BEYOND MECHANICAL PLASTIC RECYCLING

ADVENT OF HYBRID RECYCLING TECHNOLOGIESS

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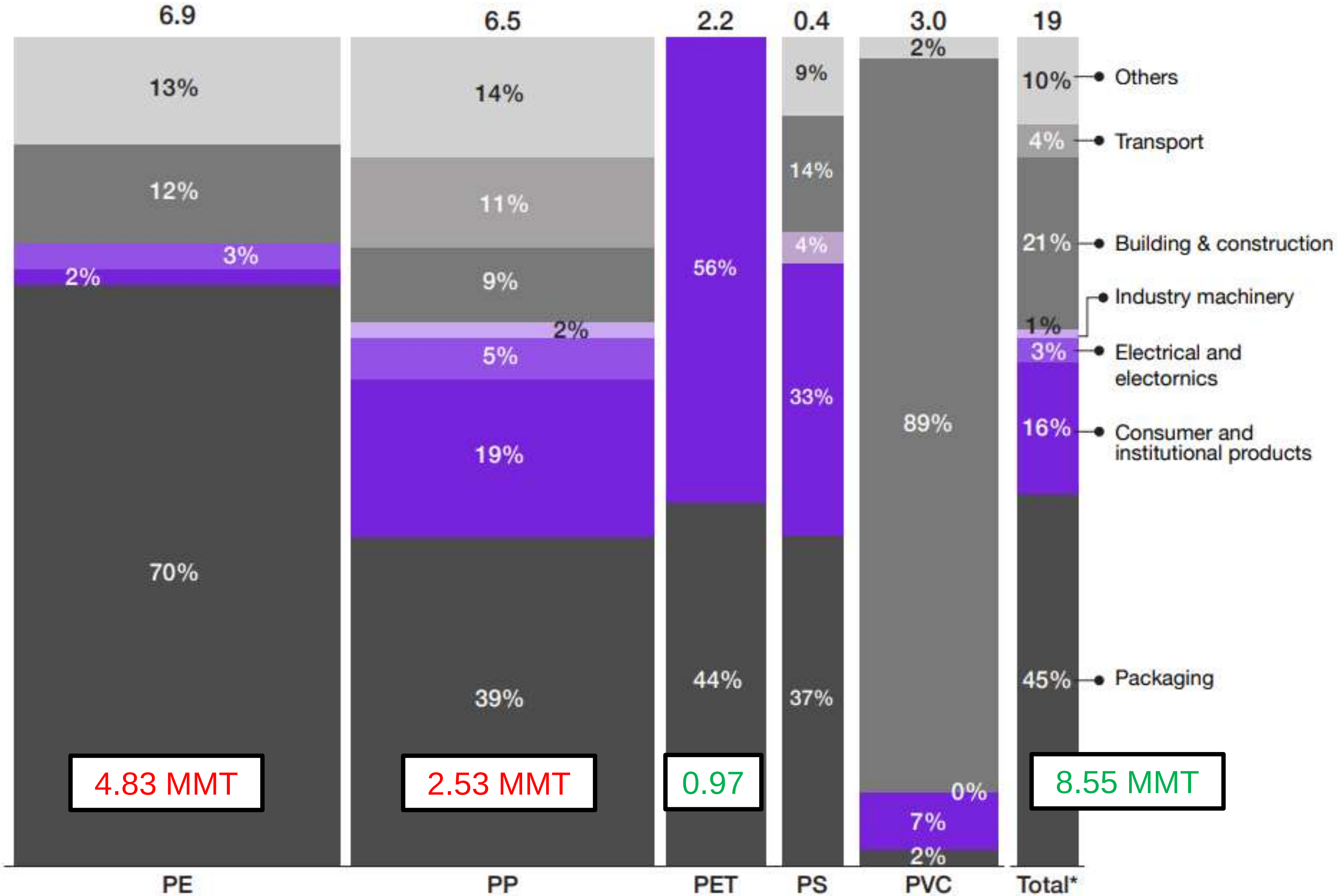
Points for Discussion

1. Limitations of mechanical recycling
2. Classification of alternative recycling technologies
3. Mechanical – Chemical hybrid recycling technologies
   > De-inking (removal of surface printing) of films
   > Targeted Solvent Dissolution & Precipitation for polymer recovery
4. Chemical Recycling – Depolymerization
   > Solvolysis (glycolysis & methanolysis of rPET)
   > Bio Enzymatic Recycling of PET
5. Chemical Recycling – Conversion
   > Pyrolysis (value added products by hydroformylation)
   > Gasification (syngas)
6. How India uses virgin plastics (proxy for feedstock availability)
7. Polymer – end application – collection -- recycling technologies

Symbol	Polymer Name	Product Examples		
1 PETE	Polyethylene Terephthalate (PETE or PET)	• Soft drink bottles • Water bottles • Sports drink bottles • Salad dressing bottles • Vegetable oil bottles	• Peanut butter jars • Pickle jars • Jelly jars • Prepared food trays • Mouthwash bottles	
2 HDPE	High-density Polyethylene (HDPE)	• Milk jugs • Juice bottles • Yogurt tubs • Butter tubs • Cereal box liners	• Shampoo bottles • Motor oil bottles • Bleach/detergent bottles • Household cleaner bottles • Grocery bags	
3 V	Polyvinyl Chloride (PVC or V)	• Clear food packaging • Wire/cable insulation • Pipes/fittings • Siding • Flooring	• Fencing • Window frames • Shower curtains • Lawn chairs • Children's toys	
4 LDPE	Low-density Polyethylene (LDPE)	• Dry cleaning bags • Bread bags • Frozen food bags • Squeezable bottles • Wash bottles	• Dispensing bottles • 6 pack rings • Various molded laboratory equipment	
5 PP	Polypropylene (PP)	• Ketchup bottles • Most yogurt tubs • Syrup bottles • Bottle caps • Straws	• Dishware • Medicine bottles • Some auto parts • Pails • Packing tape	
6 PS	Polystyrene (PS)	• Disposable plates • Disposable cutlery • Cafeteria trays • Meat trays • Egg cartons	• Carry out containers • Aspirin bottles • CD/video cases • Packaging peanuts • Other Styrofoam products	
7 OTHER	Other Plastics (OTHER or O)	• 3/5 gallon water jugs • Citrus juice bottles • Plastic lumber • Headlight lenses • Safety glasses	• Gas containers • Bullet proof materials • Acrylic, nylon, polycarbonate • Polylactic acid (a bioplastic) • Combinations of different plastics	

Applications of plastics in India (in million metric tons) as of FY2023 has been shown below:



Note: *sum of PE, PP, PET, PS and PVC, which account for ~90% of India's demand.
Source: Plastindia foundation, Kearney

Ref: Solving Plastic Waste: Roadmap for a Sustainable Future, Kearney & CII - 2024

