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Biomass-based upcycling technology for carbon-neutral biodegradable plastic

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미세 플라스틱 '230만톤' 오대양 떠다닌다

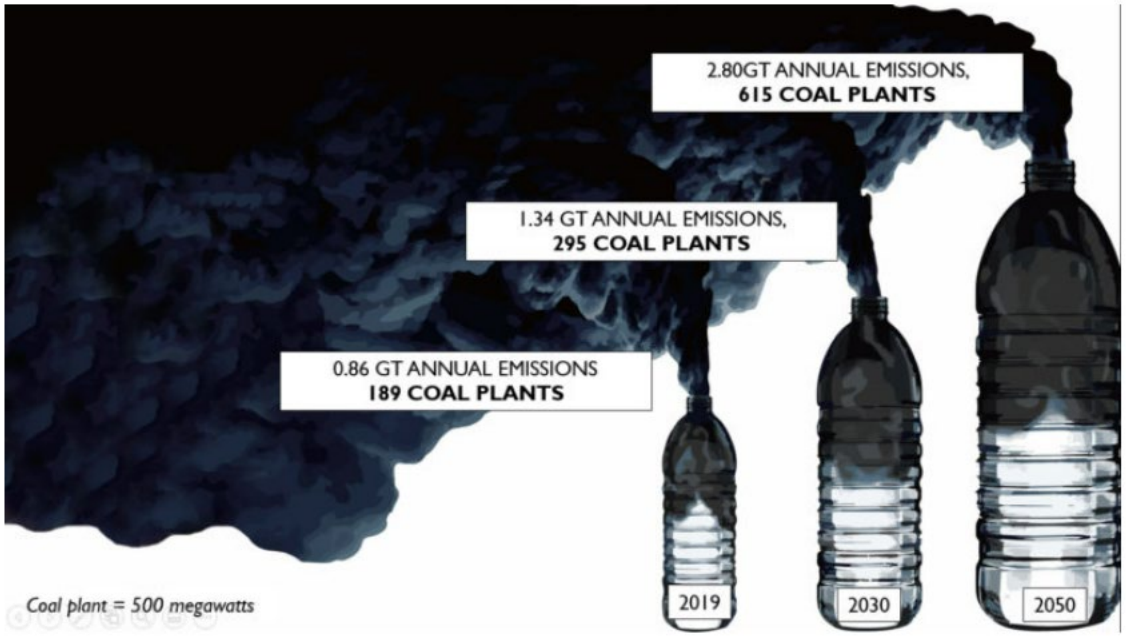
남예진 기자 | 승인 2023.03.09 15:10

미국 하와이 해안가를 뒤덮은 미세 플라스틱(사진 5 Gyres Institute)/뉴스펭귄

[뉴스펭귄 남예진 기자] 과학자들이 해양 미세 플라스틱의 근본적 문제를 해결하기 위해 플라스틱 산업에 대한 대대적인 규제가 필요하다고 주장하고 나섰다.

미국 비영리 환경단체 5대 환류대 연구소(5 Gyres Institute)등 국제 연구진은 전 세계 해양을 떠다니는 미세 플라스틱이 230만톤에 달한다고 국제 학술지 '플로스 원(PLOS ONE)'에 8일(현지시간) 발표했다.

Climate change
: GHG emissions



Estimated annual emissions from the plastics lifecycle by 2050. Source: CIEL, 2019.

Environmental pollution and human health threat

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What is microplastic?

"Tiny plastic particles (<5mm) resulting from degradation of larger plastic items or manufactured for specific purposes (e.g., microbeads in cosmetics)."

Human Health Concerns

- Ingestion through seafood, salt, and even water.
- Potential for toxin release in the digestive system.
- Unknown long-term health effects.

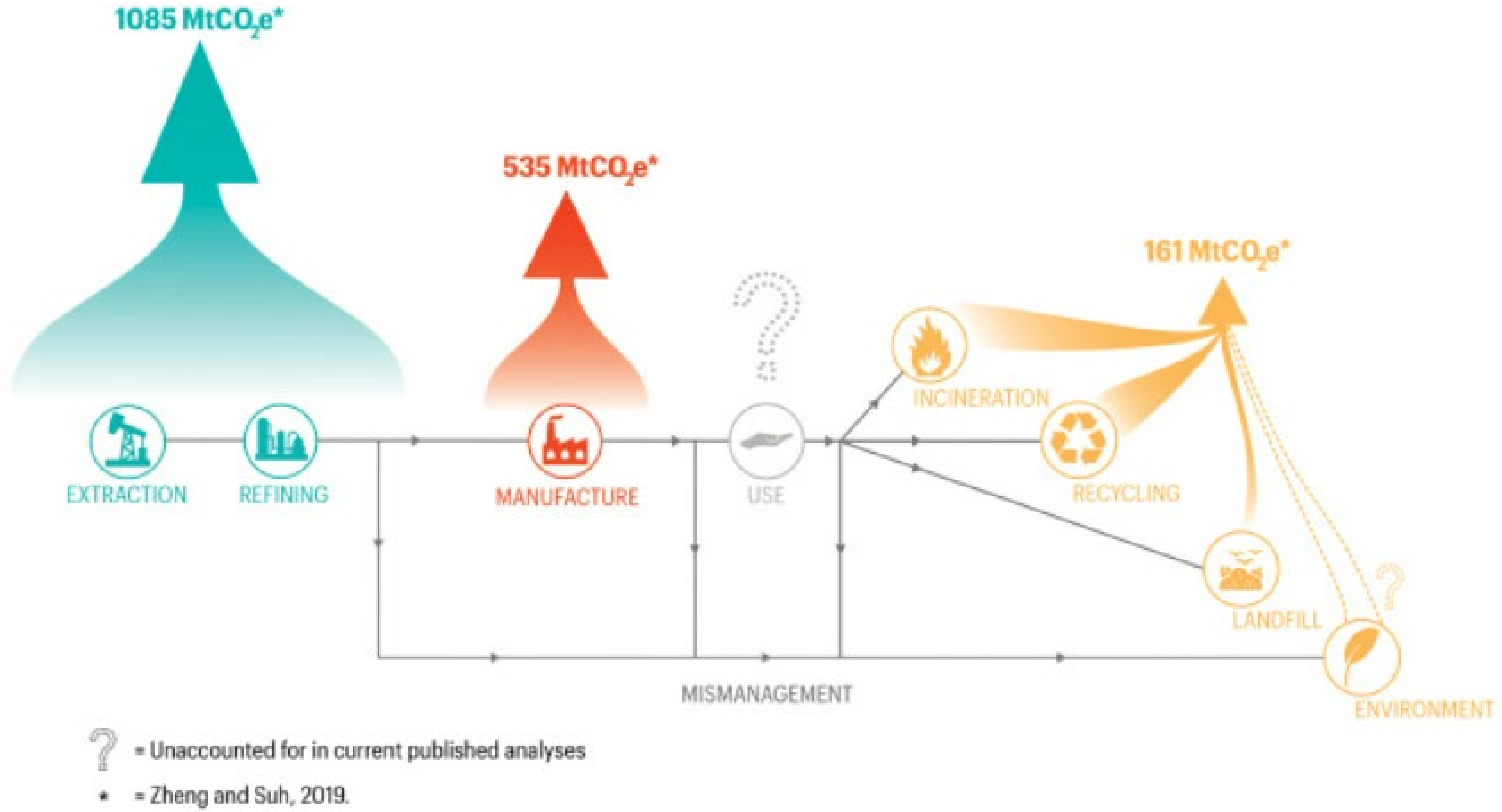
Environmental Impact

Water Contamination
→ Millions of tons enter oceans annually, affecting marine ecosystems.

