑

Designing a Circular Carbon Economy



R-ladders – e.g. 7R Model (Royal HaskoningDHV)

- Reuse, Repair/Refurbish, Recycle; cascading ☑
  - Limit energy demand, limit resource losses
- Recover: energy reclaim: not a good long-term choice! ☒
  - Recover C: CCS+U; CHP -> bonus; focus on controlling carbon cycles
- Rethink & Reduce: excellent; disruptive, out-of-the-box, paradigm shift ☑
  - Prevent linear extrapolation of current situation
  - Back-casting from desired ideal situation

Transition(s) towards a Circular Economy

Note: Simultaneous interacting transitions as part of transition to circularity

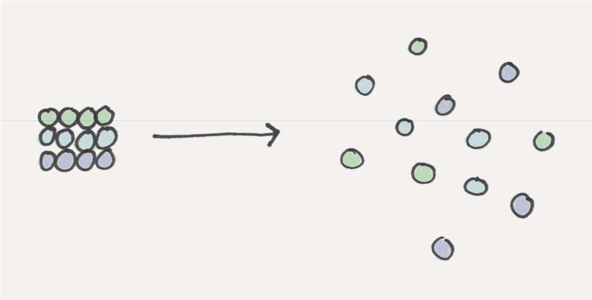
- **Renewable energy** transition: zero-net emissions technologies
    - Also driven by desire for energy independence & security
- **Circular agriculture** transition: save biodiversity, prevent soil degradation
- **Protein transition**: reduce GHG emissions, secure global food accessibility
- **Renewable chemicals** and **materials** transition
    - Move from fossil/linear- to renewable feedstocks
    - Control resource cycles; prevent losses
        - Don’t forget industrial renewable energy transition…

Circular carbon based chemicals and materials

Focus of this presentation: Carbon based chemicals and materials

- Enormous complexity and variety: excellent for functionality & performance
    - Detrimental for recycling and **control**
- Very large scale
    - » 500 million ton/a (and growing): (point)sources?
- Ideally: **Control**/limit
    - Uncontrolled emissions of GHG (not only CO_2, but also CH_4!), toxic substances, persistent chemicals and materials
    - Loss of feedstocks (500 Mt/a virgin renewable feedstocks?)