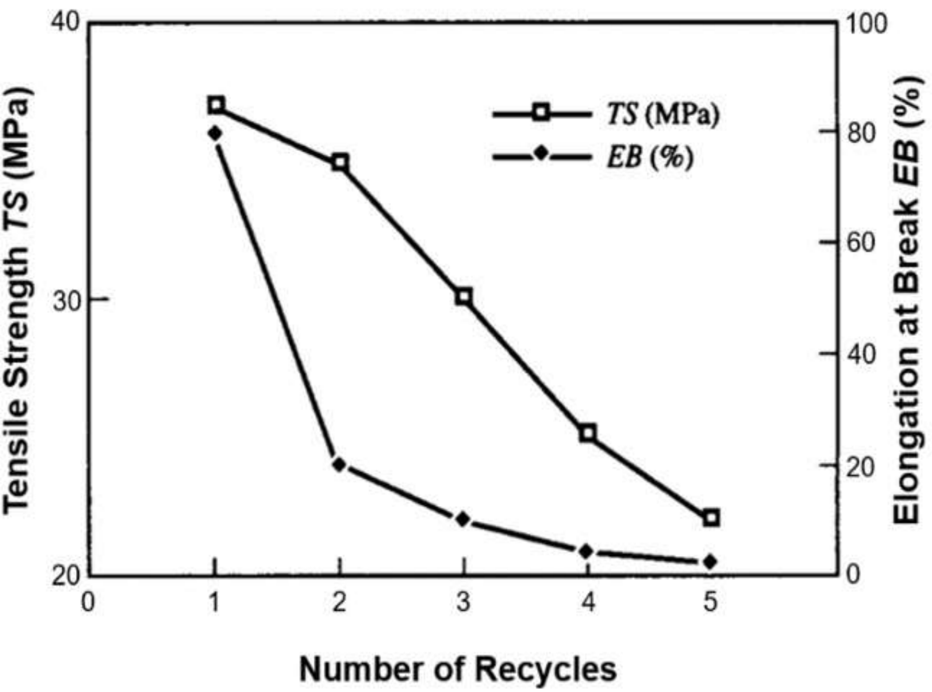
Limitations of Mechanical Recycling of Thermoplastics

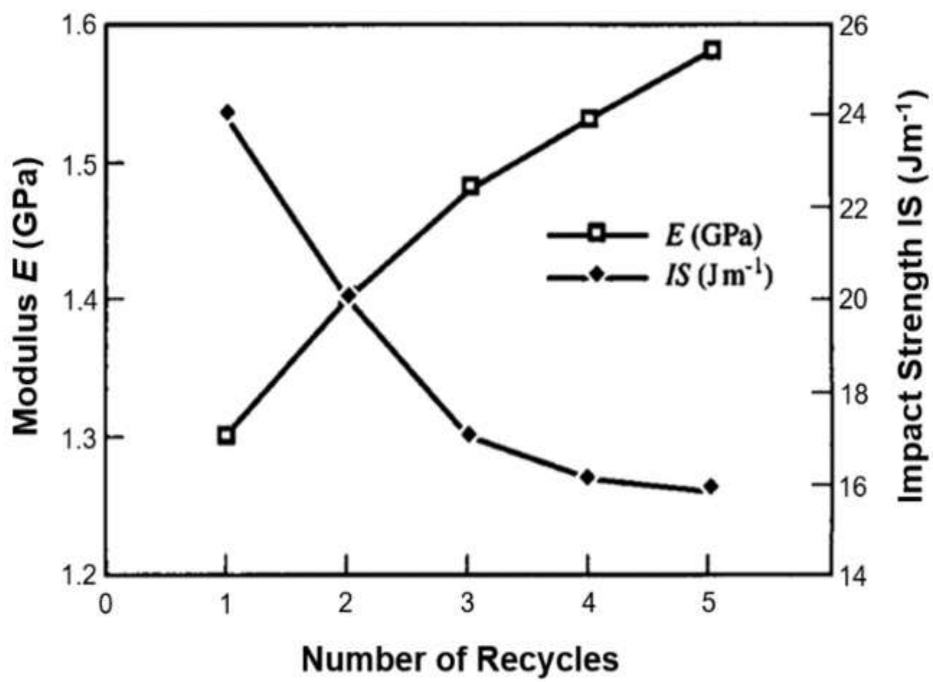
1. Limitations regarding the types of polymers and formats it can process (for example, flexible films, multilayer structures).
2. Quality of the polymer deteriorates with each recycling cycle leading to losses in material properties and build-up of additives and other contaminants.
3. Legal frameworks at present put strict limitations on the mechanical recycling of materials to be used for food contact applications.
4. It is becoming increasingly clear that the volumes of recyclate required for legislative targets and voluntary brand commitments cannot be delivered by mechanical recycling alone within the given time frame.

Down Cycling of Mechanically recycled Post Consumer Thermoplastics

- Due to the chemical & physical forces at play during extrusion, mechanical recycling deteriorates mechanical properties of the recycled polymer.
- Contamination of recycled material contributes to the decrease in quality and increase in variability of the regenerated polymer
- Discolouration / Odour - VOCs / Microbial Contamination
- Pigments accelerate degradation reactions within extruders
- Printing inks / labels introduce volatile organic components
- Fatty-acid based lubricants oxidized to produce unwanted odours
- Additives: AO, Heat Stabilizer, Light Stabilizer, Chain Extenders, AA scavengers, O_2 scavengers, UV absorber, tinting MB etc.
- Non-Intentionally Added Substances increases with each cycle
- Inorganic contaminants & additive degradation products increases with each recycle

Drop in TS & Impact strength of PET with Recycle Frequency





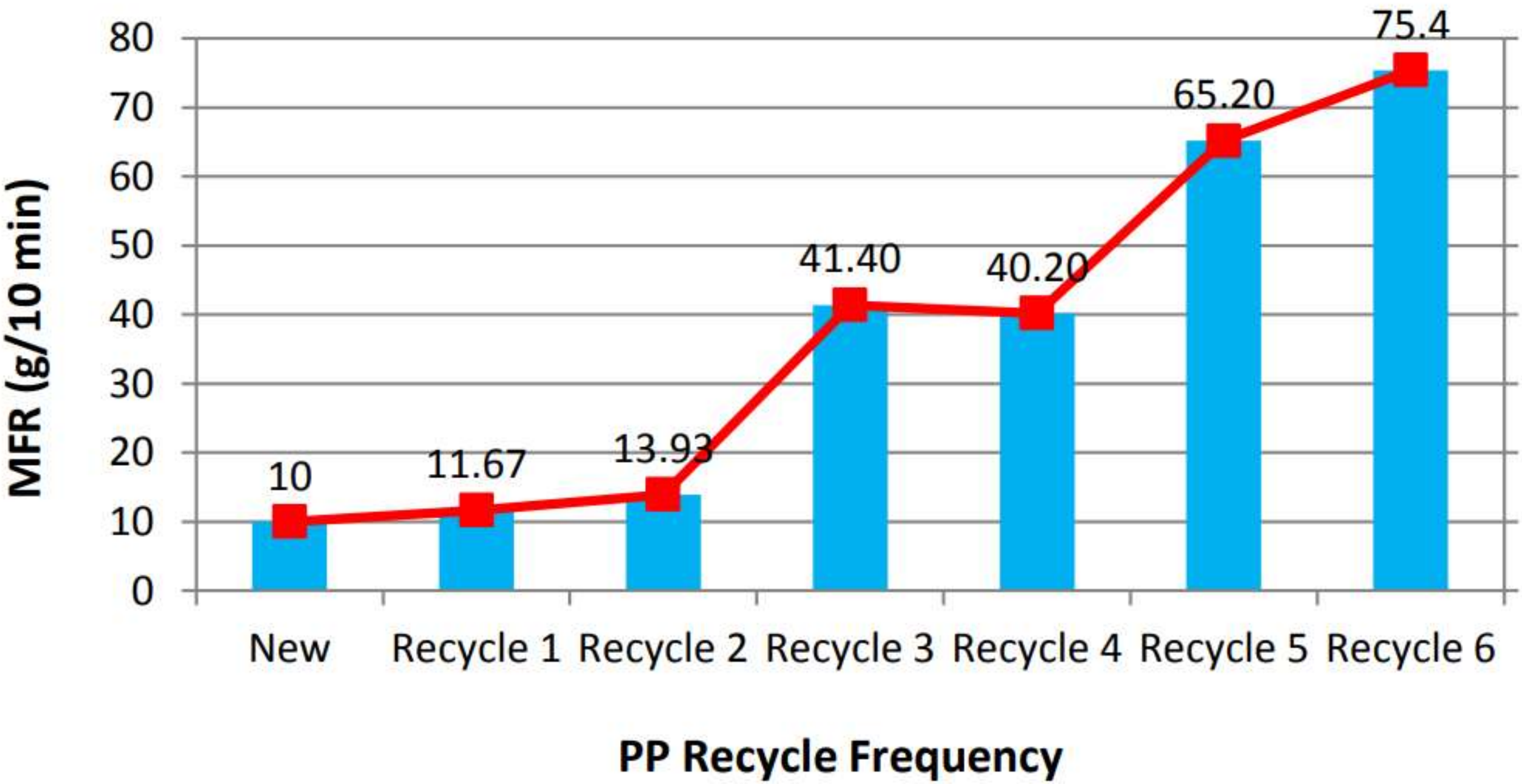
<u>Left:</u> Tensile strength and elongation at break versus number of recycles for PET.