Aquatic Life
→ Microplastics are ingested by marine organisms, leading to physical harm and toxin accumulation.

Terrestrial Impact
→ Soil contamination affects plant growth and can enter the terrestrial food chain.

GHG emissions



Estimated amounts of greenhouse gases released at each stage of the plastic life cycle (2019).

CO_2 and other GHGs emissions from plastic production in 2015: 1.96 Gt of CO_2e
→ Equivalent to $341 billion annually
(Minderoo-Monaco Commission on Plastics and Human Health, 2023)

Challenges in petroleum-based plastics

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Cannot continue…

Should find solutions to address these challenges…

No or less environmental pollution & human health	No or less GHG emissions

- More recycling, repurposing, or upcycling petroleum plastics
- More biomass-based plastics

Recycling, repurposing or upcycling petroleum plastics

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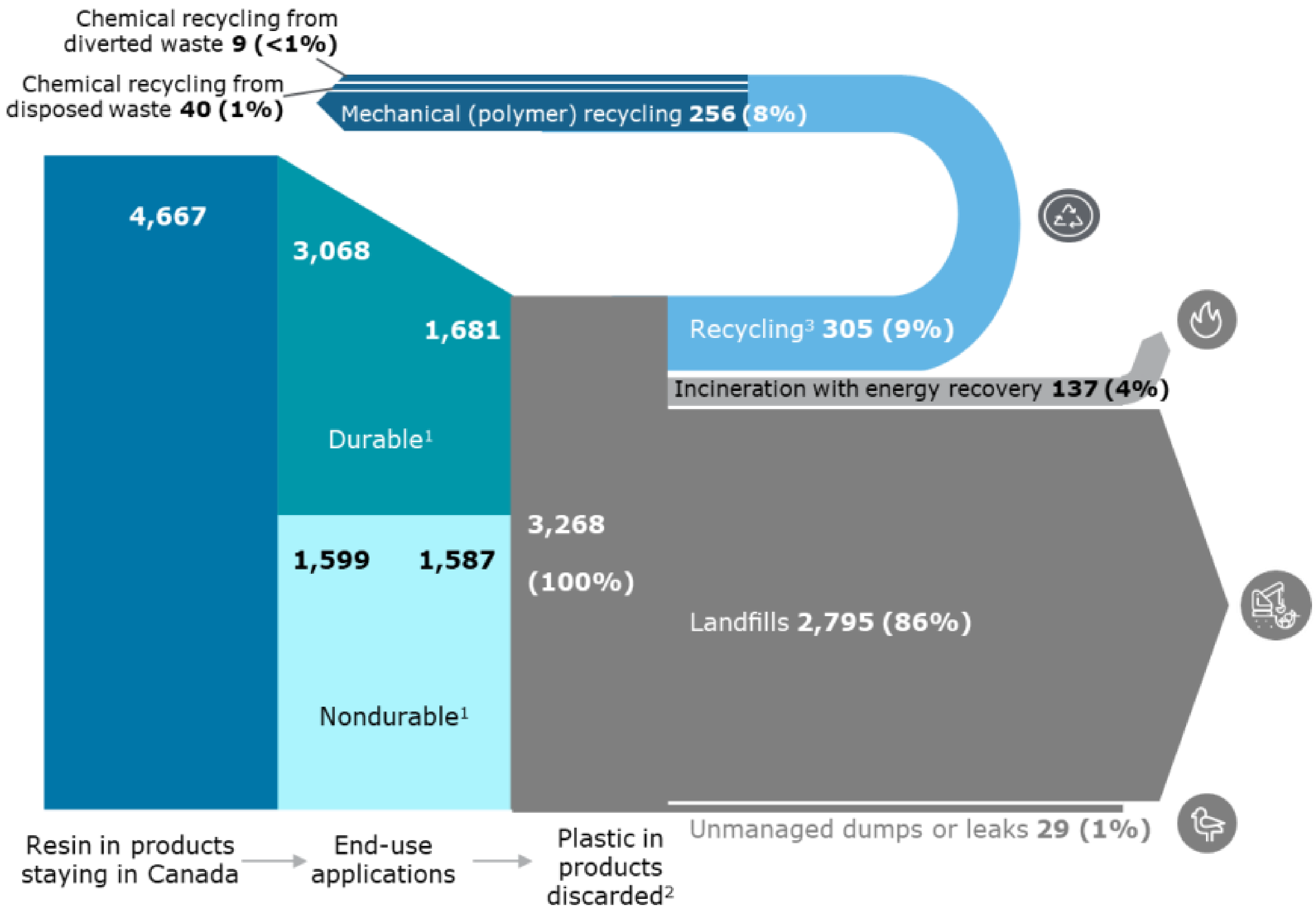
- It is very good start to deal with the current plastic industry challenges
- Relatively simple and easy to continue plastic business (retrofit concept)
  (e.g., collection→ recycling (repurposing or upcycling) process)

Can help environmental pollution & human health ???	GHG emissions Reduction ???

Example: Canada plastic industry



- 86% of plastics are landfilled (mainly packaging plastics)
- 9% recycling

Approach in parallel

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- We should bring another approach to recycling/repurposing/upcycling petroleum plastics

Can help environmental pollution
& human health

???

GHG emissions
Reduction

???

Biomass-based plastics

Routes for synthesizing polymers from fossil-based and Bio-based resources

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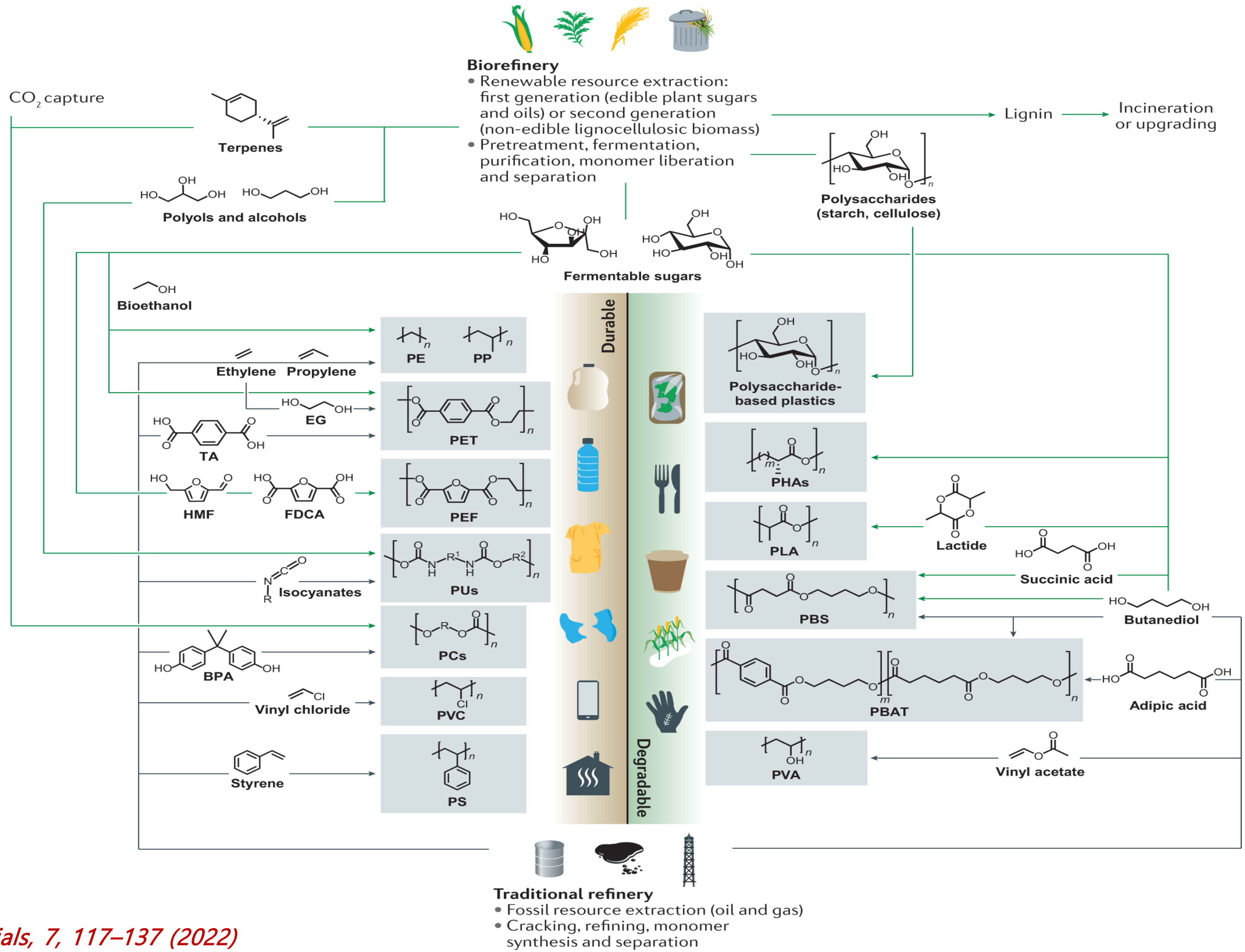


