# 5.6 Sustainability of Polymer Materials


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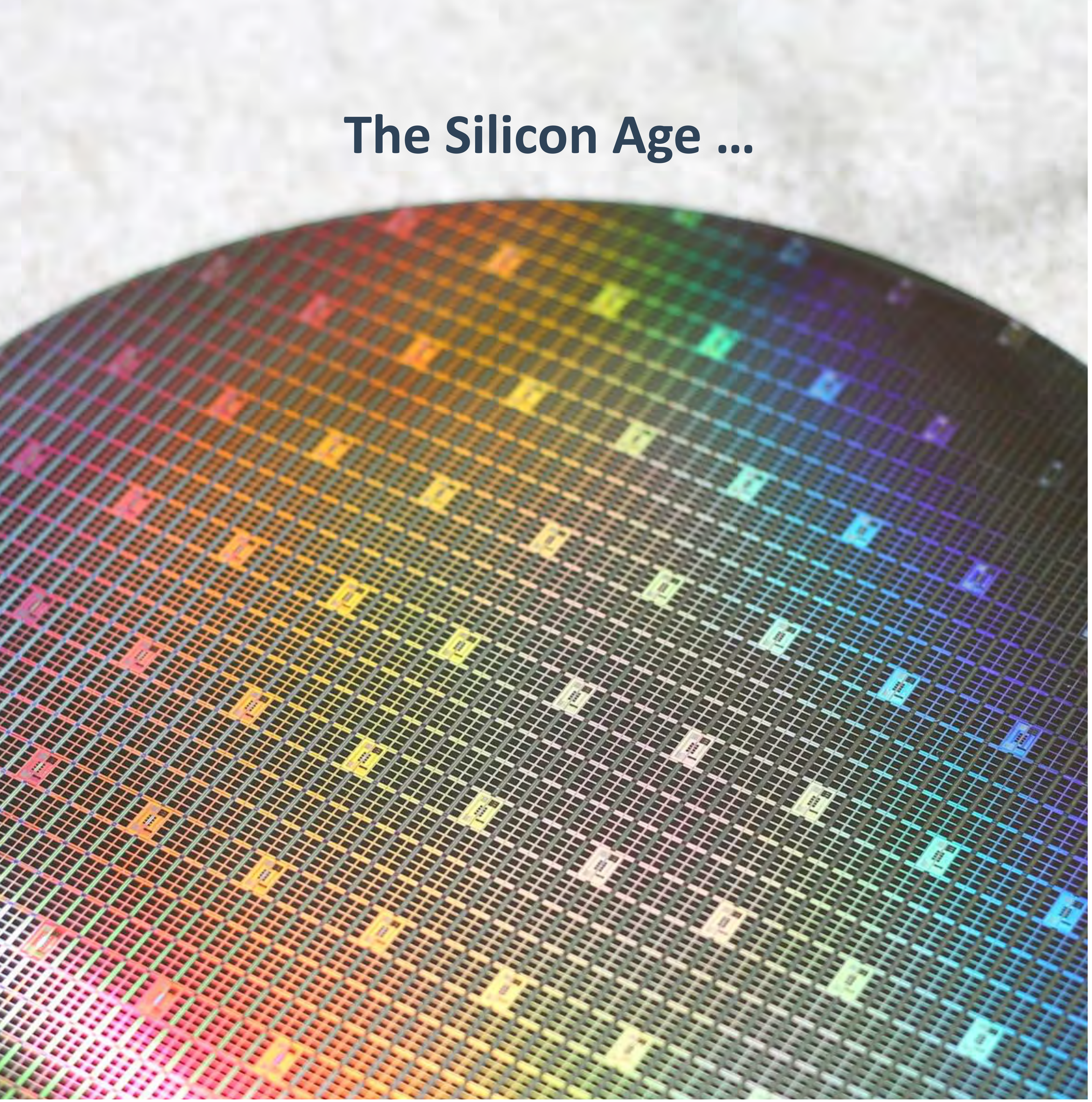
# Sustainability Challenges of the Plastics Industry

- This is not a regular landfill but the Thilafushi waste disposal site, a beach on the Maldives !



