Type them into questions box!

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SOLVING the plastic waste PROBLEM

Novel Chemical Pathway Upcycling & Chemical Recycling

Co-produced with the ACS Division of Polymer Chemistry

THIS ACS WEBINAR WILL BEGIN SHORTLY...
Solving the Plastic Waste Problem: Novel Chemical Pathway Upcycling and Chemical Recycling

Presentation slides are available now! The edited recording will be made available as soon as possible.

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This ACS Webinar is co-produced with ACS Division of Polymer Chemistry.

CHEMICAL RECYCLING: PERSPECTIVES FROM THE FAST MOVING CONSUMER GOODS INDUSTRY

Dr. Philippe REUTENAUER
**DISCLAIMER**

- The perspectives presented in this webinar are a collective from my professional experiences in the packaging R&D at Danone and Léa Nature. Any opinions are my professional opinions and do not represent those of my current or former employers.

- The situation depicted is the one I perceive from Europe.

---

**CIRCULARITY APPLIED TO PACKAGING**

Provide a frame for thinking packaging material flux
EVOLVING THE PLASTIC RECYCLING SUPPLY CHAIN

A polymer approach to circularity

Message: What can be done/What needs to be done

CHEMICAL RECYCLING EXTENDS THE RANGE OF FOOD CONTACT APPROVED RECYCLED PLASTICS

For most of the main plastics used for food packaging, the existing mechanical recycling is not sufficient to allow food contact again.
**GLOSSARY**

- **PEs**: PolyEthylenes  
  - LDPE: Low Density PolyEthylene  
  - LLDPE: Linear Low Density Polyethylene  
  - HDPE: High Density PolyEthylene (d > 940 g/L)
- **PPs**: PolyPropylenes
- **PETs**: PolyEthyleneTerephthalates
- **PSs**: PolyStyrenes

* r added before means recycled. e.g. rPET = recycled PET

---

**Audience Survey Question**

**ANSWER THE QUESTION ON BLUE SCREEN IN ONE MOMENT**

Which of the following has the highest plastic recycling rate in the world?

- United States
- Mexico
- India
- South Korea
- European Union

* If your answer differs greatly from the choices above tell us in the chat!
Plastic recycling rates vary a lot from one country to another.

MECHANICAL RECYCLING OF PET

• Bottle Grade PET is the best recycled plastic.

• rPET is the only mechanically recycled plastic approved for food contact in Europe (by EFSA) operated at large scale.

• Still limited to recycling of PET bottles
  • Homogeneous in chemical composition
  • Almost only clear and light blue bottles are recycled bottles to bottles. With discoloration challenges …
  • Colored bottles go to fibers

• Opaque PET bottles and PET trays recycling is starting

https://www.intermarche.com/enseigne/magazine/bouteille-lait-recyclee
PET recycling process

… omitting one of the most important step: solid state polymerization

MECHANICAL WAY TO rPET (AT RECYCLERS)

- PET bottle sorting (color)
- PET bottles washing
- Grinding
- Separation by floating
- Extrusion into pellets
- Solid state polymerization (SSP)

![Mechanical way to rPET diagram](image)

- Removal of volatile contaminants
- Creation of new ester bonds (equilibrium)
- Specific to polyesters

![Mechanical way to rPET process](image)
MECHANICAL RECYCLING OF PE

- Higher variety: LDPE, LLDPE, HDPE
- Even among HDPE, high variety of properties linked to chain composition -> comonomer type
topology -> polymerization mechanisms
polydispersity -> type of catalyst, reactor(s) type
- Colors ...
- Additivation
- Contaminations
- Only C-C bonds!
- What can be expected from such a mixture?
  - Mediocre properties, gray color, no food contact aptitude

HDPE RECYCLING: RARE CASE OF FOOD CONTACT HDPE

Specific segregated stream of HDPE bottles
MECHANICAL rPP’S CASE

• Even worst as even more dimensions:
  • Tacticity
  • Ethylene content
  • Chain topology (blocks)


CHEMICAL RECYCLING OPENS NEW ROUTES

• Polyester: harnessing the reversibility of the ester bond

• Polyolefins: pyrolysis to cleave C-C bonds

---

Ex: PVC Dissolution

Ex: PET solvolysis

Ex: PE/PP/PS Pyrolysis → Oils
**Chemical rPET**

- **Diverse routes:** hydrolysis, methanolysis, glycolysis + enzymatic
  Depolymerization followed by monomers separation
  Difficulties: heterophasic + mixture chemistry

- **Address different feedstocks:** multilayer bottles, colored bottles, pouches (specially if monoPET), textile, carpets
- **Selectively address polyesters in polymers’ mixtures**

- **Manage expectations:** purification cost will be high!
  -> The cruder the starting material,
  the more difficult to go to high purity.