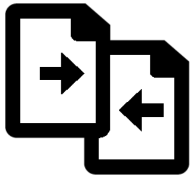
Nature Reviews Materials, 7, 117–137 (2022)

Adverse effects of microplastic – petroleum-based plastic and bioplastic

Sources of microplastic comparison

Petroleum-based plastics

Made from fossil fuels, which are a non-renewable resource.



Bioplastics

Made from renewable resources such as corn, sugarcane, and cellulose.

- Major source of microplastic pollution
- Made from non-renewable resource
- Could release harmful greenhouse gases into the atmosphere during production

- Lower carbon footprint than petroleum-based plastics
- Biodegradable → can be degraded faster biologically under specific conditions in the natural environment

Biomass-based biodegradable plastic (B3 plastic)

Biomass-based biodegradable plastic (B3 plastic): Polyhydroxyalkanoates (PHA)

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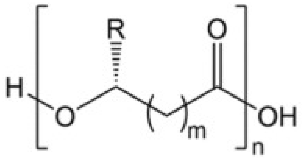
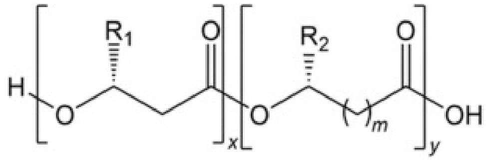
PHA definition

➔ a family of biopolymers produced by various bacteria as intracellular carbon and energy storage compounds

Types of PHA



Polyhydroxyalkanoate homo-polymer



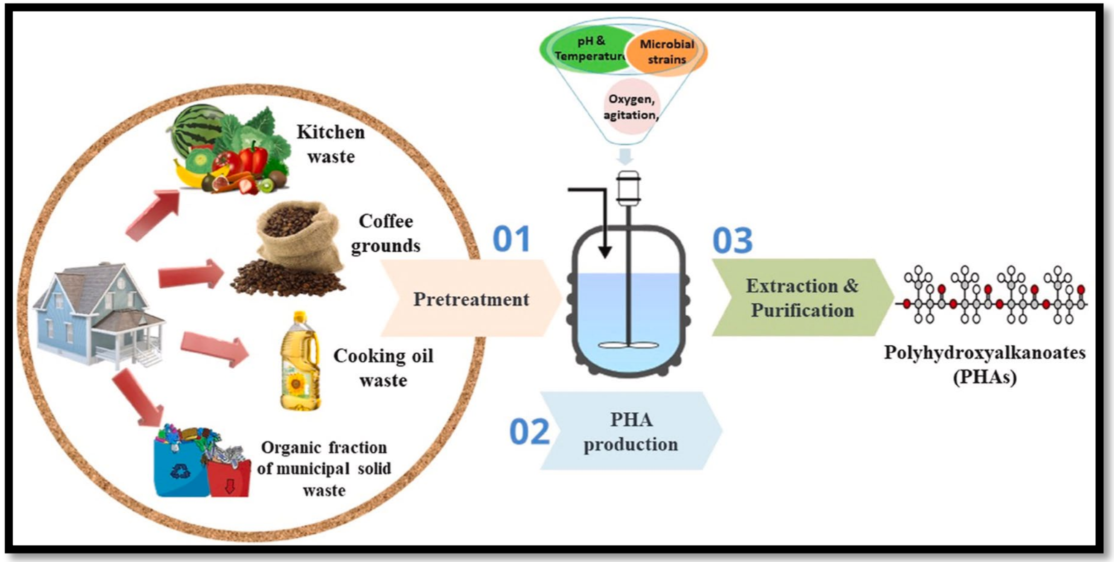
Polyhydroxyalkanoate co-polymer

m	R	PHA	Symbol
1	Hydrogen	Poly(3-hydroxypropionate)	PHP
	Methyl	Poly(3-hydroxybutyrate)	PHB
	Ethyl	Poly(3-hydroxyvalerate)	PHV
	Propyl	Poly(3-hydroxyhexanoate)	PHHx
	Pentyl	Poly(3-hydroxyoctanoate)	PHO
	Heptyl	Poly(3-hydroxydecanoate)	PHD
2	Hydrogen	Poly(4-hydroxybutyrate)	P(4HB)
	Methyl	Poly(4-hydroxyvalerate)	P(4HV)
3	Hydrogen	Poly(5-hydroxyvalerate)	P(5HV)
	Methyl	Poly(5-hydroxyhexanoate)	P(5HHx)

m	R_1	R_2	PHA	Symbol
1	Methyl	Ethyl	Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)	PHBV
	Methyl	Propyl	Poly(3-hydroxybutyrate-co-3-hydroxhexanoate)	PHBHHx
	Pentyl	Ethyl	Poly(3-hydroxyoctanoate-co-3-hydroxyhexanoate)	PHOHHx
2	Methyl	Hydrogen	Poly(3-hydroxybutyrate-co-4-hydroxybutyrate)	P3HB4HB

Eesaee et al., 2022 (https://doi.org/10.1016/j.bej.2022.108588)

Production of PHA



Guleria et al., 2022 (https://doi.org/10.1016/j.jclepro.2022.130661)

- ➢ Process: Synthesis by bacteria under nutrient-limiting conditions with an excess of carbon.
- ➢ Synthesizing bacteria: *Cupriavidus necator, Pseudomonas putida*, etc.
- ➢ Raw Materials: Renewable resources such as plant oils, molasses, or even waste streams.
- ➢ Recovery: PHA is extracted from the microbial cells post-synthesis using solvents or through cell disruption.