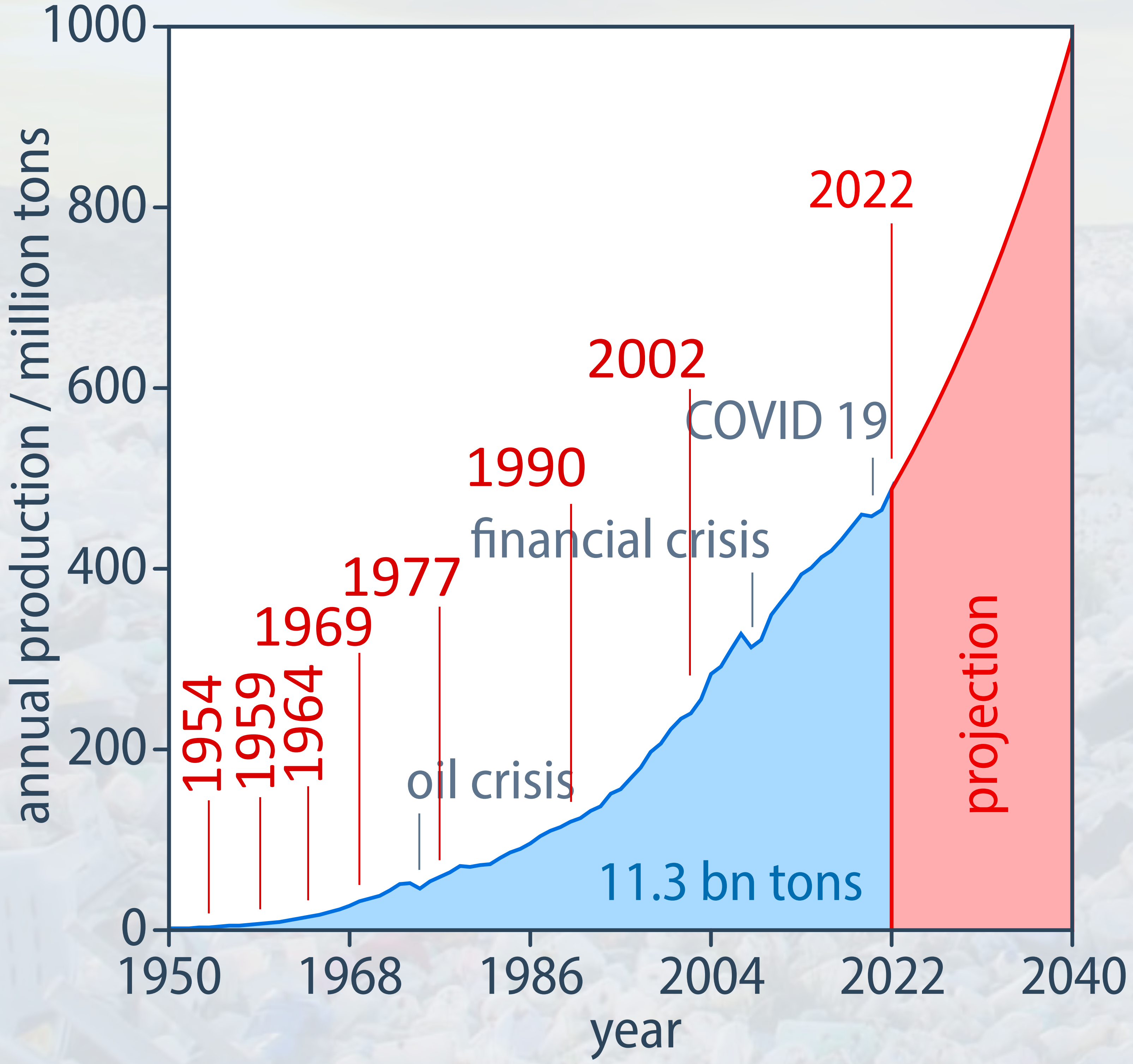
Image © Mohamed Abdulraheem

# So Which Epoch Do We Want to Be Known For ?

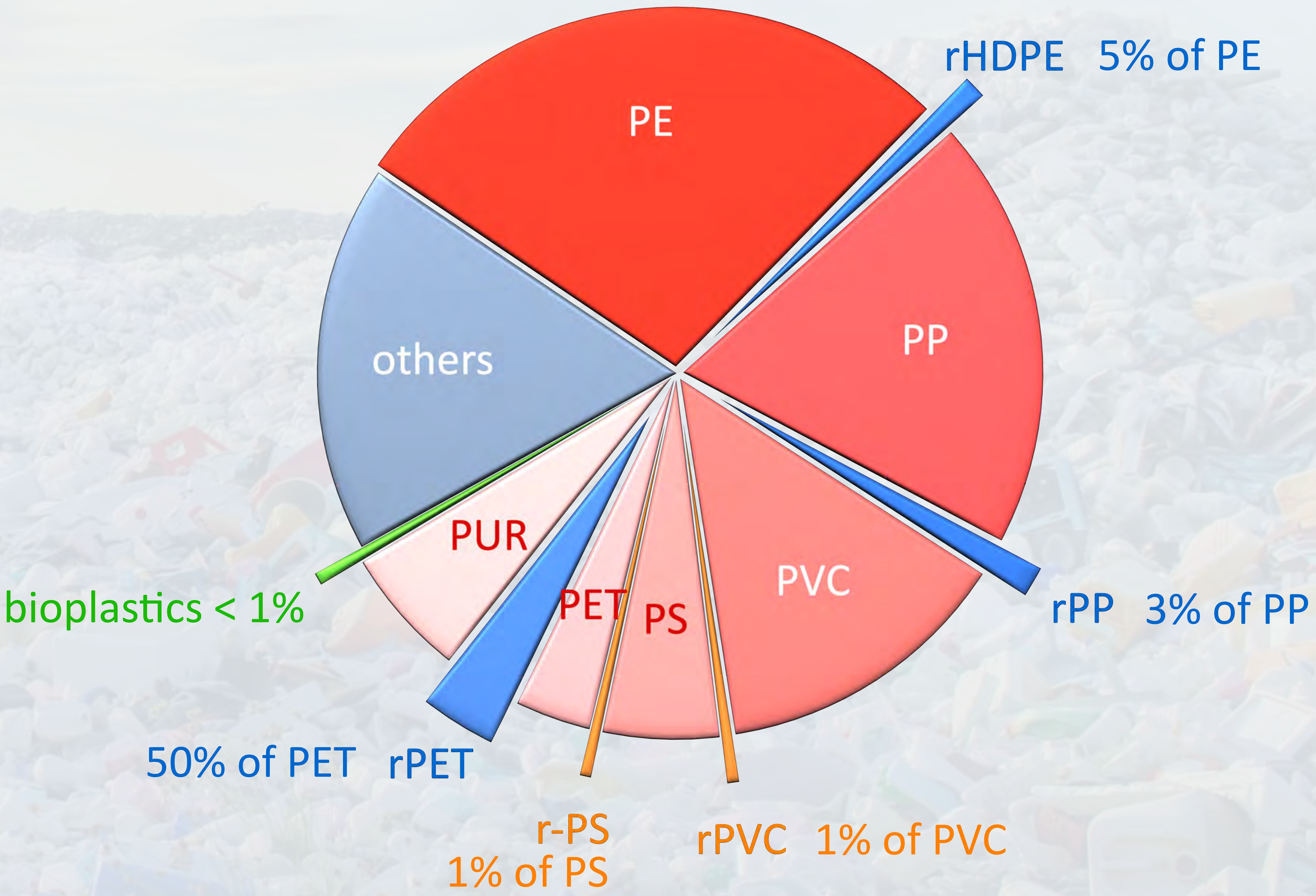



# Global Plastics Production & Recycling

## global plastics production 1950–2022




## global plastics production 2022 488 Mt total




- just **9% of all plastics recycled**, only **three open-loop** and **two closed-loop** recycling streams
- **50% incinerated, 36% landfill**, of which half is mismanaged; overall **30% leaked into environment**