Control vs Reality

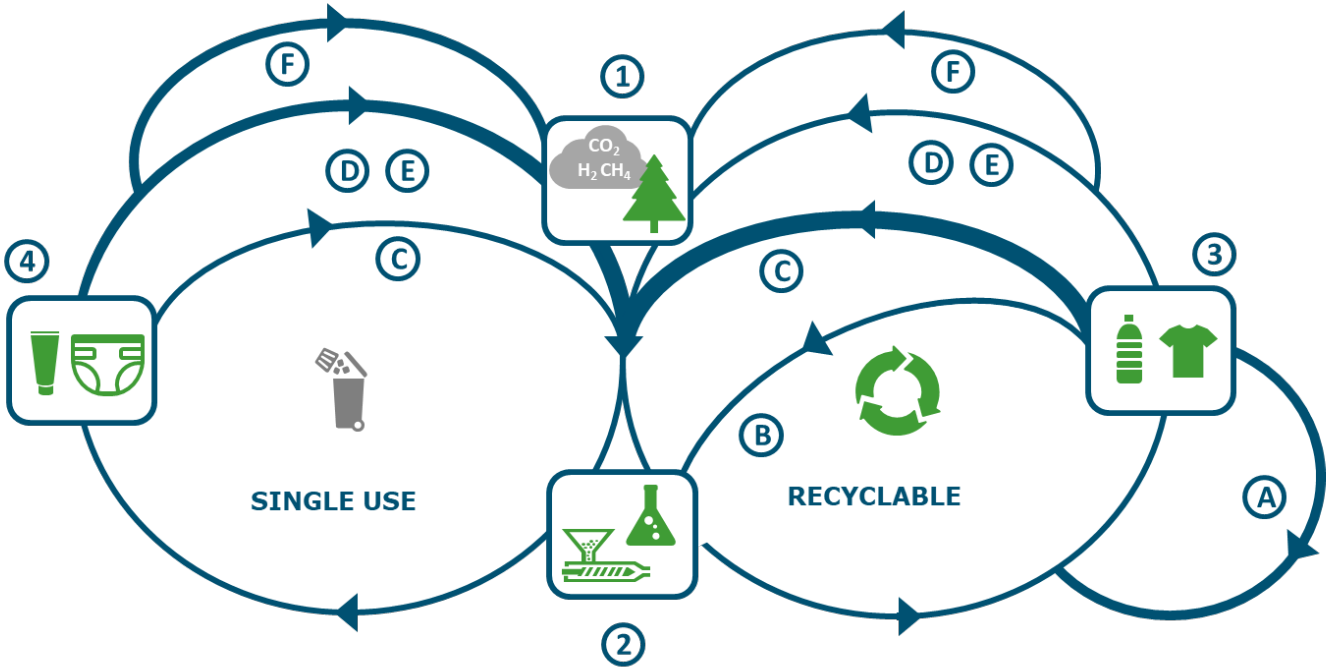


Second law of thermodynamics

- Entropy: a natural process runs only in one sense, and is not reversible
- In other words without the input of energy (work) a system tends to increase its entropy ("chaos")
    - Chemicals and materials degrade (abrasion, hydrolysis, oxidation, thermal/photo degradation, biodegradation, etc)
    - Chemicals and materials disperse (littering, leakage, leaching, etc)
- Full control is an illusion; yet reduced complexity helps

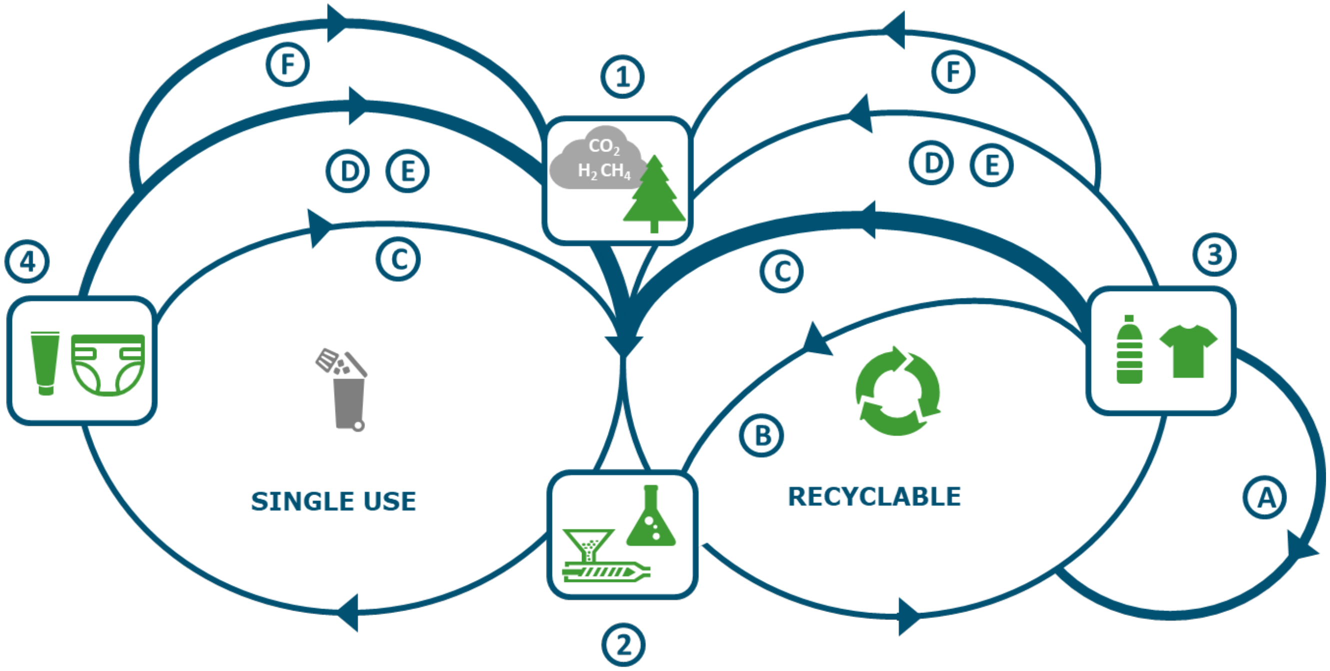
WUR Model for circular materials and chemicals