Biomass-based biodegradable plastic (B3 plastic): Polyhydroxyalkanoates (PHA)

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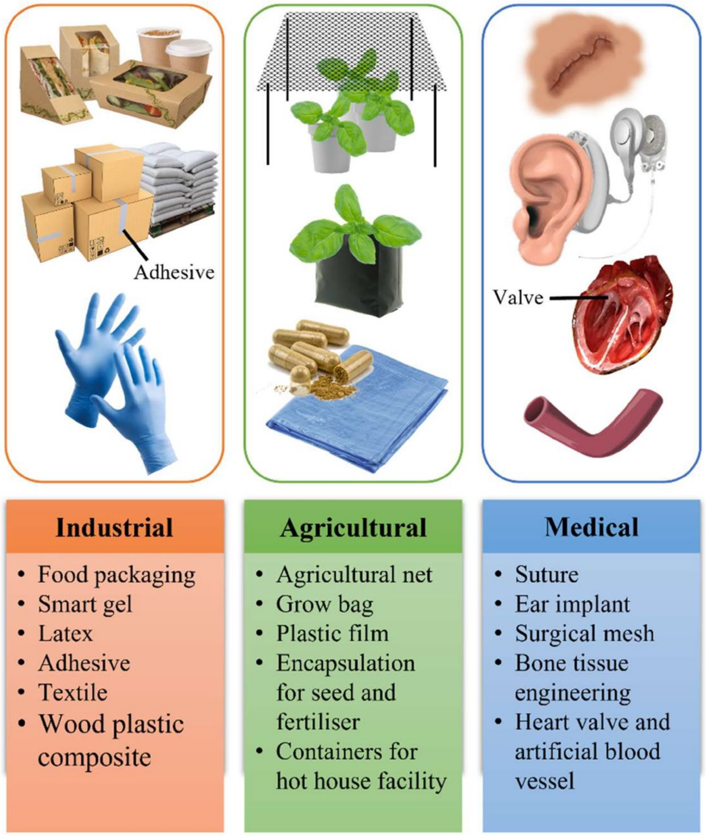
Applications of PHA



Vigneswari et al., 2021 (https://doi.org/10.3390/life11080807)

General properties of PHA

- Biodegradability → Fully biodegradable in various environments, including marine, soil, and home compost.
- Thermoplasticity → Can be processed using conventional plastic processing techniques.
- Biocompatibility → Suitable for medical applications, such as sutures and drug delivery systems.
- UV Resistance → Naturally resistant to UV degradation, making it suitable for outdoor applications.

Environmental Impact of PHA

- Carbon Neutral → The carbon in PHA is derived from atmospheric CO2 captured by plants, making it a carbon-neutral material.
- Reduction in Plastic Pollution → Being fully biodegradable, PHA doesn't contribute to long-term plastic pollution.
- Waste Reduction → Potential to convert waste streams into valuable bioplastics.

Biomass-based biodegradable plastic (B3 plastic): bio-polybutylene succinate (PBS), cellulose, and starch composites

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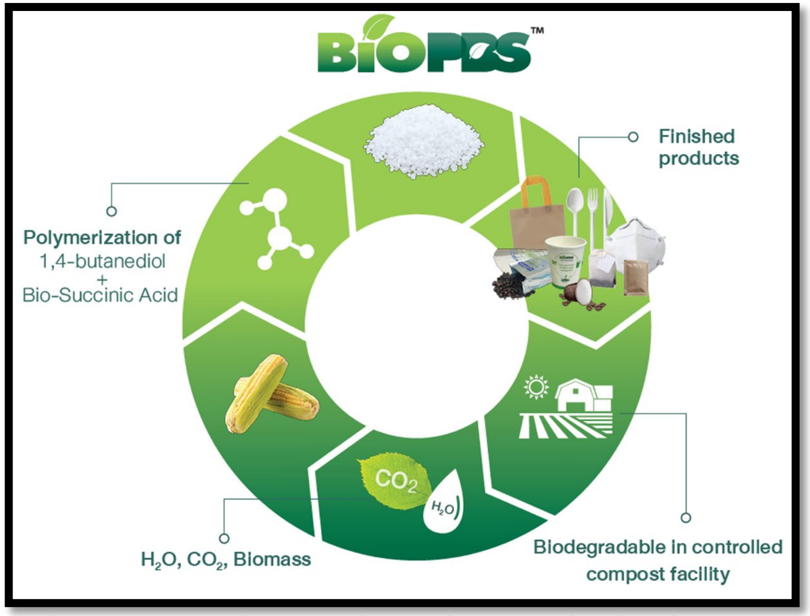
Bio-PBS

Synthesized from bio-based monomers, specifically succinic acid (derived from fermentation of glucose) and 1,4-butanediol (derived from various renewable sources).



https://www.tcdcmaterial.com/th/material/8/bioplastics/info/MI00620-01

- Semi-crystalline nature
- Good flexibility and toughness
- Excellent compostability and soil biodegradability

- Packaging → For food, due to its excellent gas barrier properties.
- Agriculture → Mulch films that can degrade in soil, reducing plastic waste.
- Automotive → Used in interior parts due to its durability and lightweight nature.
- Textiles → For manufacturing biodegradable fibers.

Decomposes into water and CO_2, leaving no microplastic residues.

Biomass-based biodegradable plastic (B3 plastic): bio-polybutylene succinate (PBS), cellulose, and starch composites

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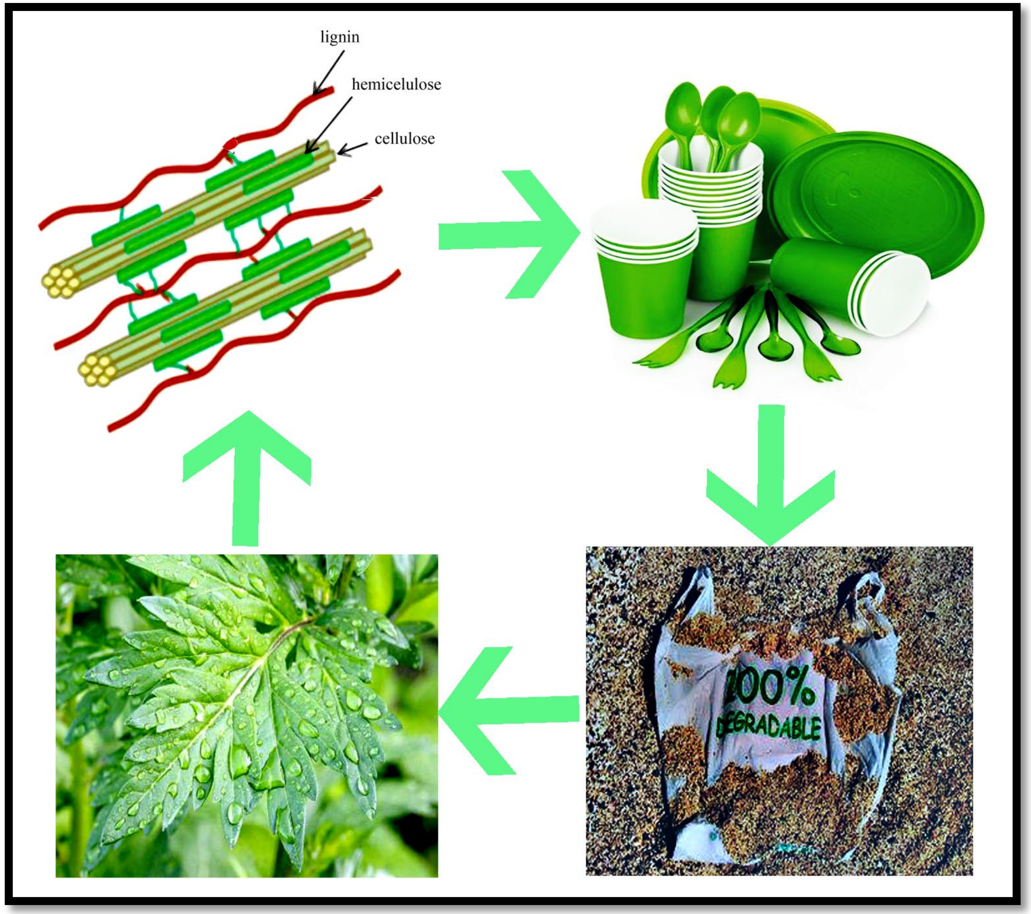
Cellulose



Yang et al., 2019 (https://doi.org/10.3390/polym11050751)

Natural polymer extracted from the cell walls of plants, especially trees and cotton.