- **Example of actor:** Loop Industry

---

Anellotech aims to convert large volumes of mixed waste plastics... 

...directly into the same valuable chemicals (using new technology Plas-TCat)... 

...widely used today in packaging and other products. 

...that manufacturers buy to produce the plastics...

Could this become true? 
Where are the heteroatoms going?
**PYROLYSIS: CRACKING POLYOLEFINS WASTES**

- Produce from Mixed Plastic wastes virgin quality polyolefins
- Mass balance approach
  - impossible to communicate to general audience
- Manage expectation

---

SABIC AND PLASTIC ENERGY SET TO START CONSTRUCTION OF PIONEERING ADVANCED RECYCLING UNIT TO INCREASE PRODUCTION OF CERTIFIED CIRCULAR POLYMERS

21/01/2021

... is expected to become operational in the second half of 2022

SABIC’s certified circular polymers are produced using Plastic Energy’s advanced recycling technology to convert low quality, mixed, and used plastic, otherwise destined for incineration or landfill, into TACOIL. The TACOIL produced in the new commercial unit will be used by SABIC in their production process as an alternative to traditional fossil materials to create new circular polymers.
WHAT ABOUT PS?

Total, Intruplas and Yoplait successfully demonstrated the feasibility of incorporating recycled polystyrene from chemical recycling into yogurt pots.

Paris, 7 December 2020 - Total, Intruplas and Yoplait announced today that they have successfully run a pilot test aiming at using certified chemically recycled polystyrene in yogurt pots. This is the first step of a collaborative initiative aiming at testing the use of chemically recycled polystyrene in yogurt pots, supporting the development of sustainable PS recycling in France.

ADVANCED RECYCLING / TECHNOLOGIES

<table>
<thead>
<tr>
<th>Waste %</th>
<th>INPUT (WASTE STREAM)</th>
<th>ADVANCED RECYCLING TECHNOLOGY</th>
<th>OUTPUT COMMODITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>70%</td>
<td>Polyethylene &amp; Polypropylene</td>
<td>Thermal Cracking</td>
<td>Solvent, Naphthal, Oil, Wax</td>
</tr>
<tr>
<td></td>
<td>PET - Polyethylene Terephthalate</td>
<td>Depolymerization</td>
<td>Monomers, Polymers (PET, PBT)</td>
</tr>
<tr>
<td>15%</td>
<td>Polystyrene</td>
<td>Solvolysis</td>
<td>Styrene, Polymers (EPS, PS)</td>
</tr>
<tr>
<td>10%</td>
<td>Others</td>
<td>Thermal Cracking, Solvolysis</td>
<td>Syngas, Monomers, Naphthal, Diesel</td>
</tr>
<tr>
<td>5%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CHEMICAL RECYCLING IS AN ACTIVE FIELD

Some actors on chemical recycling (non exhaustive list)
A very international field of research

Reproduced from Citéo, 2020

CONCLUSIONS

• Effective recycling technologies are needed to allow us solving issue of single use plastic and save our lifestyles & planet

• The culture of plastic collection and sorting after use must spread

• Can plastic evolve to become more recyclable?

THROUGH CHEMISTRY!
The Problem: Polyethylene

PE makes up over 1/3 of globally produced plastic!¹

¹Geyer, R. et al. Science Advances. 3 (7)
There is a reason we can’t go backwards...

Plastics:
• Strong
• Light-weight
• Flexible
• Durable
• Stable
• Anti-microbial
• Barrier properties

These are not more sustainable materials...

The Solution:
Innovative Recycling Technologies

Mechanical Recycling
Biological Recycling
Chemical Recycling
What types of plastic packaging can you NOT put in your recycling bin at home? (select all that apply)

- HDPE grocery bags
- LDPE dry cleaning bags
- HDPE laundry detergent bottles
- Plastic liners for cereal boxes
- PET water bottles

*If your answer differs greatly from the choices above tell us in the chat!

Mechanical Recycling

What happens when recycled products become oversaturated with “legacy” additives?