<u>Right:</u> Young's modulus and impact strength versus number of recycles for PET.

Ref: Mechanical recycling of packaging plastics: A review

Macromolecular Rapid Communications (2020)

Increase in MFR with PP Recycle Frequency



Melt Flow Rate (PP) at 230 ºC / 2.16 kg in g / 10 min as per ASTM D1238

Ref: The Effect of Recycling Frequency on the Melt Flow Rate of Polypropylene API Conference Proceedings March 2024

FIGURE 4. Melt flow rate result of as received specimen

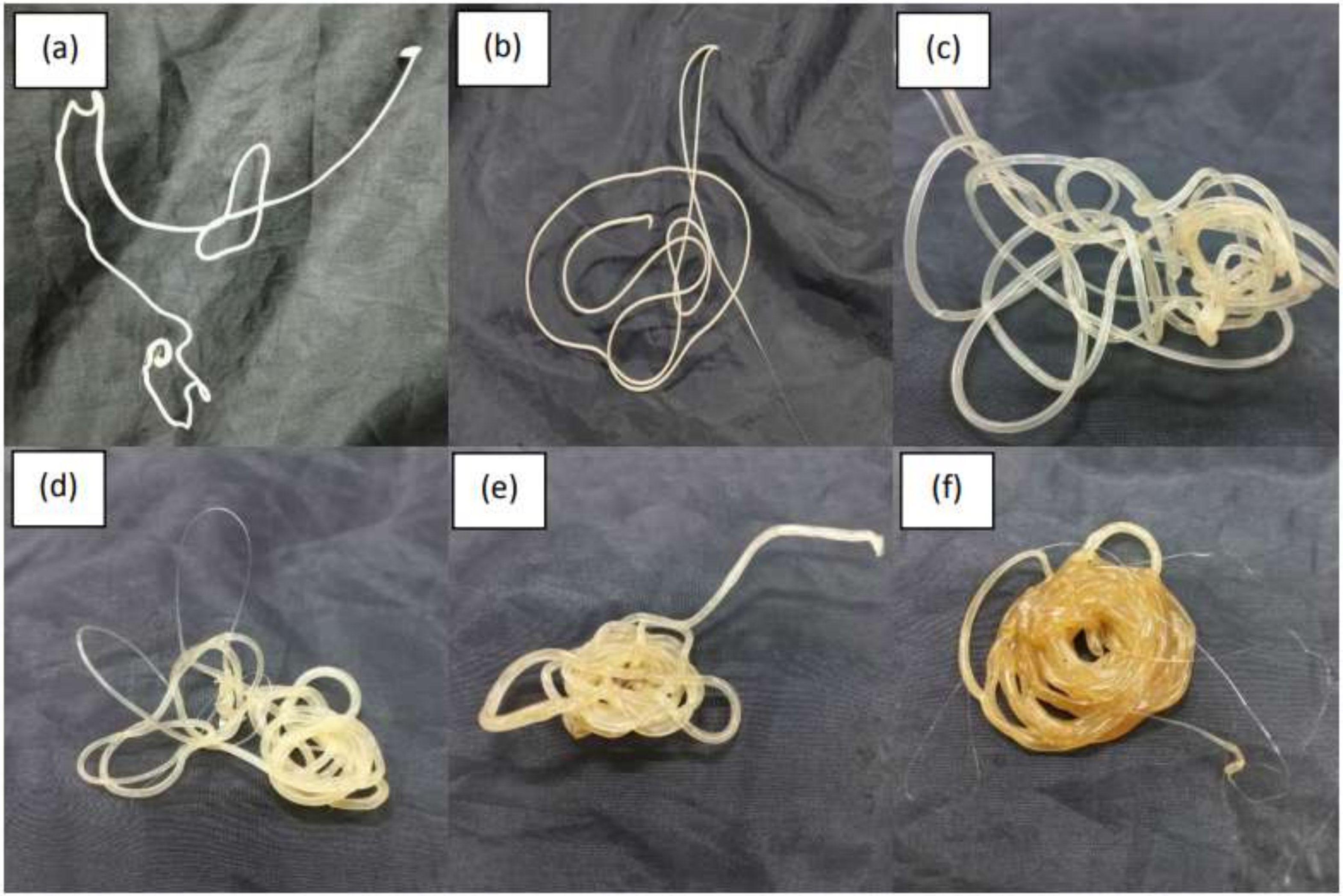
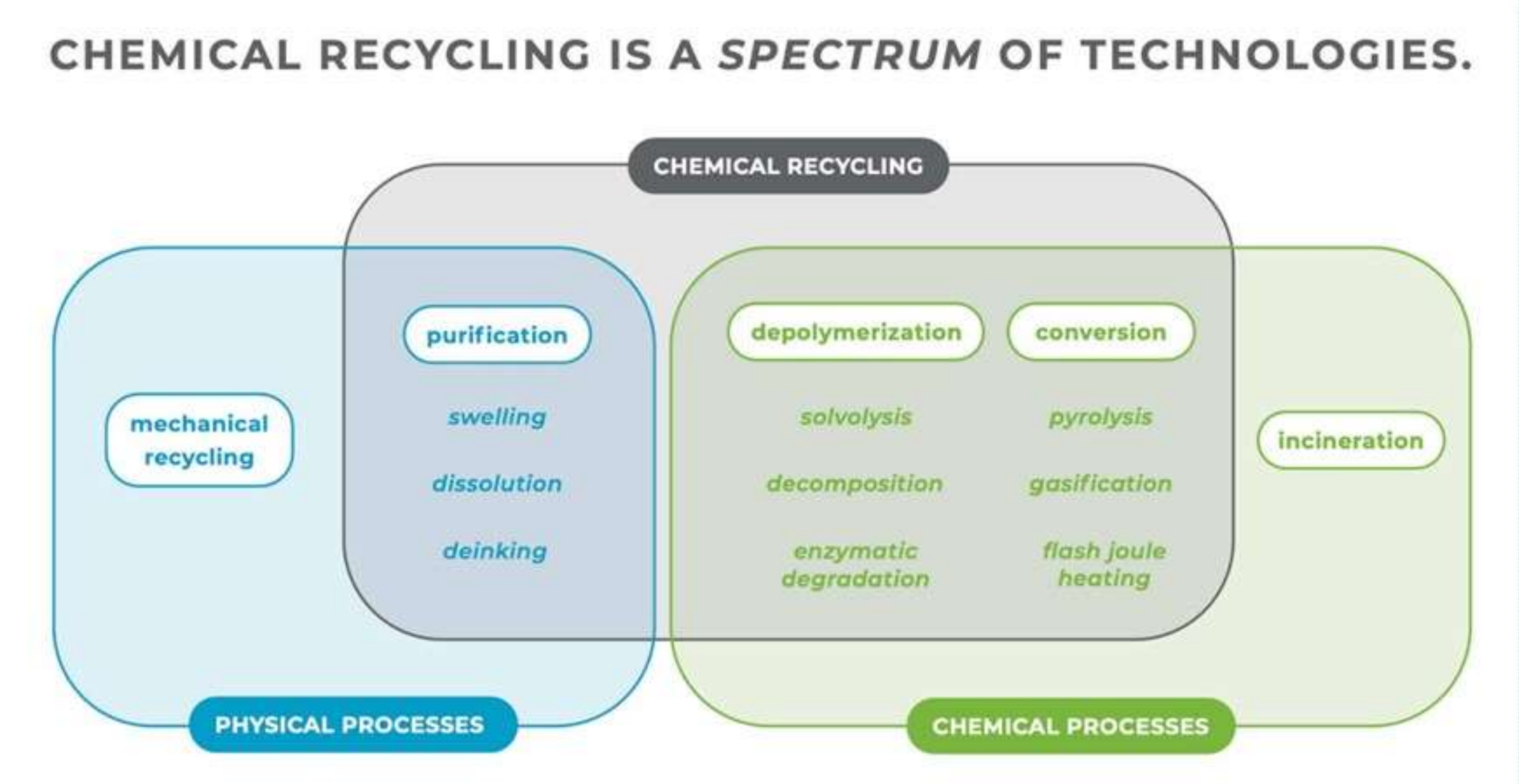
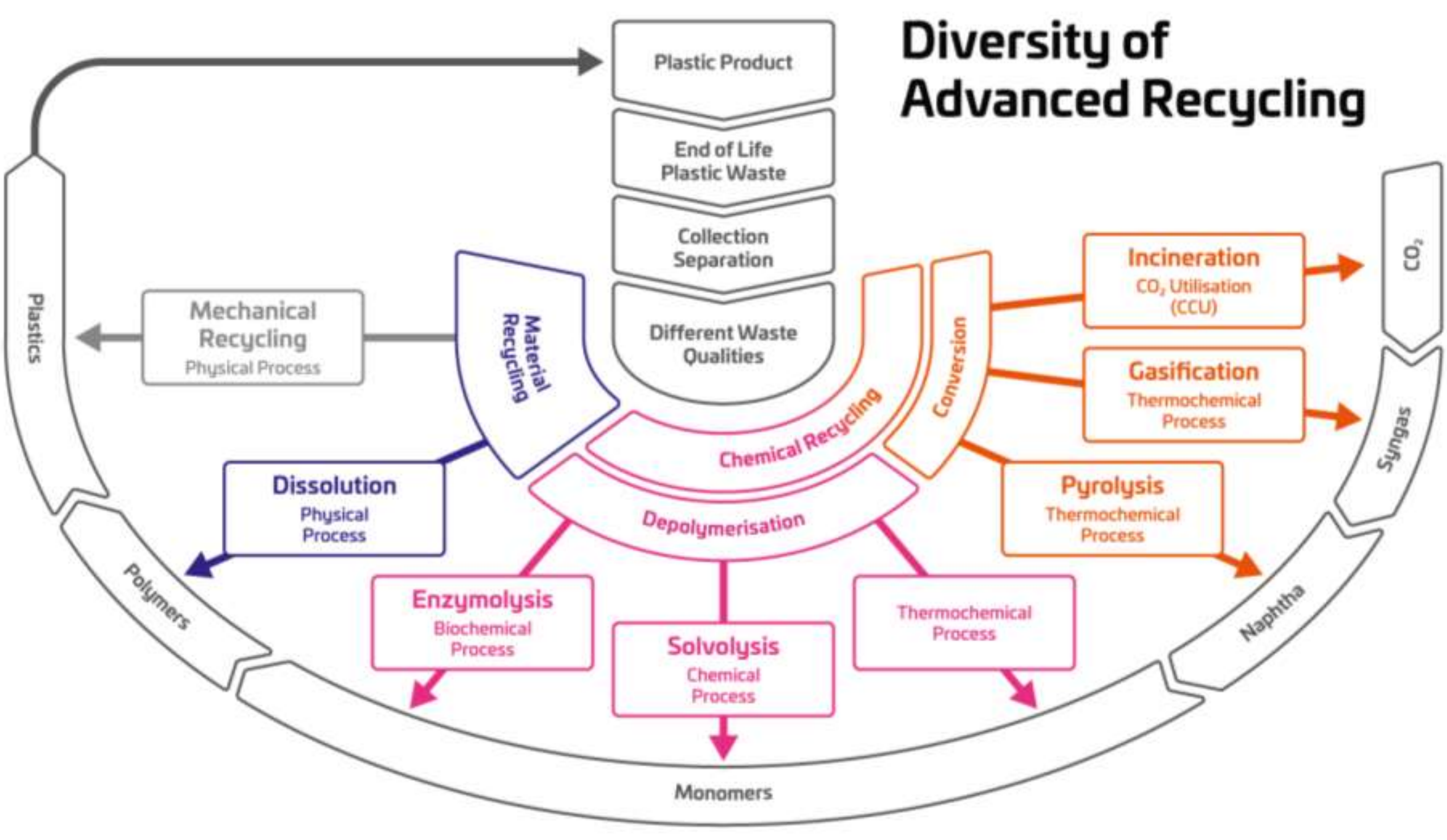