- High tensile strength.
- Hydrophilic nature.
- Biocompatible and non-toxic.

- Films → Used for packaging due to its excellent barrier properties.
- Coatings → For paper and cardboard to provide water resistance.
- Fibers → Cellulose-based textiles like rayon and cellophane.
- Medical → Wound dressings, drug delivery systems due to its biocompatibility.

Fully biodegradable and compostable, returning to nature as water, CO_2, and biomass.

Biomass-based biodegradable plastic (B3 plastic): bio-polybutylene succinate (PBS), cellulose, and starch composites

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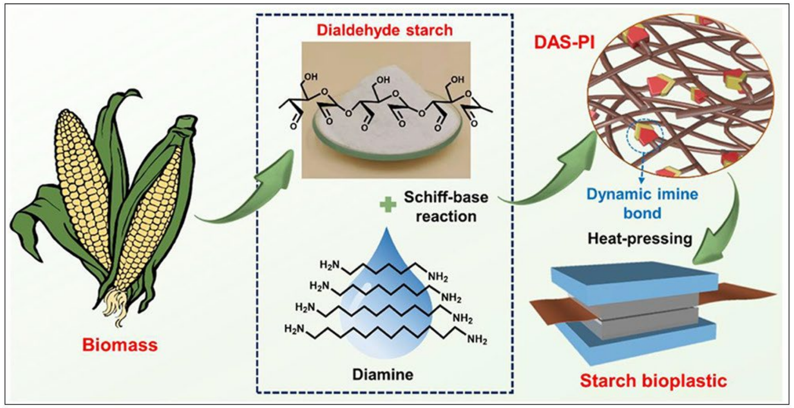

Zhang et al., 2022 (https://doi.org/10.1021/acssuschemeng.2c02537)

Starch

Natural glucose polymer extracted from plants, notably corn, potatoes, and rice.

- Thermoplastic nature when mixed with plasticizers.
- Biodegradable and renewable.
- Edible, making it suitable for specific applications.

- Packaging → For food items, as it's non-toxic and can be composted.
- Agriculture → Biodegradable pots, seed coatings, and mulch films.
- Medical → Drug delivery systems and wound care products.
- Edible Films → Used in the food industry for coatings or as edible containers.

Fully degradable under composting conditions, turning into water, CO_2, and biomass without leaving harmful residues.

Repurposing and upcycling of b3 plastic
: can be less energy intensive and carbon footprint

Repurposing b3 plastic

- **Direct Reuse**: Using b3 plastic products for alternative purposes after their initial use. For example, using b3 plastic containers for storage or as plant pots.
- **Creative Repurposing**: Turning b3 plastic waste into art, crafts, or DIY projects. This not only gives the plastic a second life but also raises awareness about sustainable materials.

Upcycling b3 plastic

- **Material Enhancement**: Modifying the physical properties of b3 plastic waste to create a product with higher quality or value. For instance, blending b3 plastic with other bioplastics or additives to enhance its properties.
- **Product Creation**: Designing new products from b3 plastic waste, such as furniture, home decor, or fashion items.

Benefits of Repurposing and Upcycling b3 plastic

- **Waste Reduction**: Diverts b3 plastic from landfills and reduces the environmental impact associated with waste disposal.
- **Resource Efficiency**: Maximizes the utility of b3 plastic, reducing the need for new material production.
- **Economic Value: Upcycled** products can be sold at a premium due to their sustainable and unique nature.

Repurposing and upcycling of b3 plastic

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Challenges and Solutions

- **Government support**
- **Collection and Sorting**: Efficient systems are needed to collect and sort b3 plastic waste for repurposing and upcycling.
- **Consumer Awareness**: Educating consumers about the benefits of repurposed and upcycled products can drive demand.
- **Innovation**: Encouraging designers and manufacturers to think creatively about how to give b3 plastic a second life.

Case Studies

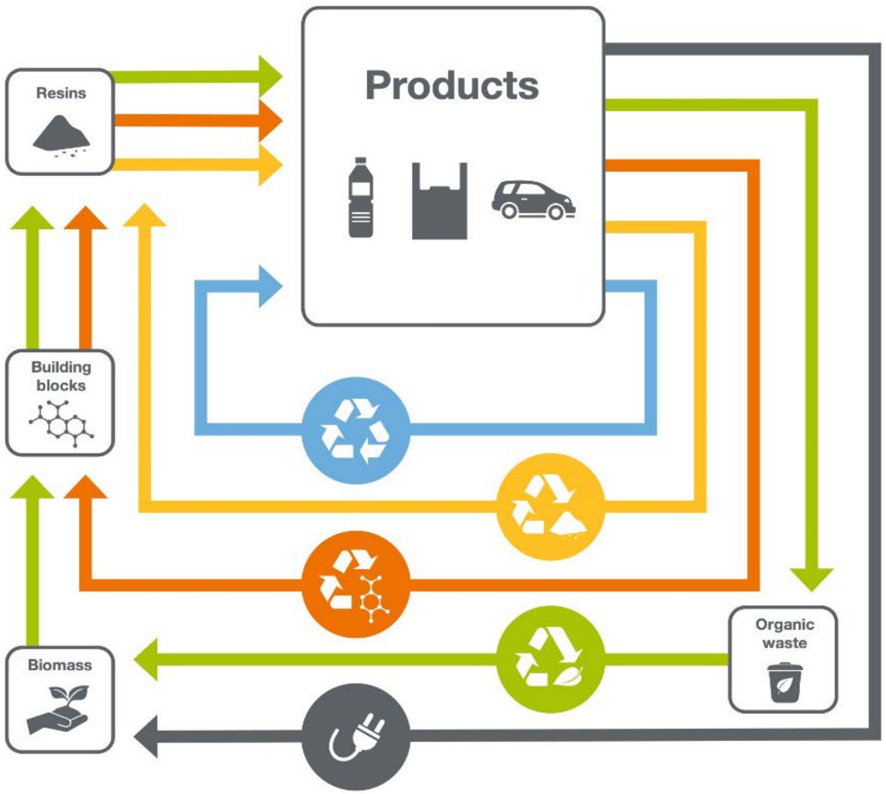
“Highlight successful examples of companies or initiatives that have effectively repurposed or upcycled b3 plastic. This could include fashion brands using b3 plastic waste in their designs or community projects turning b3 plastic waste into public art”

Carbon emissions reduction of B3 plastic – LCA analysis

- ✓ The greater utilization of renewable resources and a higher proportion of biobased items represent a crucial stride in attaining these objectives.
- ✓ Life cycle assessments indicate that biobased plastics can lead to substantial CO_2 reduction, potentially reaching carbon neutrality when compared to traditional plastics, contingent upon the input materials, the product, and its usage.

END-OF-LIFE OPTIONS FOR BIOBASED AND BIODEGRADABLE PLASTICS

Closing the loop



REUSE ranks higher than recycling in the **EU waste hierarchy** and should be considered first. Biobased plastics offer numerous opportunities for creating reusable products.