# Plastics in The Earth System

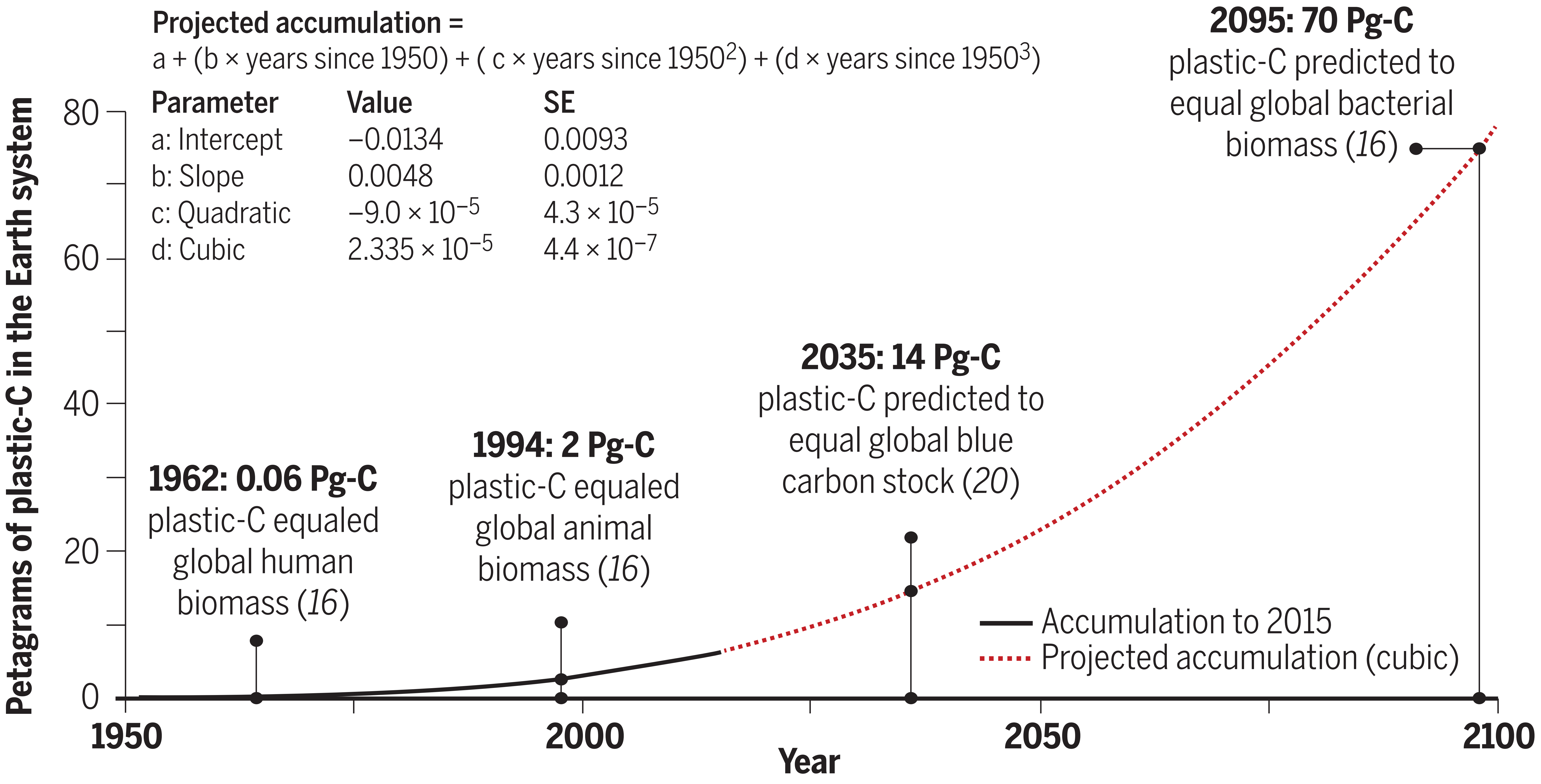
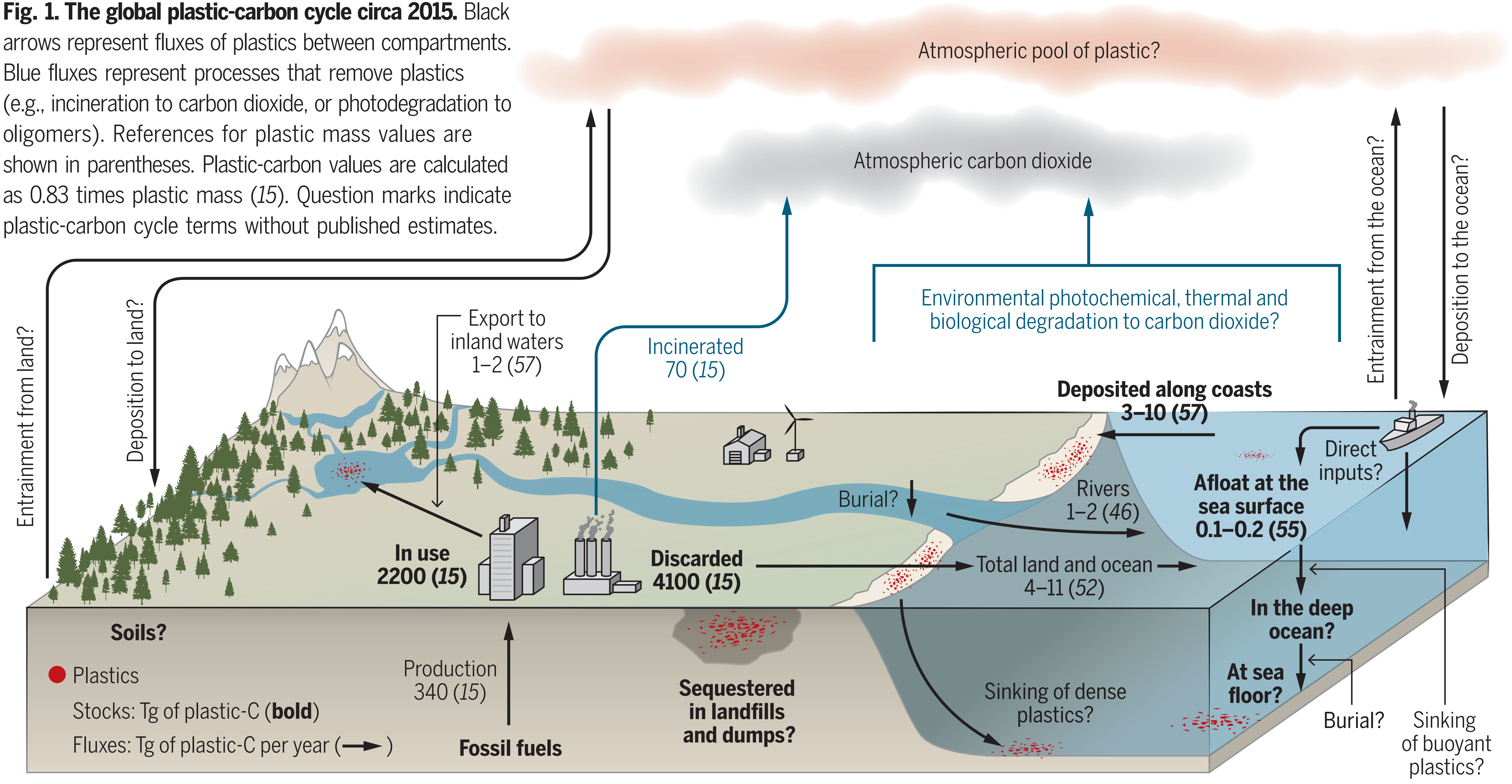



**Fig. 3. Accumulation of plastic-carbon in the Earth system.** Accumulation of plastic up to 2015 calculated as production minus incineration (*15*). Projected accumulation calculated assuming current trend (cubic growth) for plastic accumulation will continue into the future. The cubic model had the lowest Akaike information criterion of models in JMP. Actual future plastic-carbon accumulation will depend on hard-to-predict socioeconomic factors. Biomass numbers refer to living biomass.