(work in progress)



In a circular carbon economy:

- All feedstocks (and energy) are renewable ①
- All products are either single use or (potentially) recyclable



Single use products (4)

- EoL - Disperse, complex, contaminated, toxic
- Focus on long cascading carbon cycles

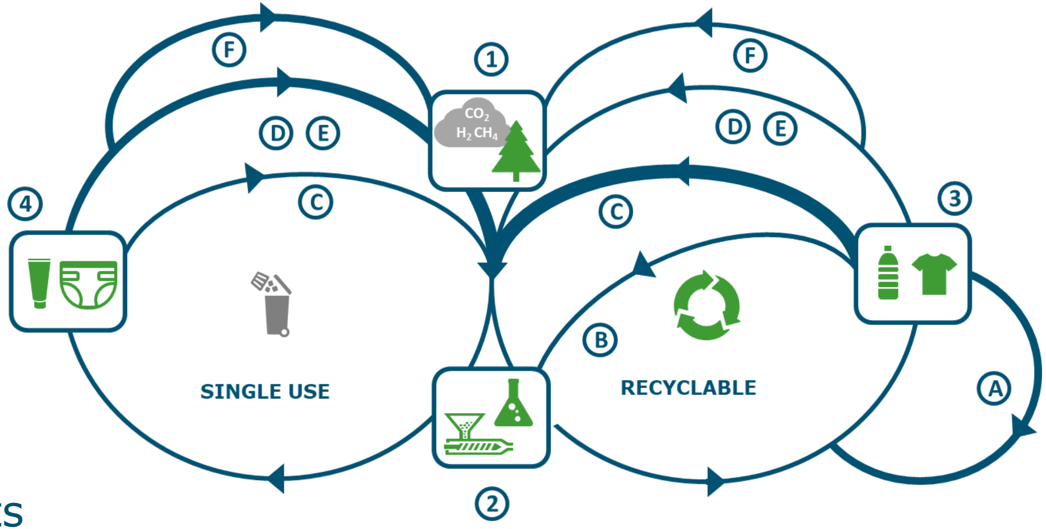
(C) Chemical recycling if possible

(D) Digestion (funnel to CO_2/CH_4)

(E) Incineration (sanitise, funnel to CO_2)

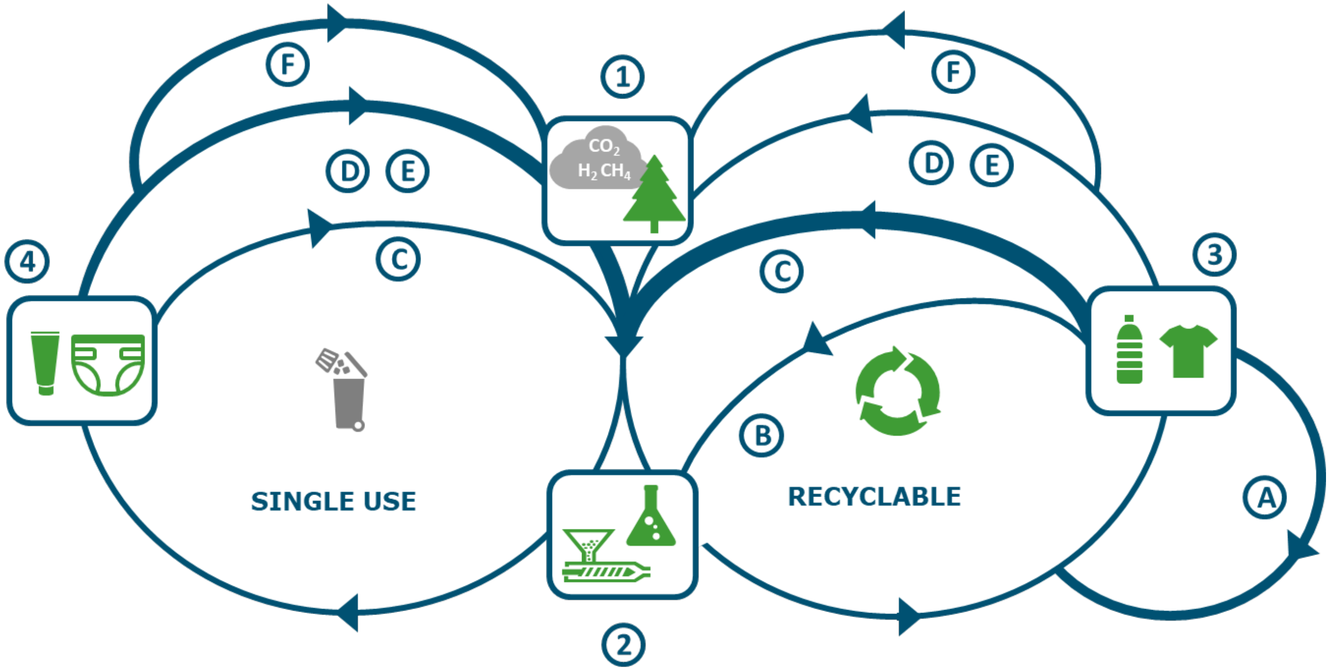
(F) Biodegradation (prevent persistence)