FIGURE 5. Melt flow rate result at (a) first recycle, (b) second recycle, (c) third recycle, (d) fourth recycle, (e) fifth recycle, (f) sixth recycle.

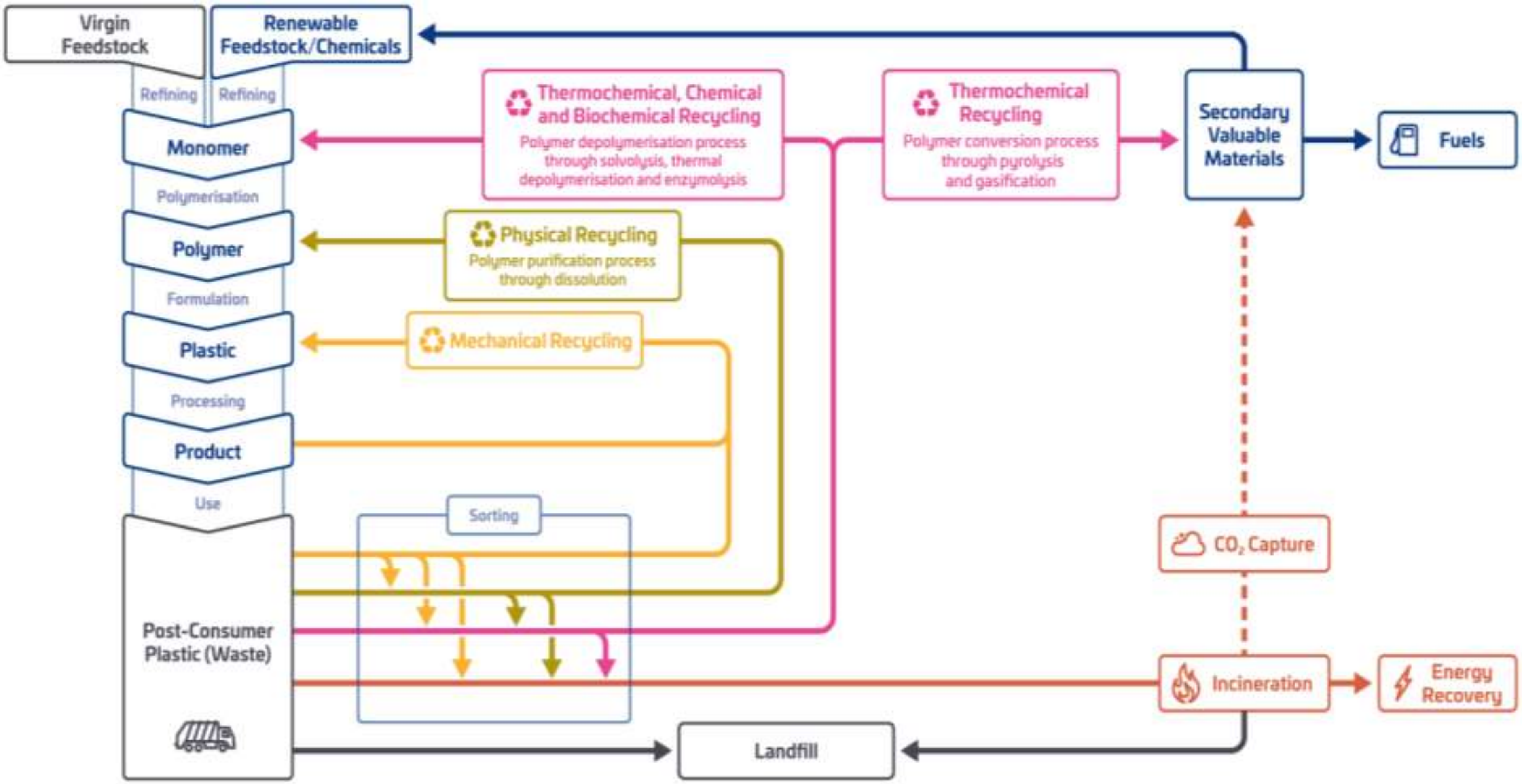


CHEMICAL RECYCLING IS A SPECTRUM OF TECHNOLOGIES.
CHEMICAL RECYCLING
mechanical recycling
purification
swelling
dissolution
deinking
depolymerization
solvolysis
decomposition
enzymatic degradation
conversion
pyrolysis
gasification
flash joule heating
incineration
PHYSICAL PROCESSES
CHEMICAL PROCESSES



Source: www.renewable-carbon.eu/graphics

Spectrum of available recycling technologies based on their basic working principles

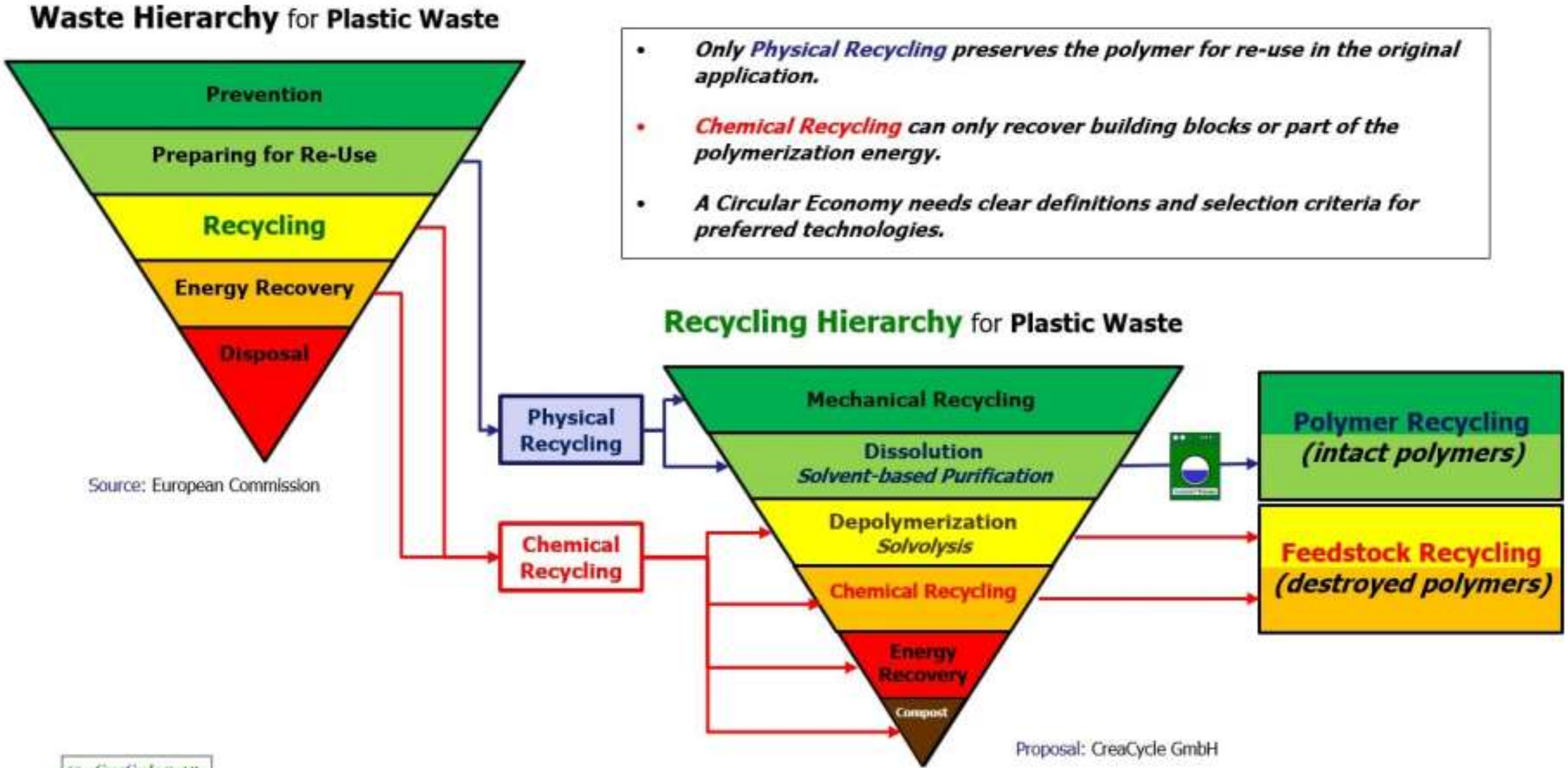


Source: " Mapping of advanced technologies for plastic waste" Nova Institute, Germany

No Waste Hierarchy without Recycling Hierarchy for Plastic Waste

Selection Criteria for a Circular Economy

- ***Only Physical Recycling preserves the polymer for re-use in the original application.***
- ***Chemical Recycling can only recover building blocks or part of the polymerization energy.***
- ***A Circular Economy needs clear definitions and selection criteria for preferred technologies.***