# Plastics in The Earth System

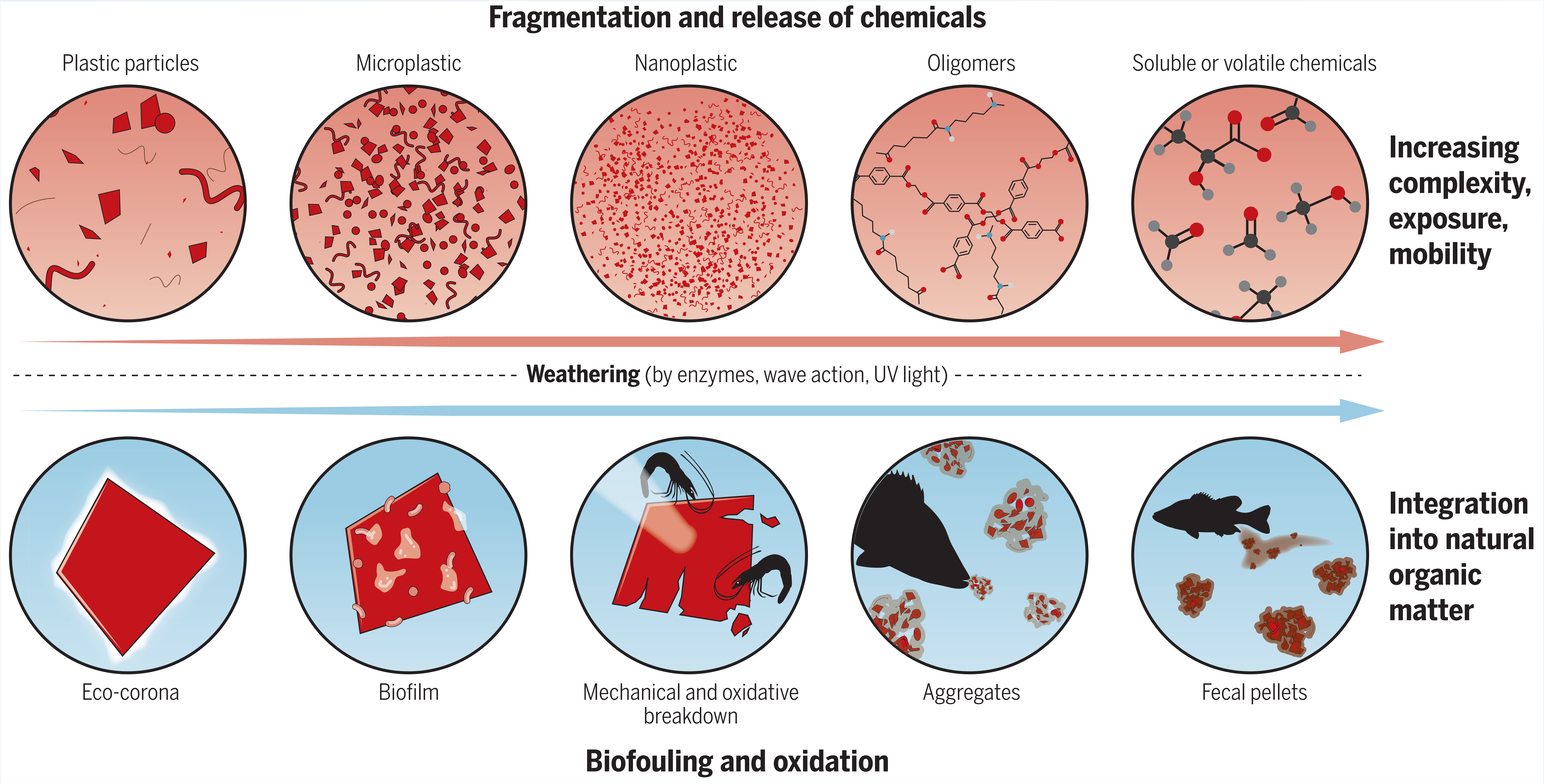
**Fig. 1. The global plastic-carbon cycle circa 2015.** Black arrows represent fluxes of plastics between compartments. Blue fluxes represent processes that remove plastics (e.g., incineration to carbon dioxide, or photodegradation to oligomers). References for plastic mass values are shown in parentheses. Plastic-carbon values are calculated as 0.83 times plastic mass (*15*). Question marks indicate plastic-carbon cycle terms without published estimates.





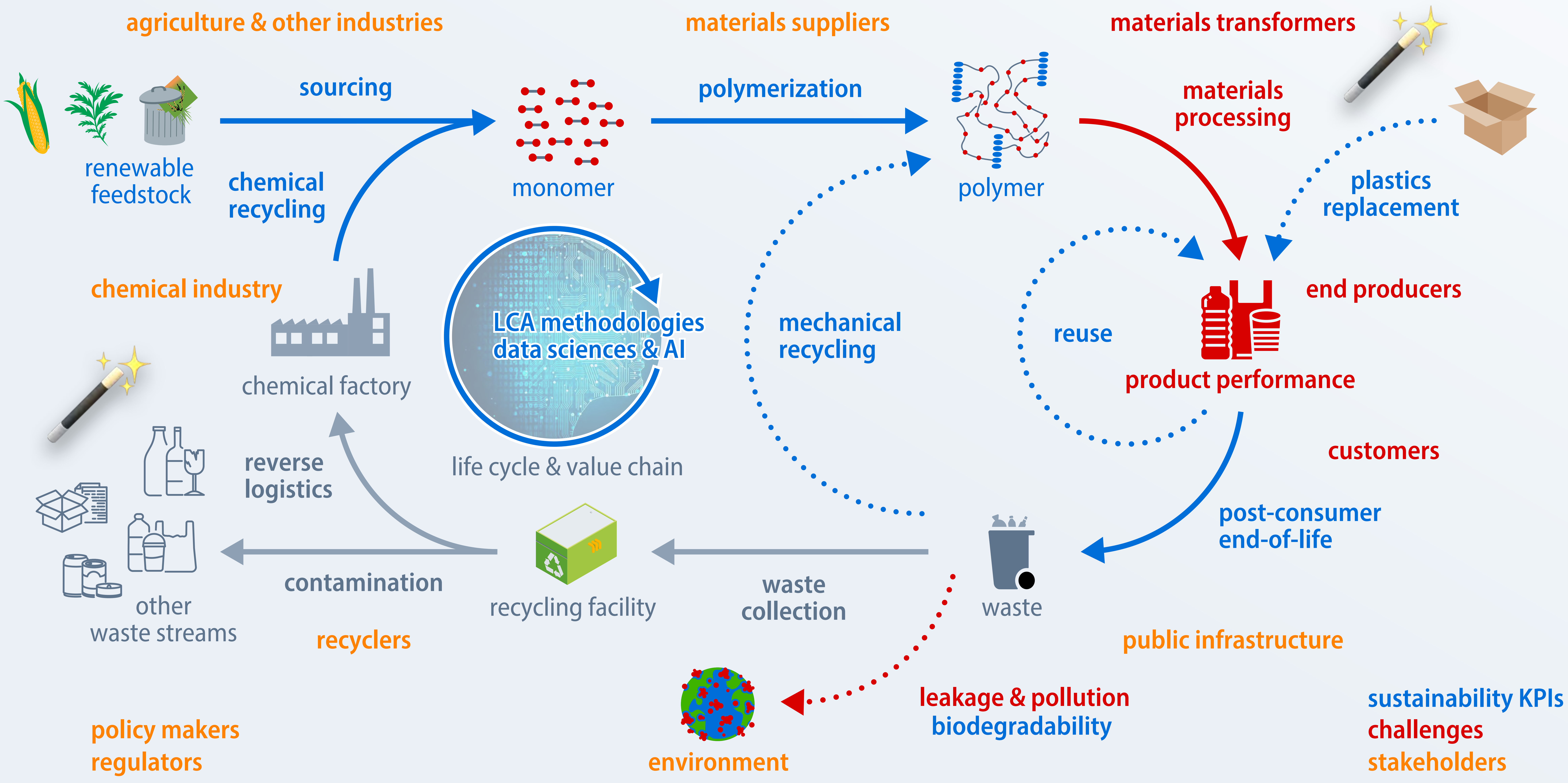

Stubbins, *Science* **2021**, *373*, 51; see also Santos, *Science* **2021**, *373*, 56; MacLeod *Science* **2021**, *373*, 61.

# Plastics Weathering and Degradation




MacLeod, *Science* **2021**, *373*, 61–65.