WAGENINGEN UNIVERSITY & RESEARCH



Single use products

- Complexity possible (H&PC formulations, CASE, hygiene products)
- Funnel complex/contaminated to C1 resources with known/new technology
- Control required at EoL; waste collection, waste water treatment, etc.
- Sustainable & <u>selective</u> C1 conversion methods (fermentation, electrochem, etc)

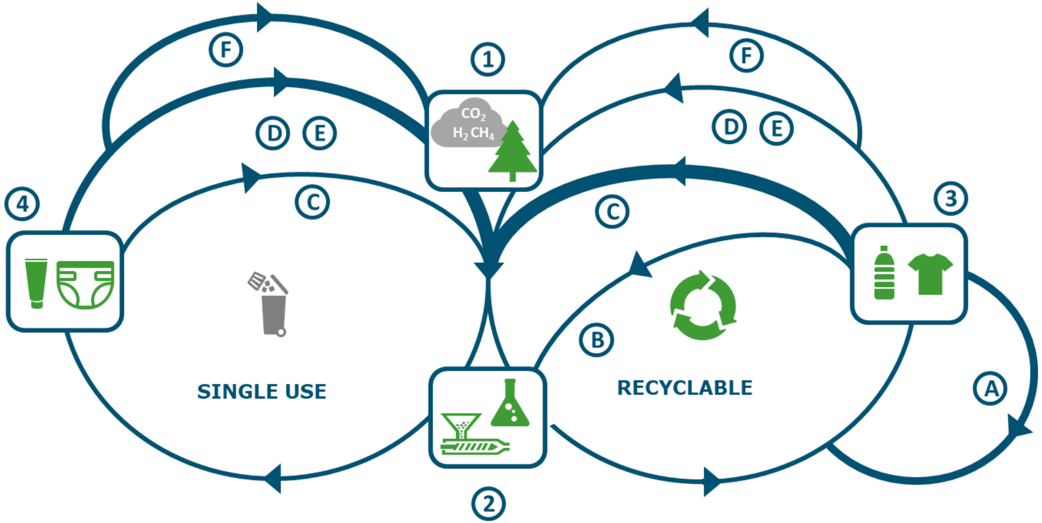


Recyclable products ③

- EoL - Concentrated, simple, deconstructable
- Focus on short cascading carbon cycles

Ⓐ Reuse
Ⓑ Mechanical recycling
Ⓒ Chemical recycling
Ⓓ Digestion
Ⓔ Incineration
Ⓕ Biodegradation