CreaCycle GmbH

Physical vs. Chemical Recycling

8

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DE-INKING (REMOVAL OF SURFACE PRINTING) MILK POUCH

MILK POUCHES ARE THE LARGEST SOURCE OF FOOD GRADE POST CONSUMER SOURCE OF LDPE / LLDPE POLYMERS IN INDIA

SUSTAINABILITY DRIVEN RECYCLED NATURAL OR CLEAR RESINS

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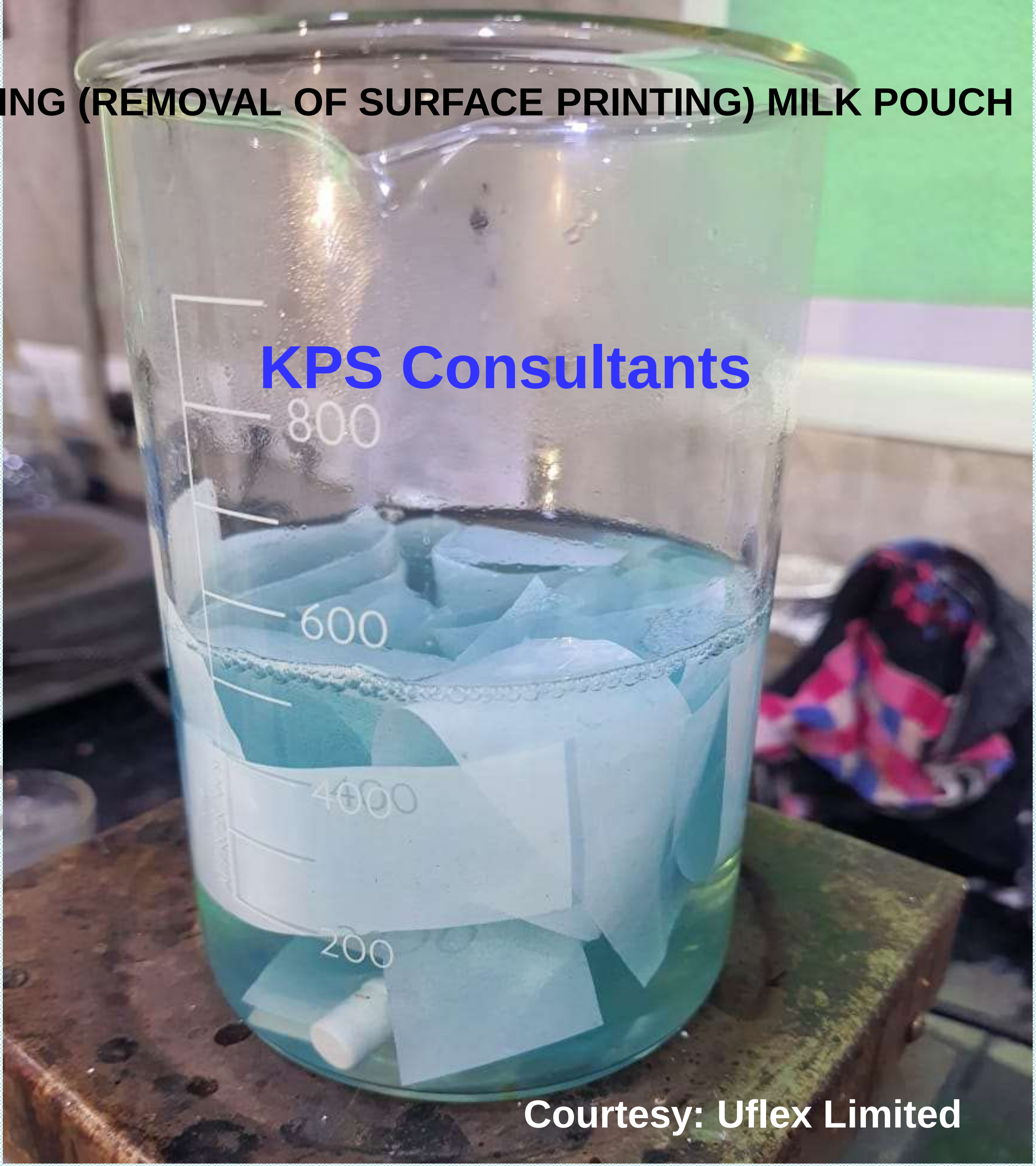
DE-INKING (REMOVAL OF SURFACE PRINTING) MILK POUCH

DE-INKING OF CUT PIECES OF MILK POUCH IN PROCESS

> CAUSTIC WASHING WITH SURFACTANTS
> NO USE OF SOLVENTS OR TOXIC CHEMICALS
> REUSE OF PROCESS WATER



Courtesy: Uflex Limited

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DE-INKED MILK POUCH PIECES AFTER DRYING

COLOUR DIFFERENCE MEASURED BY DELTA E (CIE 2000) & DIFFERENCE IN GRAMMAGE VALUES BETWEEN NON-PRINTIED SAMPLE AND DEINKED SAMPLES INDICTES HIGH LEVEL OF DEINKING EFFICIENCY (> 95%)

DE-INKING (REMOVAL OF SURFACE PRINTING) BREAD BAGS

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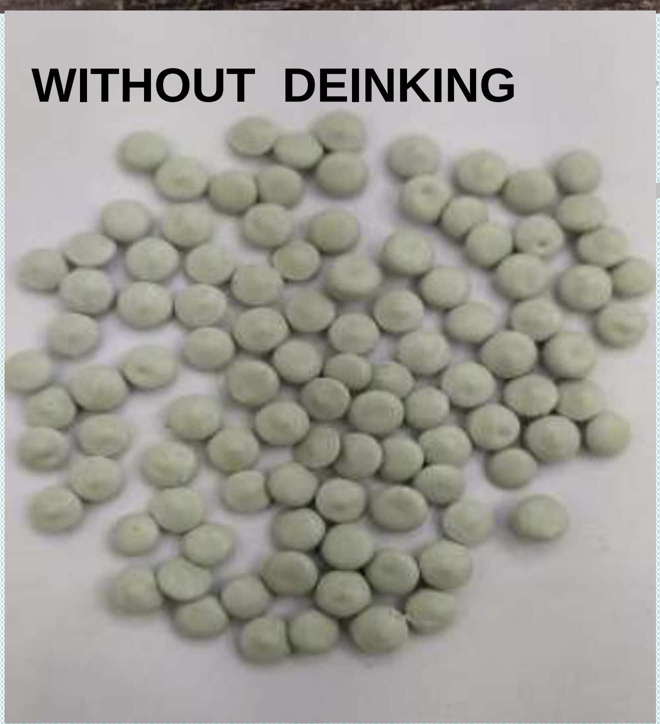
BREAD BAGS ARE THE LARGEST SOURCE OF FOOD GRADE CLEAR POST CONSUMER LDPE OR C-PP



DE-INKED SHREDDED

POST CONSUMER FILM

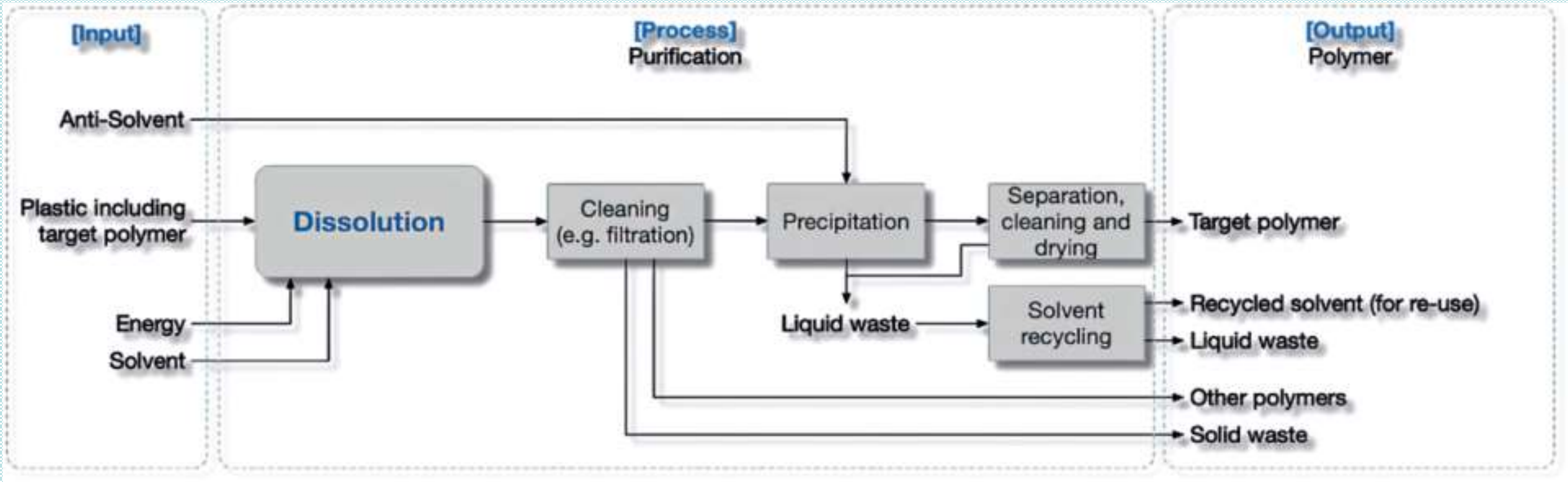
Examples of De-inking at commercial scale