# Materials Challenges on the Way to a Circular Plastics Economy



# Plastics from Renewable Feedstocks

- **monomers obtained from renewable resources in order to replace petroleum-based plastics**

- **selection of feedstock**
  - ”first generation” from agricultural plants – competition with food production
  - ”second generation” from food or agricultural waste – huge amounts of source material required
  - ”third generation” from processes using primitive organisms – environmental impact on large scale

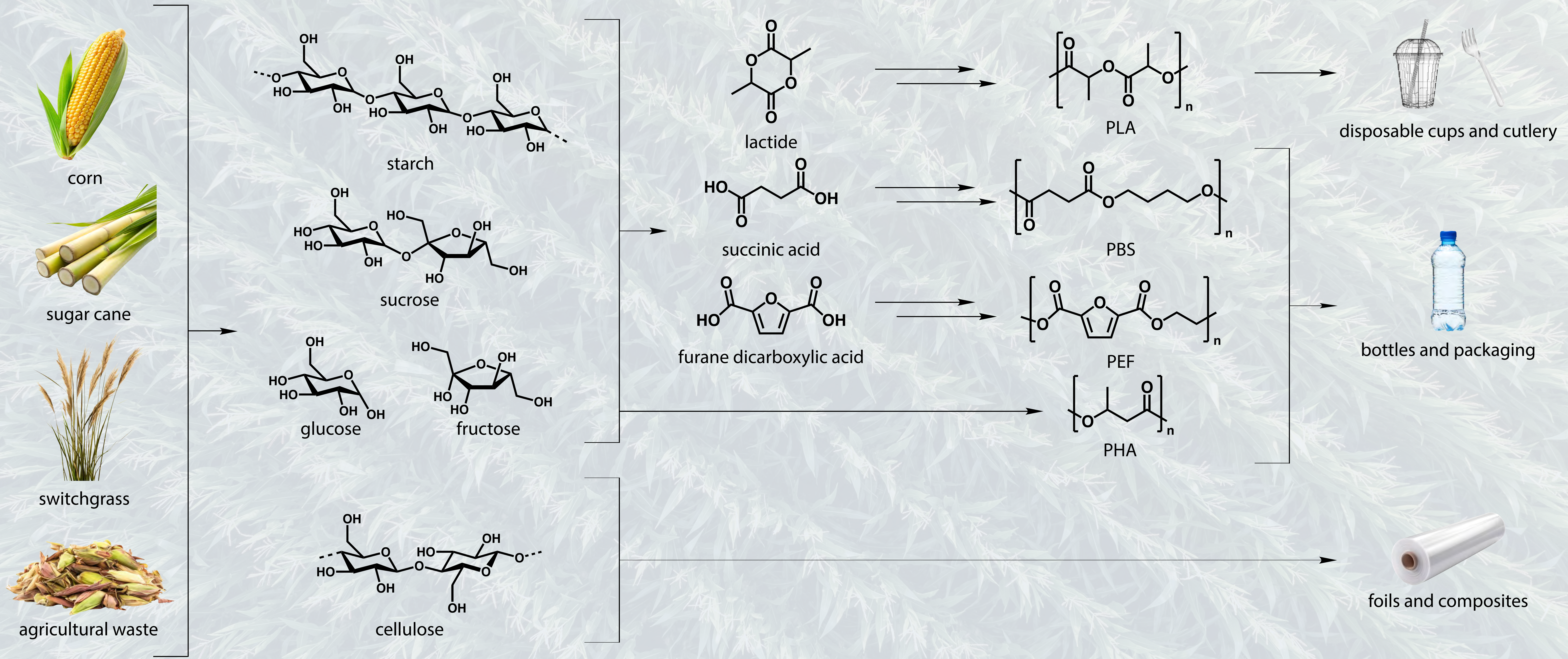
- **even for second generation feedstock: consider competition with other value chains**

- **end-of-life solutions, recyclability, and biodegradability are additional requirements**



Zhu et al., *Nature* **2016**, 540 *(7633)*, 354-362.

# Examples from Renewable Resources

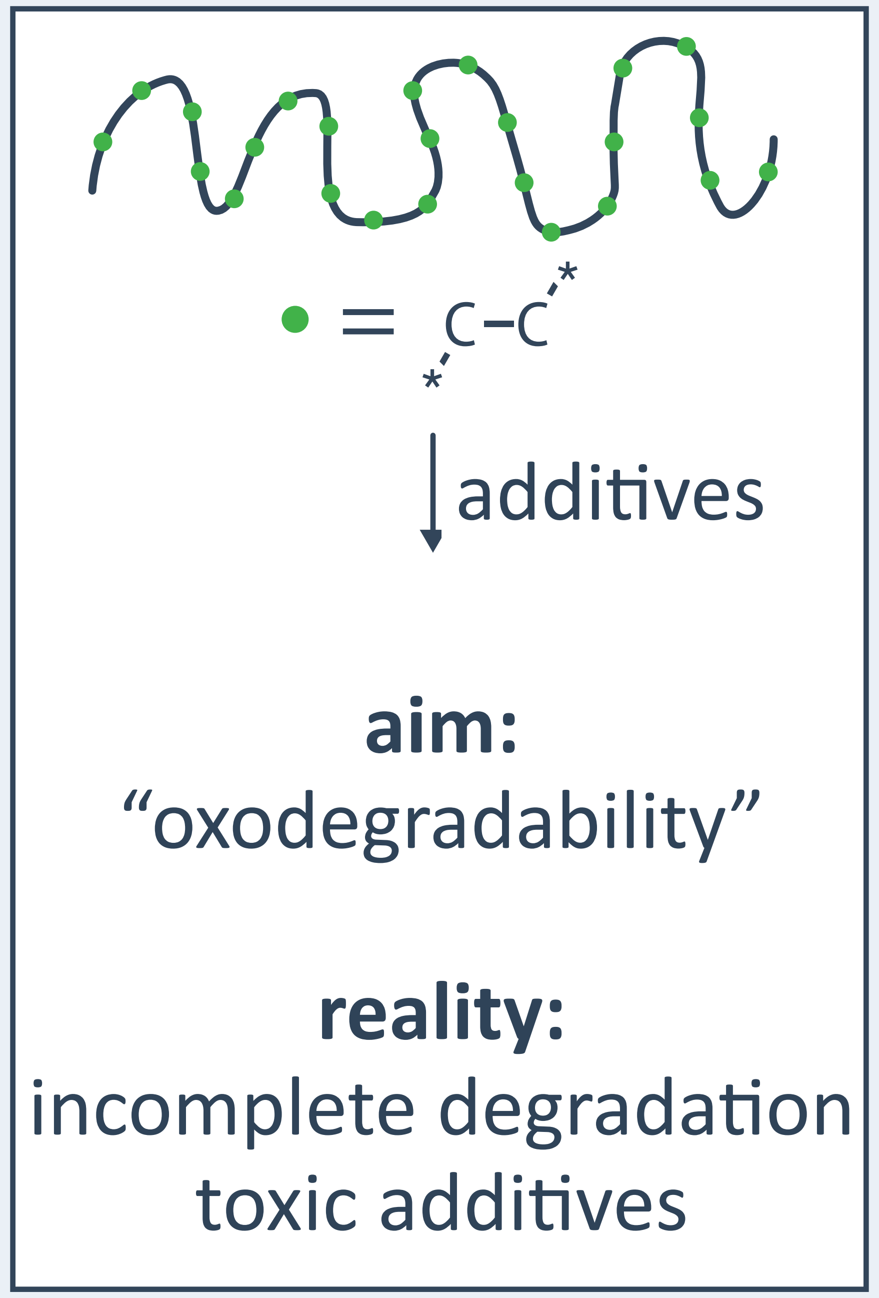



Zhu et al., *Nature* **2016**, 540 *(7633)*, 354-362.