WAGENINGEN UNIVERSITY & RESEARCH



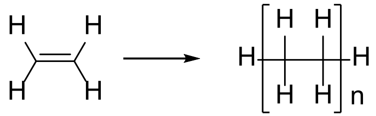
Recyclable products

- Limit complexity; ease Collection & Sorting; increase concentration
- Mechanical recycling options limited for materials (degradation, contamination)
- Chemical recycling required to retrieve carbon and retain energy
- Most important variable: selective deconstruction and efficient DSP

Examples for circular materials
PE vs PLA
An exercise for discussion

(work in progress)

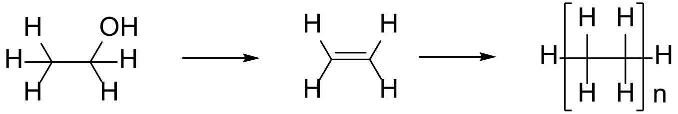
Example: PE – current situation



- PE -> ethylene: >200,000 kt/a (www.statista.com)
    - Many other outlets for ethylene: PVC, EO, EG, PS, LAO, etc.
- Many different grades of PE: LLDPE, HDPE, UHMWPE, etc.
- Currently majority of fossil based ethylene via steam cracking (naphta or ethane)
    - 850°C: 1-1.6 tons CO_2 emission per ton of ethylene
    - Selectivity from naphta 25-35 wt% (+15wt% propylene)*
    - Selectivity from ethane 53 wt% (70% conversion)*
- Cost-efficient due to mega-scale; 1 ton ethylene requires 3-4 tons of naphta

* source TechnipFMC

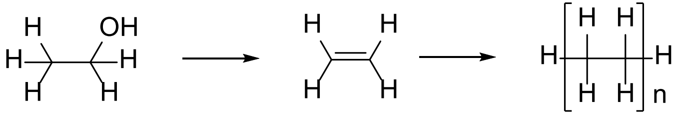
Example: renewable PE?



Renewable ethylene

- SOTA: Fermentation of glucose to bioethanol -> dehydration to ethylene
    - Selectivity: 1 glucose -> 2 ethanol + 2 CO2 -> 66% carbon efficient
    - 1 ton of glucose yields 450-500 kg ethanol
    - 1 ton of ethanol yields approx. 1 ton of CO2
- Ethanol dehydration to ethylene
    - 300-500 °C; Selectivity 95-99% at 89-99% conversion
    - 1 ton of ethylene requires 1.64 tons of ethanol
- Overall: 1 ton of bio-ethylene requires 3.2 tons of glucose

Example: renewable PE?



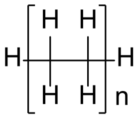
Current global bioethanol production approx. 80,000 kt

- 80,000 kt ethanol -> 61,000 kt ethylene = 31% of current fossil production
- Bioethanol production by fermentation is mature and scalable

Alternative routes to Renewable Ethylene

- Fermentation of CO_x gas to ethanol
  - Syngas (CO/H_2) to ethanol, industrial e.g. 80 kt plant by Lanzatech
  - CO_2 + H_2 to ethanol, low TRL level
- Direct electrochemical reduction of CO_2, low TRL level
- Biomass gasification/combustion + CCU + renewable H2

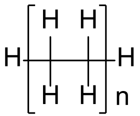
Example: circular PE?



PE End-of-Life scenarios

- Mechanical recycling: challenging due to separation of (incompatible) grades from mixed polyolefin waste
- Chemical depolymerisation:
    - Current practice
        - Pyrolysis (700-900°C): traditional focus on liquid fuel
        - Low selectivity to ethylene (30-40%)
    - Potential technology: gasification/combustion followed by fermentation or electrochem; hydrocracking to methane; possible yet low TRL

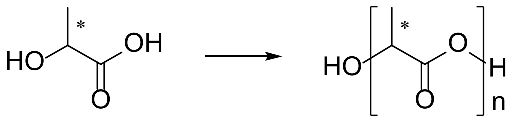
Example: circular PE?