MECHANICAL RECYCLING recovers (biobased) plastic waste through **mechanical processes** to **recreate resins** without changing the chemical structure. It's an end-of-life option for the majority of biobased plastics.

CHEMICAL RECYCLING comprises different varying technologies that convert (biobased) plastic waste into an **upstream feedstock** resulting in **secondary raw materials** that have the **same quality as virgin materials**.

ORGANIC RECYCLING includes **industrial composting** and **anaerobic digestion**. Compostable plastics save valuable organic waste from landfill and incineration and help turning waste into **beneficial high-quality compost**.

ENERGY RECOVERY is an **additional end-of-life option for biobased and/or biodegradable plastic** materials where an alternative waste management infrastructure does not exist. In the case of biobased plastics, renewable energy can be obtained from the **biogenic carbon** – a significant advantage compared to fossil-based plastics.

https://www.european-bioplastics.org/bioplastics/environment/

Simplified schematic of a plastic value chain represented in LCA

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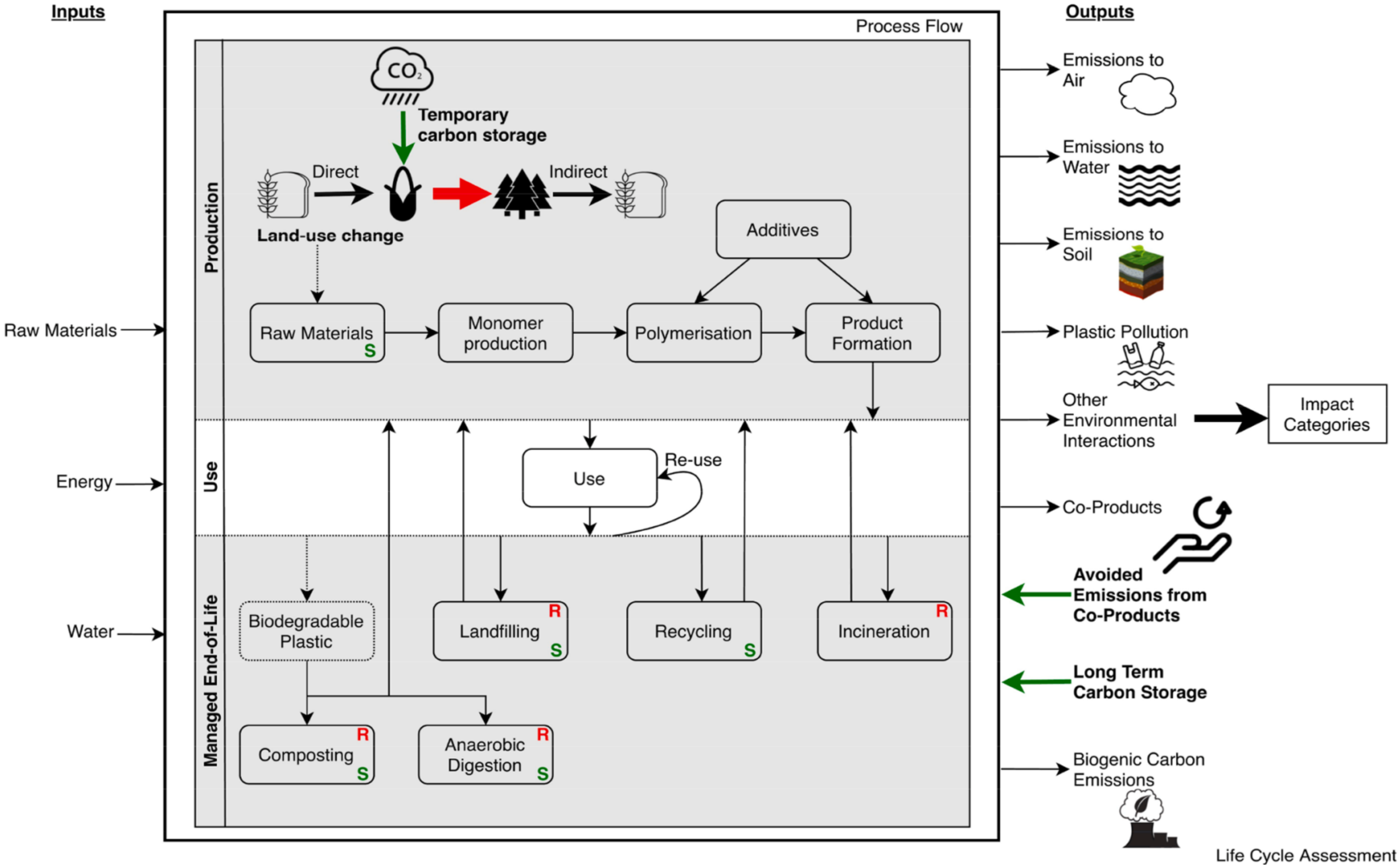

S representing carbon storage, and R representing the release of the carbon.

Resour. Conserv. Recycl., 168, 2021, 105451

Case Study: Environmental Life Cycle Analysis (LCA) of Polyhydroxyalkanoate (PHA) Production (A Techno environmental Assessment)