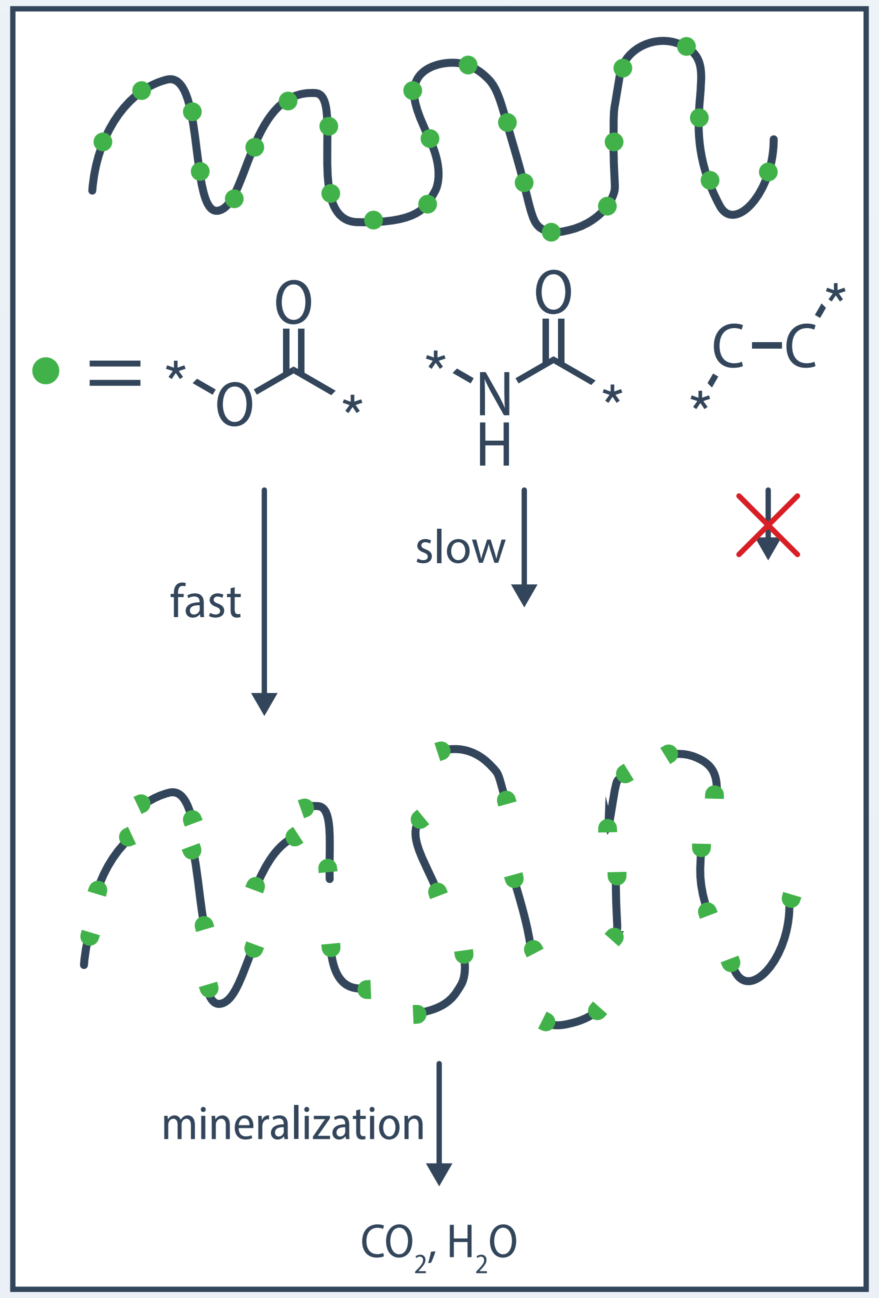
# Biodegradable Plastics

- leakage of plastic into the environment can never be fully prevented but should be reversible

“pro-oxidant” additives:
banned in EU (2019)




biodegradable polymers:
enzymatic scission or hydrolysis



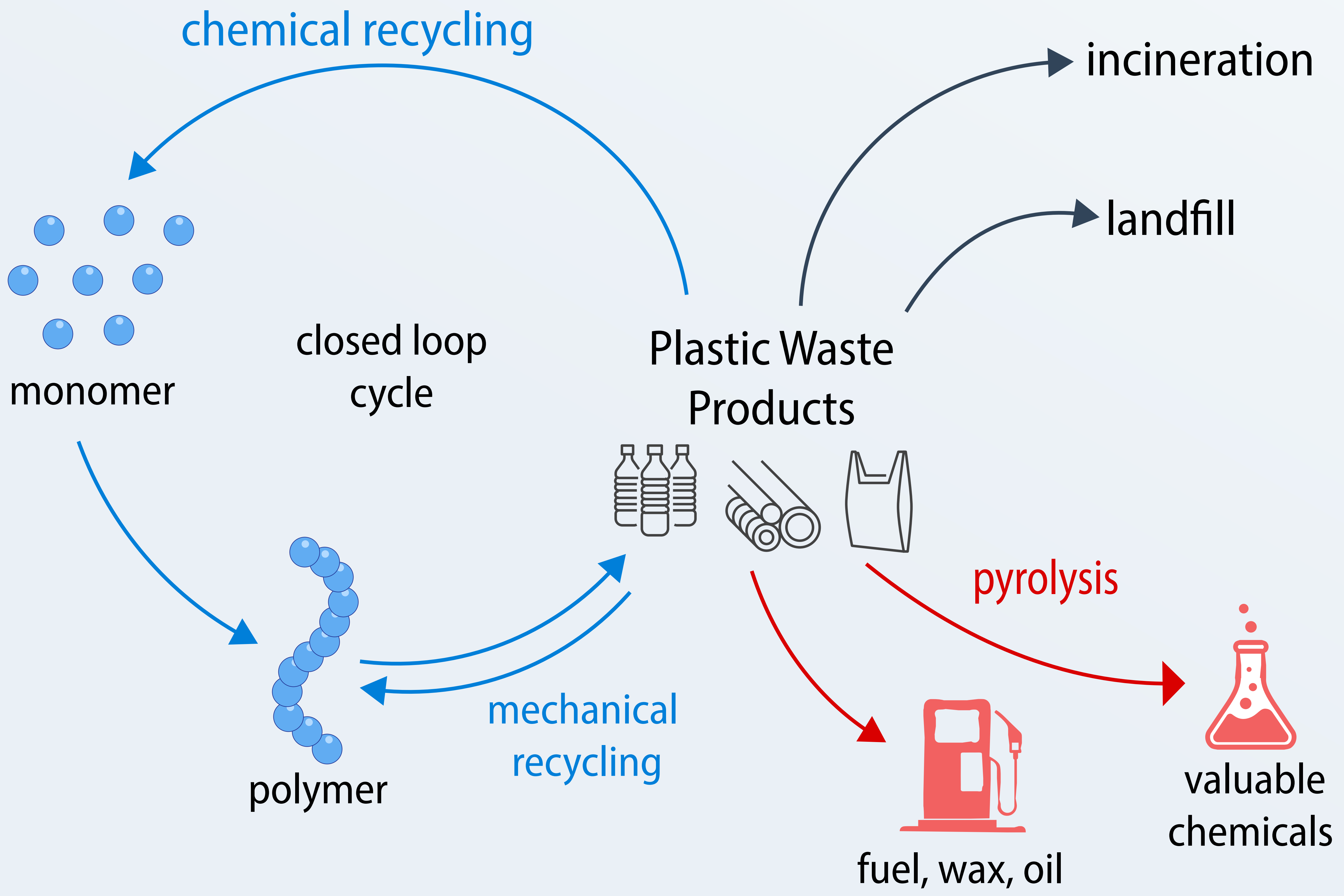

degradability as end-of-life option
for selected examples only

- **polymers must be biodegradable because of leakage, but desired end-of-life solution is recycling**
- **biodegradability should only be considered as end-of-life solution in rare exceptions !**
- **industrial composting is possible particularly in closed loop but remains hard to control**