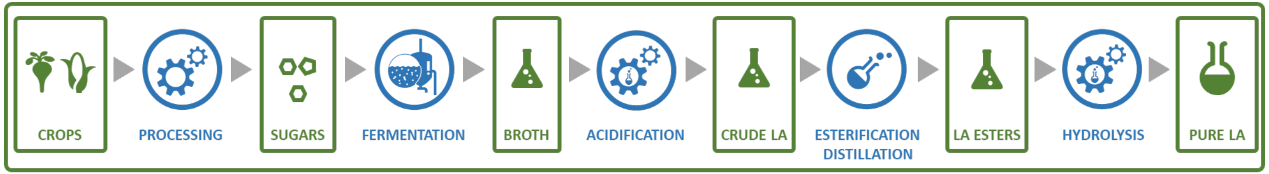


PE End-of-Life scenarios

- Biodegradability of PE is extremely low
    - Littering -> environmental persistence
- Combustion (waste incineration); partial energy recovery
    - Note: 1 ton of PE (or general polyolefin) generates 3.1 tons of CO_2
- Landfill: Undesirable? -> uncontrolled emissions e.g. CO_2 and CH_4
    - Storing biologically inert polyolefins reduces CO_2 emissions
        - Renewable polyolefins -> condensed carbon sequestration
        - Out of the box solution?

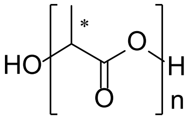
Example: circular PLA?





- Lactic acid (LA); almost exclusively from sugar fermentation; approx. > 1,000 kton/a
- Polylactic acid (PLA) from LA; approx. 500 kt/a, typically in 100-150 kt plants
  - Technology proven and scalable
- Industrial LA yields are typically 900 kg LA per ton of glucose
  - Very C-efficient and selective

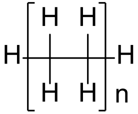
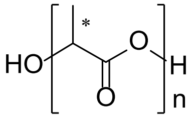
Example: circular PLA?



PLA End-of-Life?

- PLA is mechanically recyclable
- PLA can be chemically recycled via
  - Solvolysis to lactic acid (esters): >98%, industrial practice
  - Thermolysis to lactide: 50-80%, low TRL
- PLA is not readily biodegradable (though ultimately biodeg, and biocompatible): durable products possible, yet not persistent
- Biodegradable under controlled industrial conditions (e.g. anaerobic digester)

Example: (bio)PE vs PLA

(bio)PE 		PLA 
Industrial: very large scale		Industrial: large scale
Renewable: potentially		Renewable: yes
Steps from glucose: 3		Steps from glucose: 3
1 ton PE -> 3.2 ton glucose	<- Production ->	1 ton PLA -> 1.1 ton glucose
Biodeg: No	<- EoL->	Biodeg: yes (not readily)
ChemRec: <40% ethylene	<- EoL->	ChemRec: >90% LA
Incineration: 3.1t CO_2/tPE	<- EoL->	Incineration: 1.8t CO_2/tPLA

WAGENINGEN
UNIVERSITY & RESEARCH

Example: (bio)PE vs PLA

Preliminary conclusions from comparison

- Use glucose as feedstock for (P)LA (more efficient C-use)
- Identify which PE applications can be substituted with PLA
- Design full scale circular system for PLA (replace part polyolefins, part PET)
- Use C1 stream from biomass for ethanol -> ethylene
- Develop more selective ChemRec processes for (bio)PE; until then sequester, don’t incinerate
- Part of on-going internal WUR project (TEE and early stage LCA)

Conclusions

- The definitions and concepts of circularity are still developing and improving
    - Note: 100% recycling is impossible
- Performance of a substance or material should include circularity
    - Resource renewability and efficiency
    - Carbon footprint (i.e. selectivity and sustainability in production)
    - Closing carbon cycles at EoL
    - Control over EoL (e.g. emission control and environmental half-life)
- All future chemicals and materials (existing and new) should be designed for circular

Acknowledgements

All colleagues from KB3B-1 project

This research was funded by the Knowledge Base programme “Towards a circular and climate positive society” of Wageningen University & Research (WUR), in the project “Biobased materials and chemicals for relieving and replacing the fossil feedstock system” (KB-34-010-001). The WUR Knowledge Base programme is financed by the Dutch Ministry of Agriculture, Nature and Food Quality.