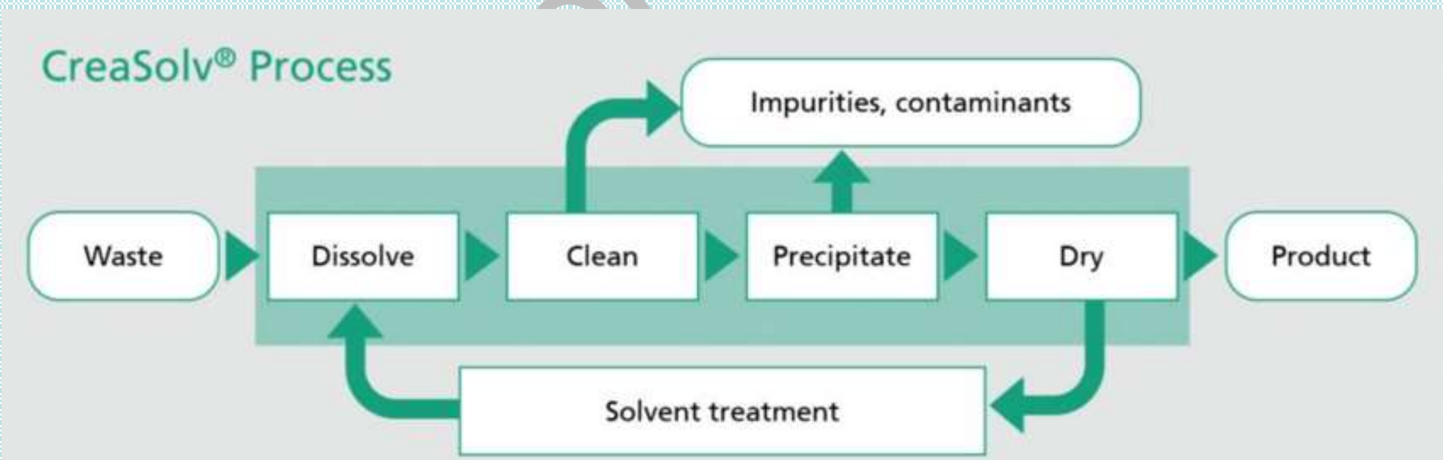
- CADEL Deinking (KEYCYCLE GmbH – EREMA group)
- SOREMA S.r.l
- Reborn’s de-inking line -- B.Clear in France for PE films
- Coveris (UK) deinking line for PIW
- Greiner packaging, Siegwerk & Krones – deinking of printed rigid containers
- DIN SPEC 91496: Recycling of printed polymer packaging – Evaluation of deinking using a test procedure

Targeted Dissolution & Precipitation of polymers

- Targeted polymers from (mixed or single) plastic wastes are dissolved in a suitable solvent while the chemical structure of the polymer remains intact.
- Other components (additives, pigments, fillers, non-targeted polymers) are not dissolved and can be cleaned (filtered) from the solvent.
- After cleaning an anti-solvent is added to initiate the precipitation of the target polymer.
- After this polymer can directly be obtained by filtration from solvent. In contrast to solvolysis, no polymerization step is needed.

Process diagram - inputs and outputs of solvent-based dissolution process





Source: CreaCycle GmbH and Fraunhofer Institute (IVV)

Polymer Recovery by Targeted Solvent Dissolution and Precipitation

- LDPE / LLDPE (surface printed)
- HDPE (flexible with surface printing / rigid with labels)
- PP (rigid with labels)
- LDPE / PET (reverse printed)
- LDPE / METALLIZED PET (with printing)
- LDPE / METALLIZED BOPP (with printing)
- BARRIER FILMS (LDPE / PA or EVOH / LDPE)
- LDPE / PAPER laminates
- LDPE / ALUMINIUM laminates

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DISSOLUTION OF PRINTED MILK POUCH IN SOLVENT

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DISSOLUTION PROCESS STARTS IN FEW MINUTES

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DISSOLUTION PROCESS COMPLETE

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FILTRATION OF PRECIPITATED POLYMER FROM SOLVENTS

POLYMER FILTERED FROM SOLVENTS

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RECOVERED POLYMER & SOLVENT MIX