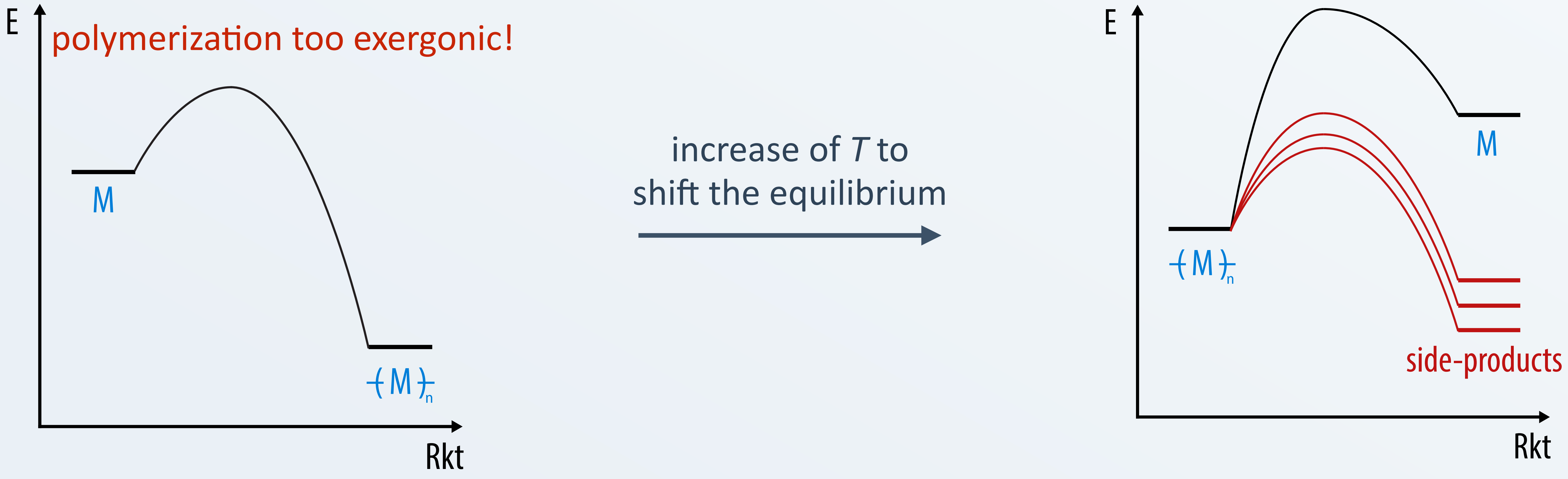
Albertsson and Hakkarainen *Science* **2017.** Aarsen *et al. Chem. Rev.* **2024.** EUR-Lex-32019L0904 (europa.eu).

# End of Life of Plastic Products



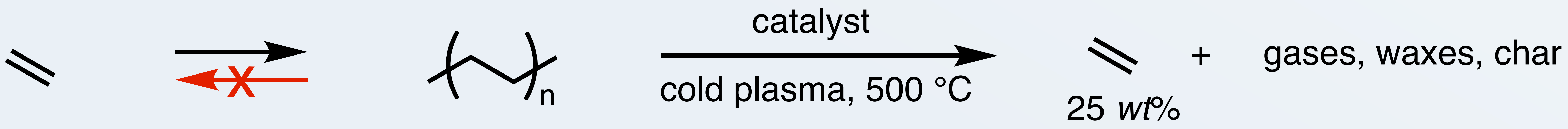

- **chemical recycling is the selective depolymerisation back into monomers under mild conditions**
- **pyrolysis is thermal decomposition into small molecules (not monomer), requires high energy**

# Pyrolsis of Vinyl Polymers

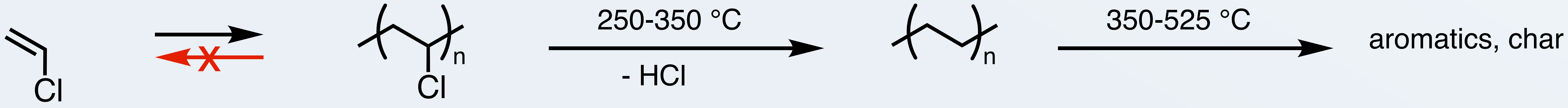



**polypropylene**


**polyethylene**




**polyvinyl chloride**

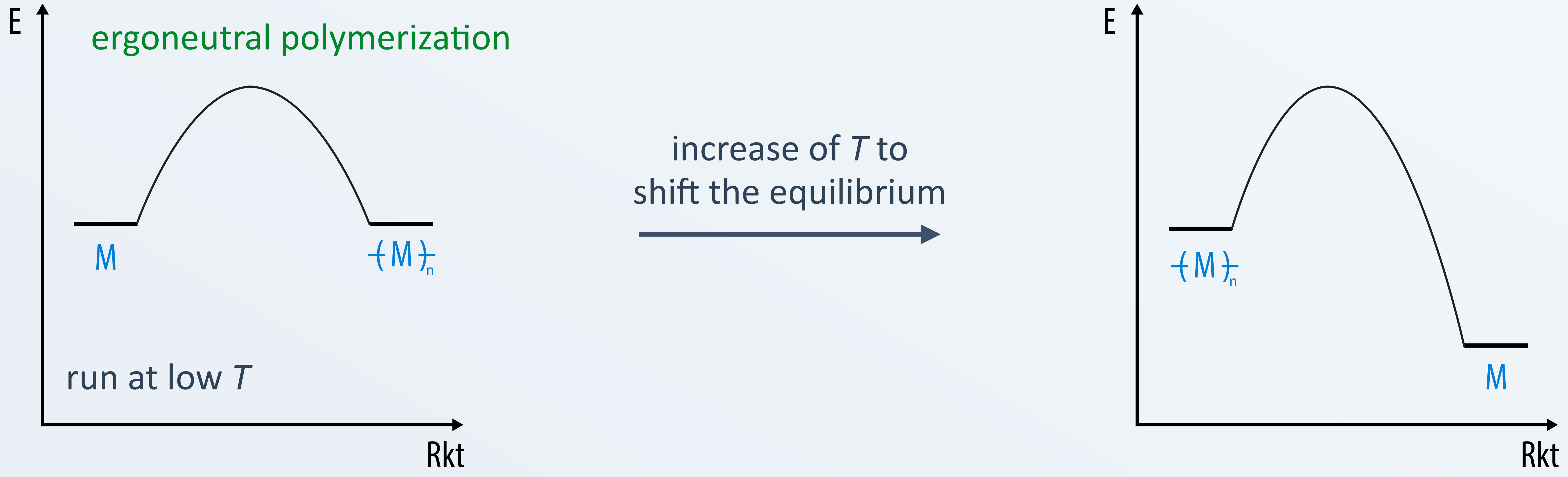



- **high depolymerization temperatures result in down-cycling to lower-energy side products**
- **pyrolysis (even to monomer) is not "chemical recycling to monomer under mild conditions"**