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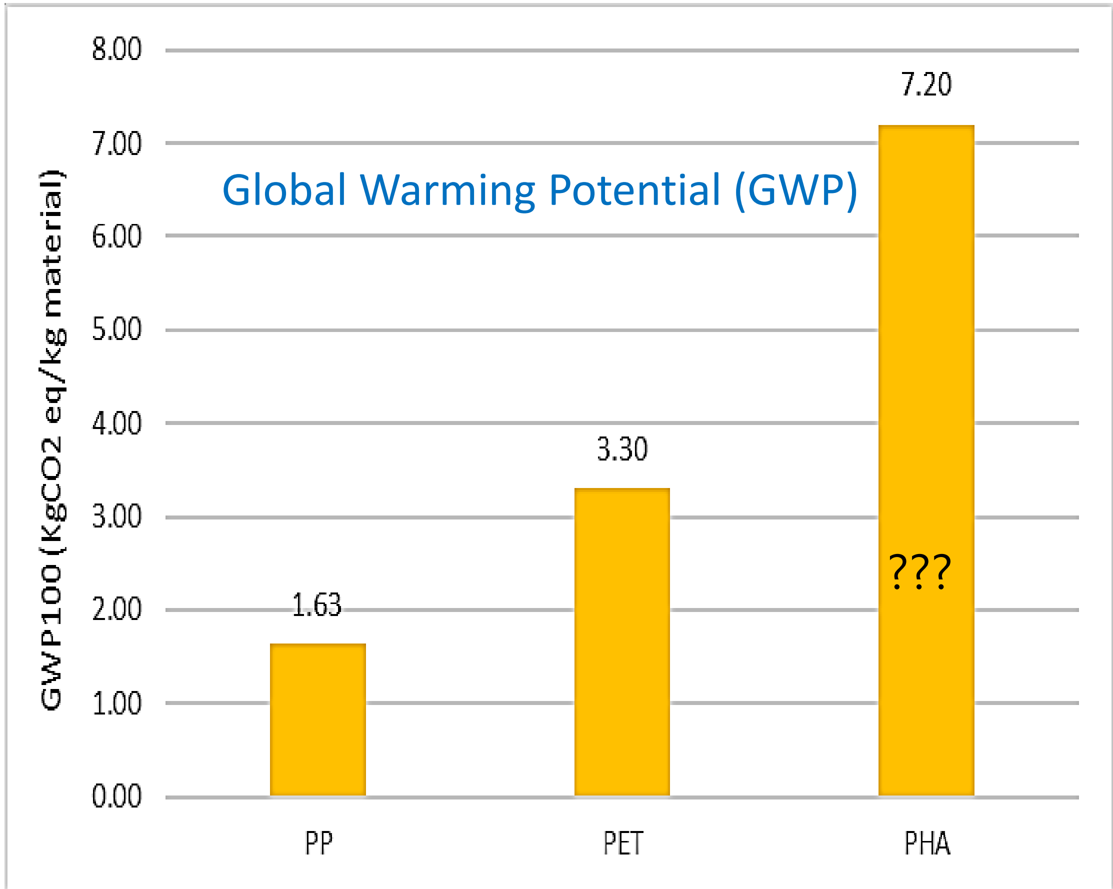
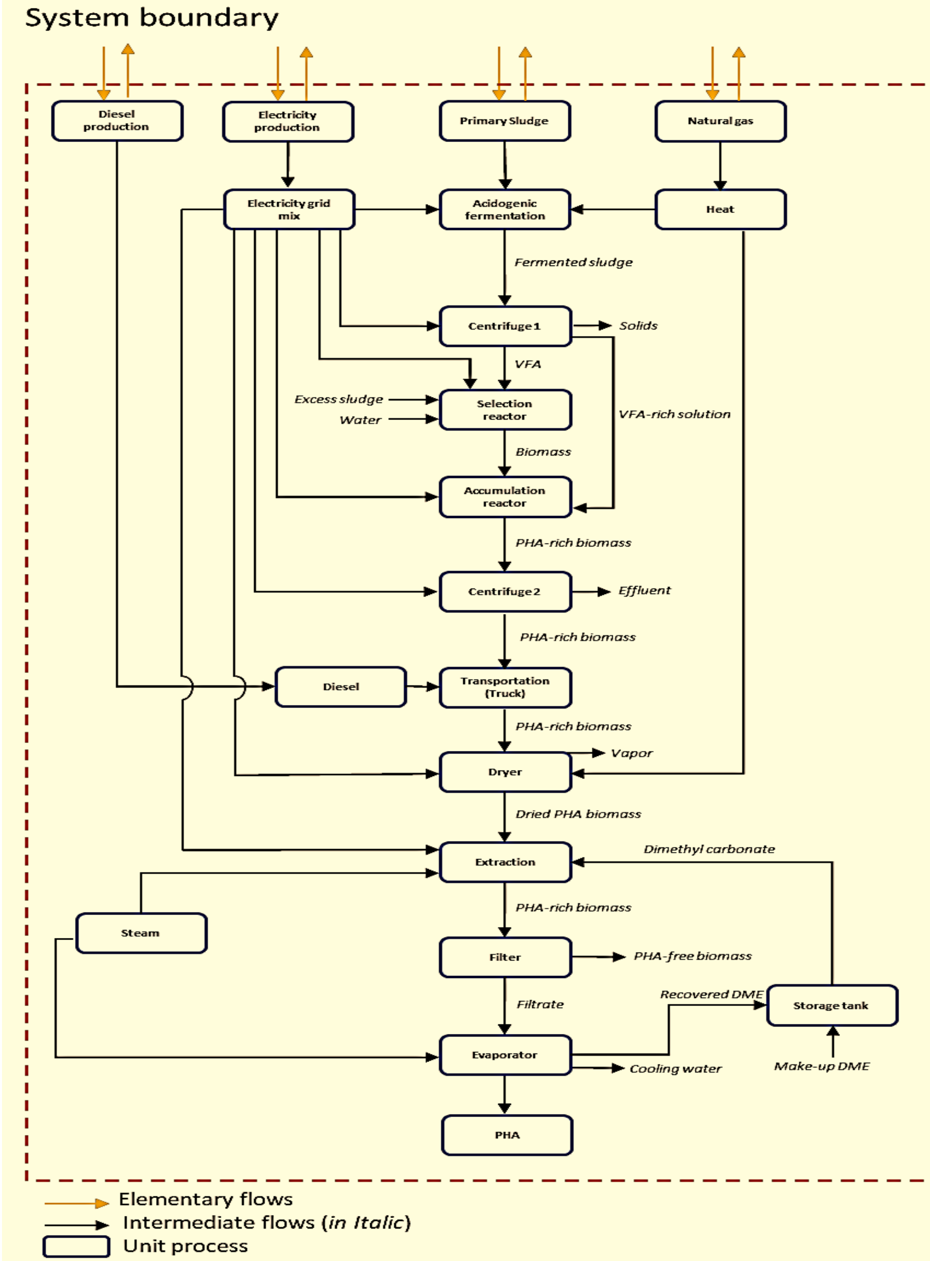
F Abedi – Thesis - Lappeenranta–Lahti University of Technology LUT





Case Study: Techno-economic analysis and life cycle assessment of poly (butylene succinate) production using food waste

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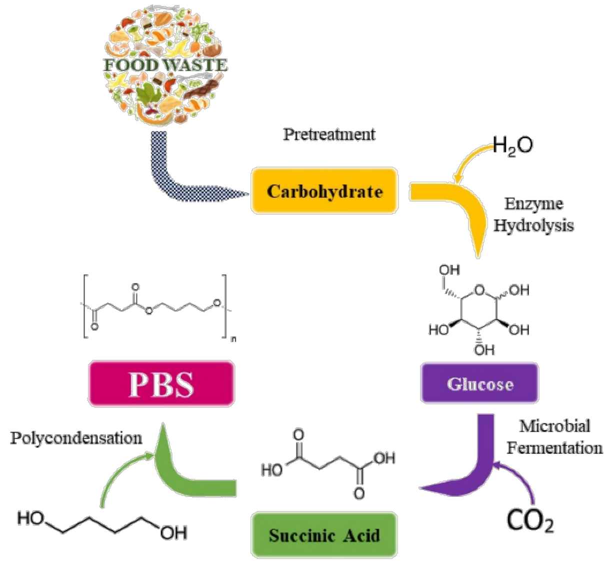
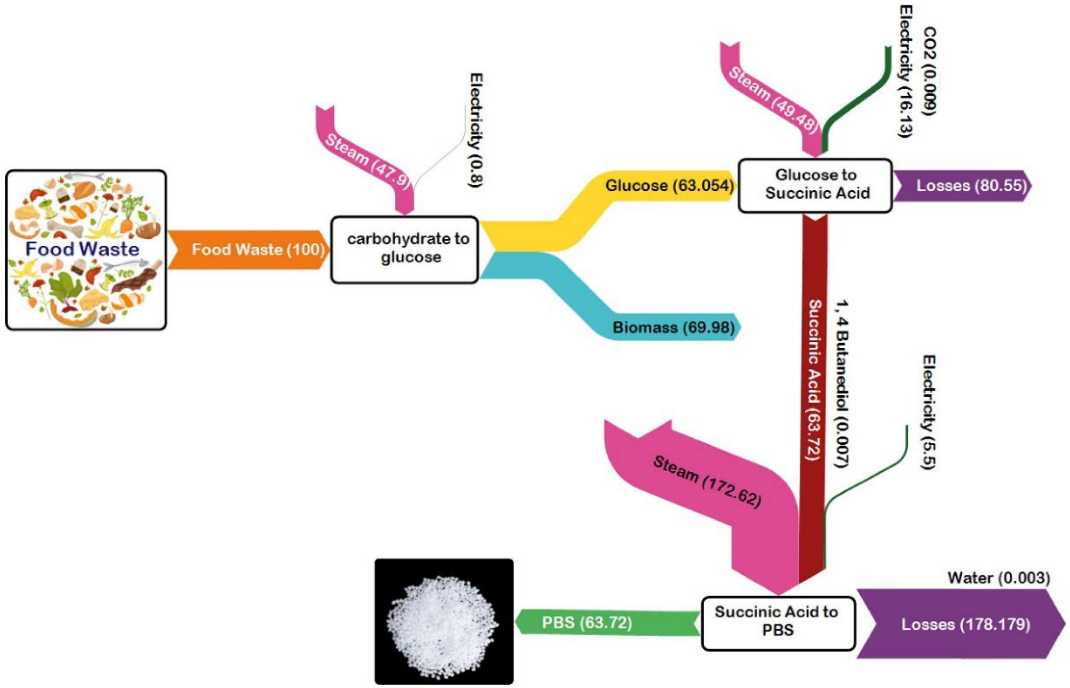
Rajendran and Han, 2023, Waste Management, 156, 168-176