Some Common Plastic Additives
**Biological Recycling**

**Polyethylene Terephthalate (PET)**

- PETase enzyme expressed from *Indeonella Sakaiensis* can cleave PET at the ester bonds and depolymerize the plastic
- Biorecycling process takes up to six days and has been demonstrated on low crystallinity PET films

**Chemical Recycling**

**Chemical Extraction of PP**
- Removal of small molecules (additives, pigments, etc.)
- "Virgin"-like polymer

**Depolymerization of PET**
- Glycolysis
- Microwaves
- Diols and diacids

**Depolymerization of PS**
- Microwaves
- Heat + Catalysts
- Styrene monomers

**Pyrolysis & Gasification**
- 600-1000°C
- Mixed plastics
- Fuel/Naphtha

---


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*BioCellection Inc.*

---

*BioCellection Inc.*
PE continues to be a significant challenge...

**Mechanical Recycling**
- PE degrades during multiple heat processing
- Recycle streams become saturated with additives

**Biological Recycling**
- PE structure not compatible with biological systems
- Very long time frames & high costs

**Chemical Recycling**
- Requires very high temperatures
- Multi-step process to achieve new polymer

---

**Thermo-Oxidation of Polyolefins**
Polyethylene readily undergoes auto-oxidation

Auto-oxidation results in:
• Alcohols
• Aldehydes
• Ketones
• Carboxylic Acids
• Discoloration
• Microplastics


ATOD™ Chemical Recycling

ATOD™

BioCollection

Dicarboxylic Acids (DCA's)

Materials synthesis

Quality polymers, consumer

Chemical recycling

Oxidant

BioCollection

Post-Consumer Polyethylene

Hard-to-recycle

Film waste

Shipping

Food packaging waste

Degradation of PE over time

Taking a closer look at PE oxidation...

Carbon centered free radical!
Upcycling Intermediates into New Products
Virgin quality monomers can be made into new, valuable materials

- Polyamides
- Esters
- Polyurethanes
- Polyesters
- Surfactants
- Additives

Unique functionality on polyester backbone yields higher tensile strength when compared to virgin counterparts!

Polyester component is made up of recycled DCA monomers

Thermoplastic Polyurethane Elastomers
High performing polymers designed for long lifetimes

What was once garbage…

Average Price of Virgin Polyethylene: $0.75/kg

Average Price of Virgin TPU: $5-15/kg

---

XIRC TPU’s in Action

**Elongation:** XIRC vs. Virgin TPU

**Grip Strength:** XIRC vs. LDPE

**Adhesion:** XIRC vs LDPE

**Rebound:** XIRC vs. Synthetic Rubber & LDPE

**Strength:** XIRC vs. HDPE Bag

---

Our Materials are Sustainable
Superior Environmental Footprint to Existing Sources

Cradle-to-gate LCA scoping to compare the production of a PU from a conventional route to a PU made of upcycled plastic.

We started out at the benchtop…

100 mL: 0.0025Kg PE/Day
250 mL: 0.0125Kg PE/Day
10 Liters: 0.5 Kg PE/Day
100 Liters: 50 Kg PE/Day
What else can we do with DCA’s?

DCA’s Are Excellent Microbial Feedstocks

*With unique metabolic pathways in yeast*

- DCA’s act as a carbon source for aerobic growth of diverse microbial strains
- Succinyl-CoA enters TCA cycle to provide energy for host growth and metabolism
- Acetyl-CoA is a building block for **carotenoids**

**Polyesters**

**Nylons**

**Polyurethanes**

**Esters**

**3D Printing**

**Shoe: adidas.com**

**Microbes: sciencefriday.com**
Chemical + Biological Innovations

Dicarboxylic Acids (DCA's)

Conagen Fermentation → Carotenoid Production

Beta-carotene, Vitamin A, Astaxanthin & Canthaxanthin

• Cosmetic → anti-aging, acne prevention, reduces wrinkles
• Supplement → Dietary supplements for eye and skin health
• Animal Feed → Feed for salmon and chickens for coloration

BioCollection

2019 Rolex Awards Laureate Documentary: Miranda Wang

https://youtu.be/eXqLs7xkA
Thank-you!

katrina@biocellection.com

Solving the Plastic Waste Problem: Novel Chemical Pathway Upcycling and Chemical Recycling

Philippe Reutenauer
Sustainable Packaging Manager, Léa Nature

Katrina Knauer
Senior Scientist, Materials Innovation Lead, BioCellection Inc.

Peter Boul
Senior Research Scientist, Aramco Americas

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