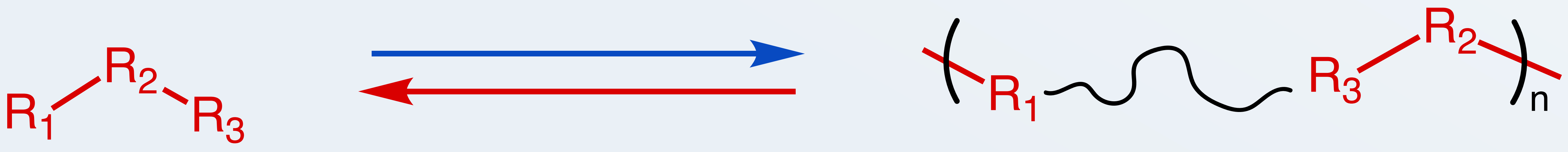


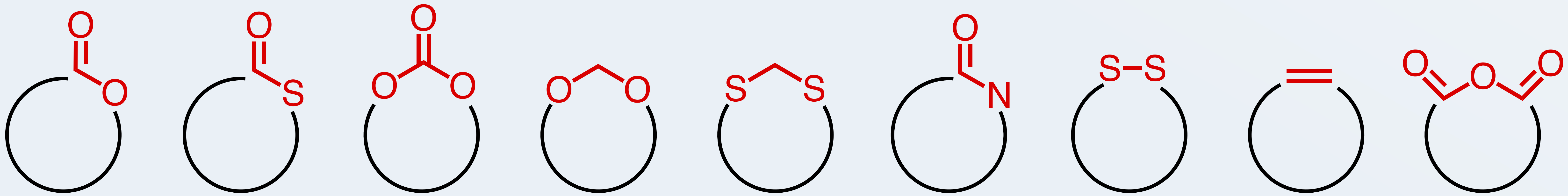
Grossmann, *Ind. Eng. Chem. Res.* **2000**, *39*, 1171; Phan, *Green Chem.* **2018**, *20*, 1813; Yao, *Waste Management* **2016**, *48*, 300.

# Chemical Recycling by Ring-Closing Depolymerization




Reversible ring-opening-polymerizations (ROPs)



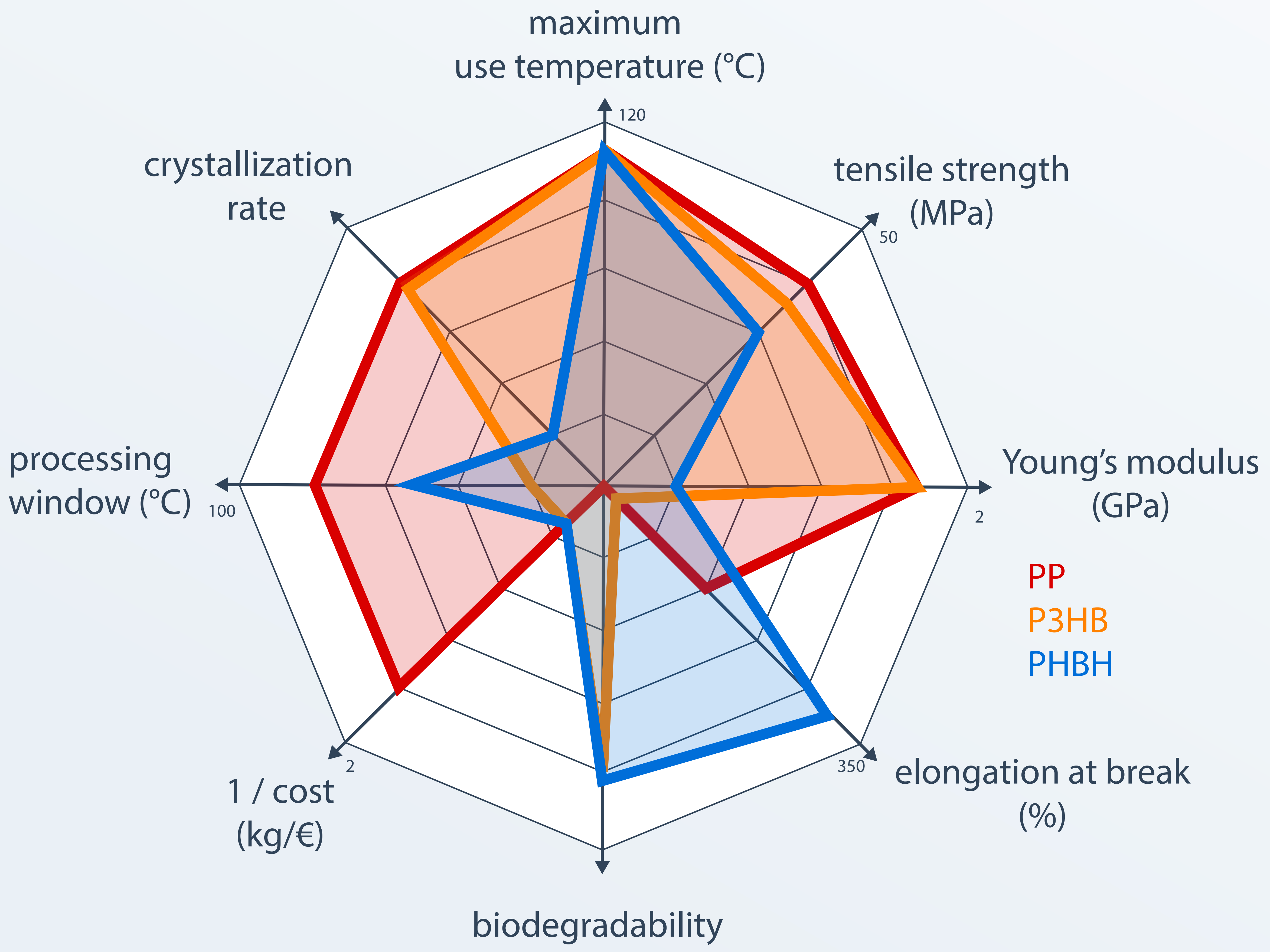

- **polymers made by ring-opening polymerization of heterocyclic monomers are ideally suited**
- **polymerization is almost ergoneutral, selective depolymerization occurs above ceiling temperature**



Yang, S.; Du, S.; Zhu, J.; Ma, S. Closed-Loop Recyclable Polymers: From Monomer and Polymer Design to the Polymerization–Depolymerization Cycle. Chemical Society Reviews 2024, 53 (19), 9609–9651.

# Why is it so Hard to Replace Plastics with Sustainable Alternatives ?

- commodity polymers such as PE and PP have seen seven decades of technological development
- various grades exist for different industrial processing methods (film drawing, moulding …)
- virtuous cycle: industrial production lines optimized for existing polymers and vice versa
- changes to existing production line non-trivial or require significant capex investment
- typical "sustainable polymers" often have severe shortcomings: heat stability, melt stability …
- sustainability requirements ask for small set of base polymers




- **challenge: reduced set of polymer materials and components must be adapted to the broad range of processing requirements and final product performance solutions they are intended to replace !**



EASAC, *Packaging Plastics in the Circular Economy*, **2020**.


The End