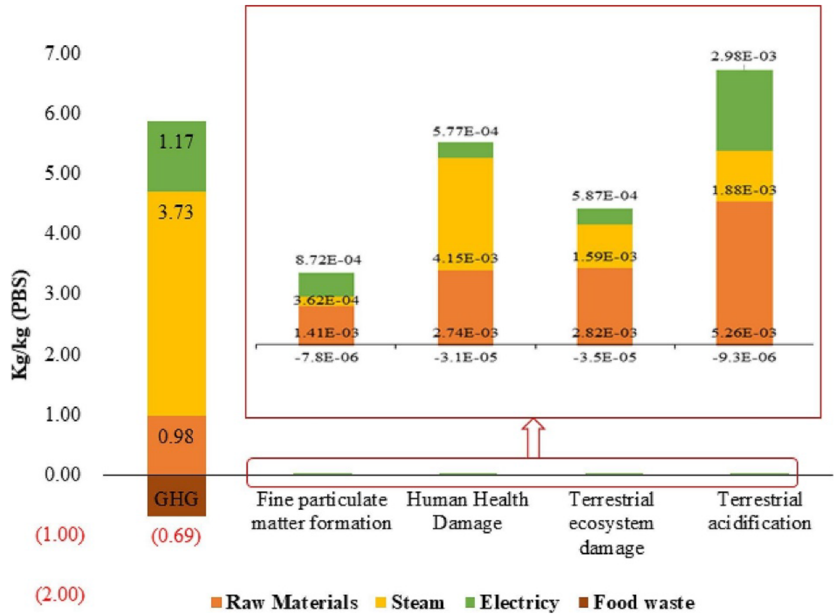
- The production of poly (butylene succinate) (PBS) from food waste was investigated
- The minimum selling price of PBS was calculated as 3.5 $/kg.
- The plant's return on investment (ROI), payback period, internal rate of return (IRR), and net present value (NPV) were 15.79 %, 6.33 years, 16.48 %, and 58,879,000 USD, respectively.
- GHG emission from the process was 5.19 kg CO2-eq/kg of PBS lower than conventional PBS production.



Process pathway of PBS production from food waste.



Energy balance of FW to PBS production.



Environmental impact analysis of PBS production from FW

Comparison of environmental properties and prices of commercially relevant synthetic fossil-based and bio-based polymers

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Polymer	Biodegradation (industrial)	Biodegradation (ocean)	GWP cradle-to-gate (ton CO_2 eq per ton polymer)	AP cradle-to-gate (kg SO_2eq per ton polymer)	Price (US$ per kg)
Fossil-based and durable					
HDPE	NA	NA	1.8–2.6	6–22	1.4–1.6
LDPE	NA	NA	1.9–3.1	27	1.36
PP	NA	NA	1.5–3.6	49	1.1
PS	NA	NA	3.2	NA	0.7–1.5
PET	NA	NA	2.4–5	10–18	1.2–1.4
PVC	NA	NA	1.5–2.2	3	1.9
Fossil-based and degradable					
PBAT	2–3 months	>1 year	NA	NA	4.1
PBS	2–5 months	>1 year	NA	NA	4.5
PVA	1–2 weeks	4 months	NA	NA	2
PCL	4–6 weeks	6 weeks	NA	NA	NA
Bio-based and durable					
PEF	9 months	NA	2.1	NA	NA
bioPET	NA	NA	2–5.5	13–75	NA
bioPE	NA	NA	0.68	30	1.8–2.4
Bio-based and degradable					
bioPBS	>3 months	>1 year	2.2	75	NA
PLA	6–9 weeks	>1.5 years	0.5–2.9	7–21	2–3
PGA	2–3 months	1–2 months	NA	NA	NA
P3HB	1–4 months	1–6 months	−2.3–4	14–25	3–8
P4HB	4–6 weeks	1–6 months	NA	NA	3–8

Global warming potential (GWP) and Acidification potential (AP)

HDPE, high-density polyethylene; LDPE, low-density polyethylene; NA, not available; P3HB, poly(3-hydroxybutyrate); P4HB, poly(4-hydroxybutyrate); PBAT, polybutylene adipate-co-terephthalate; PBS, polybutylene succinate; PCL, polycaprolactone; PE, polyethylene; PEF, polyethylene furanoate; PET, polyethylene terephthalate; PGA, polyglycolic acid; PLA, polylactic acid; PP, polypropylene; PS, polystyrene; PVA, polyvinyl alcohol; PVC, polyvinylchloride.

Nature Reviews Materials, 7, 117–137 (2022)

Technoeconomic Challenges of Bioplastics

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Raw Material Costs: Agricultural feedstocks, are subject to price fluctuations and supply uncertainties, impacting production costs.	**Production Scale:** The smaller production scale for bioplastics, compared to traditional plastics
Bioplastic Conversion Technology: can be complex and costly, affecting overall production costs.	**Infrastructure Investment:** significant investments in new production facilities and equipment.
Bioplastic Properties: requiring adjustments in production processes.	**Limited Feedstock Availability:** The availability of suitable biomass feedstocks for bioplastics is limited, leading to supply chain challenges and potentially increased costs.
Biodegradation Challenges: Biodegradable bioplastics may not always break down efficiently in all environments, leading to uncertainty in their disposal pathways and potential negative impacts.	**Regulatory Environment:** Evolving regulations and standards related to plastics and sustainability influence the adoption of bioplastics
Consumer Acceptance and Demand: Bioplastics may require consumer education and acceptance to sustain demand, especially if they differ from traditional plastics.	**End-of-Life Management: disposal, recycle, repurpose, and upcycle**
Technological Innovation: Ongoing research and development are necessary to improve bioplastic properties, production efficiency, and cost-effectiveness to remain competitive.	**Competing with Petrochemical Plastics:** Bioplastics often compete with well-established petrochemical plastics, which have a significant market share and established supply chains.

Bioplastic Performance: Meeting performance requirements across various applications and industries is crucial for bio plastics' adoption, and developing cost-effective solutions that match or exceed conventional plastics is challenging.

Conclusions

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- B3 plastics can address key challenges in petroleum plastics
- Reuse, repurpose and upcycle of petroleum plastic should be done in parallel with B3 plastic
- Large scale of B3 plastic production comparable to petroleum plastic is essential to better compare **GHG emissions reduction and cost**
- **Properties** of B3 plastics for target plastics should be studied more to penetrate into market
- **Clear regulation and financial incentives** remain essential to scale from niche polymers to large-scale bioplastic market applications with truly sustainable impact

Thank you
for your attention~