www.kpsimpex.com

THE RECOVERED POLYMER IS DRIED TO REMOVE TRACE SOLVENTS AND EXTRUDED INTO PELLETS

THE SOLVENT MIX IS DISTILLED TO RECOVER THE PURE SOLVENTS FOR REUSE

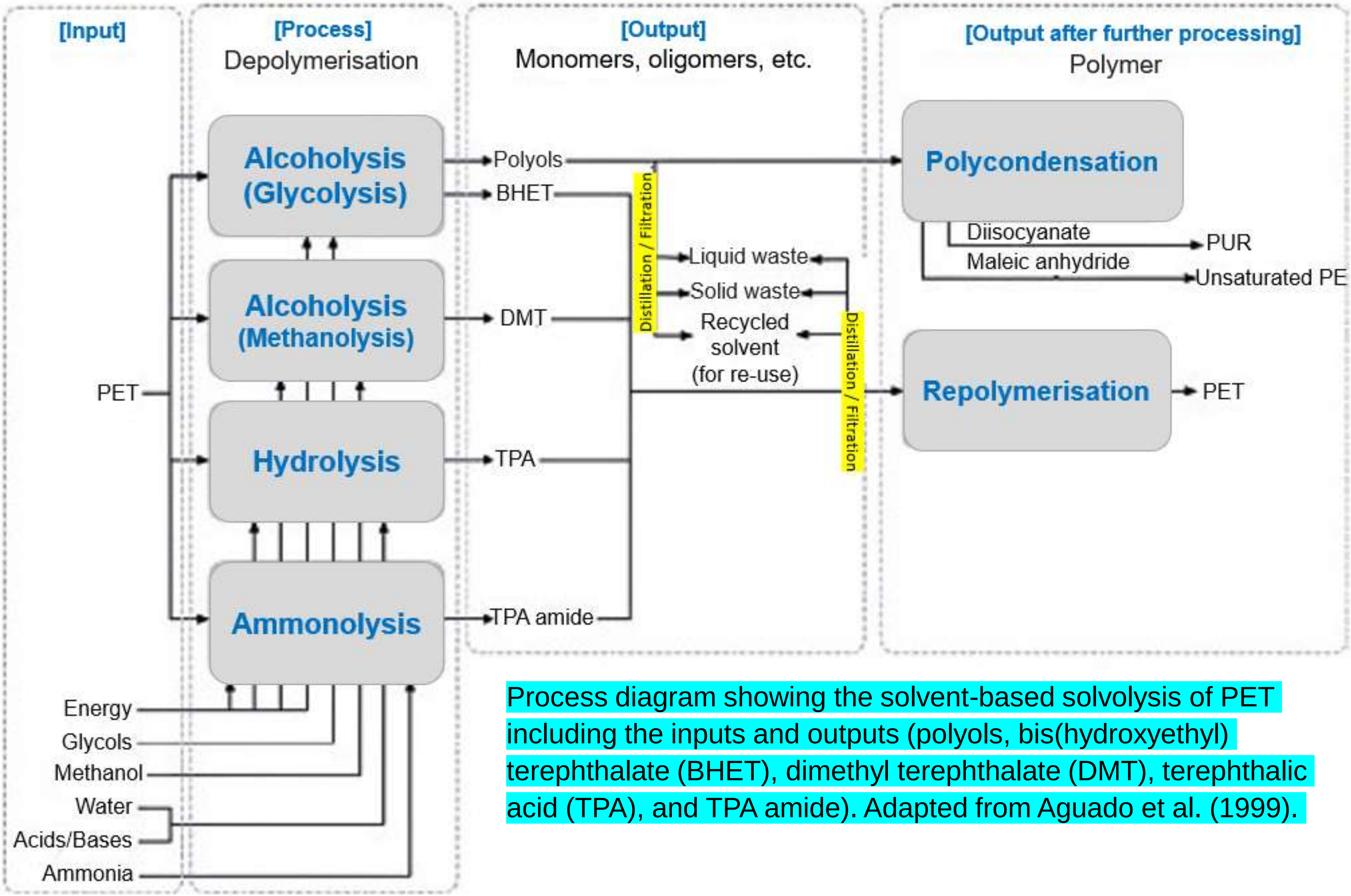
MASS BALNACE - PURE POLYMER (LDPE / LLDPE) RECOVERED

TESTING OF RECOVERED POLYMER FOR FOOD GRADE APPLICATION – DSC, FTIR, TGA, PRESENCE OF HEAVY METALS, INK RESIDUE, MIGRATION TESTING ETC.

Targeted Solvent Dissolution & Recovery of Polymers

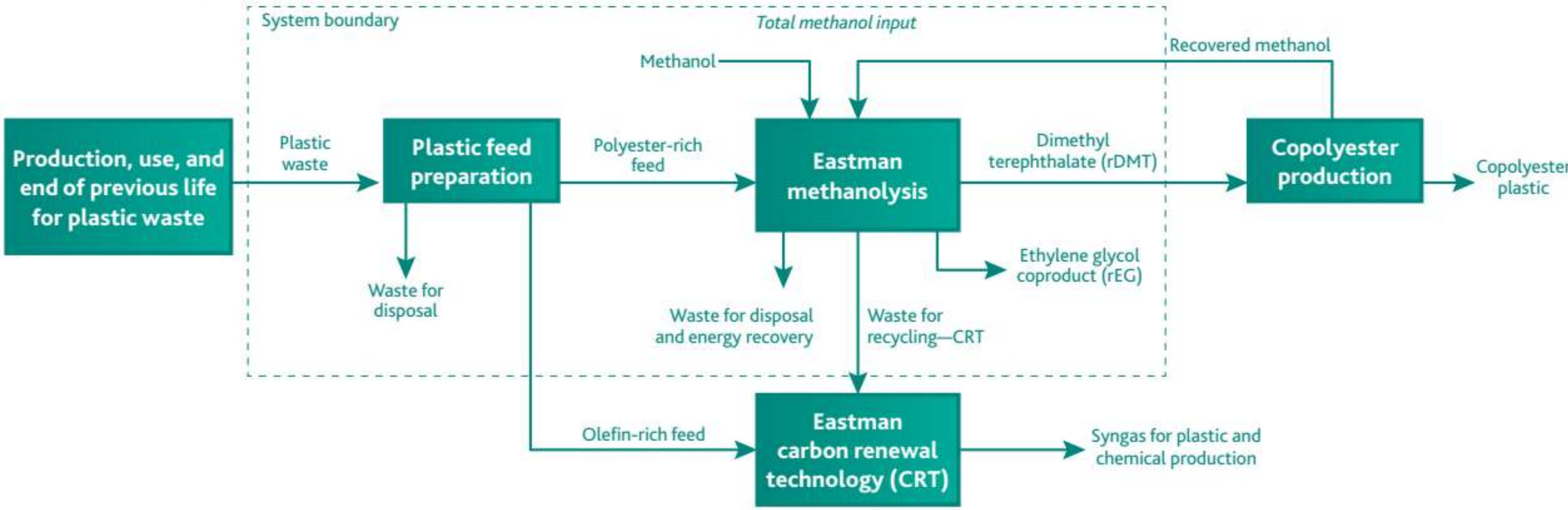
- PureCycle™ Technologies - Polypropylene, technology licensed from P&G
- Lyondell Basell and APK AG – LDPE & PA from multilayer films
- Fraunhofer's CreaSolv™ process is being further developed by CreaCycle in Germany and its PS Loop project in the Netherlands.
- Braskem and TNO -- Möbius dissolution-based recycling technology for polyolefin plastics
- Polystyvert (Canada) is focusing its efforts on PS.

- The solvent-based **solvolysis** is a chemical process based on depolymerization which can be realized with different solvents. The process breaks down polymers (mainly PET) into their building units (monomers, dimers, oligomers).
- After breakdown, the building units need to be cleaned from the other plastic components (additives, pigments, fillers, non-targeted polymers).
- After cleaning, the building units are polymerized to synthesize new polymers.
- Process most suitable for use with step-growth polymers such as PET, which are polymerized by polycondensation.
- Solvolytic depolymerization technique is not suitable for use with polymers produced by chain growth or polyaddition reactions, such as PE, PP and PS.



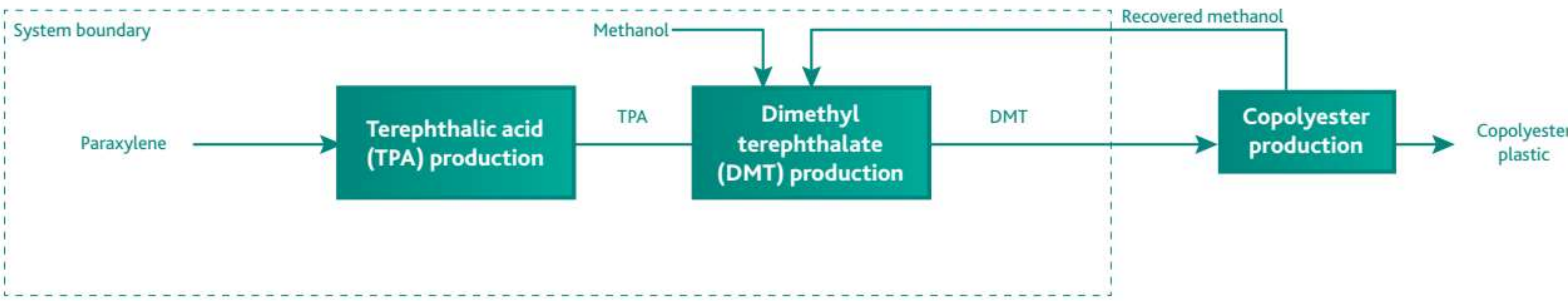
Process diagram showing the solvent-based solvolysis of PET including the inputs and outputs (polyols, bis(hydroxyethyl) terephthalate (BHET), dimethyl terephthalate (DMT), terephthalic acid (TPA), and TPA amide). Adapted from Aguado et al. (1999).

Eastman methanolysis system



Note: Figure shows a simplification of the methanolysis system and its mass flows to produce rDMT and rEG based on the planned feedstock mix for 2023.

Comparative system: conventional DMT production at Eastman

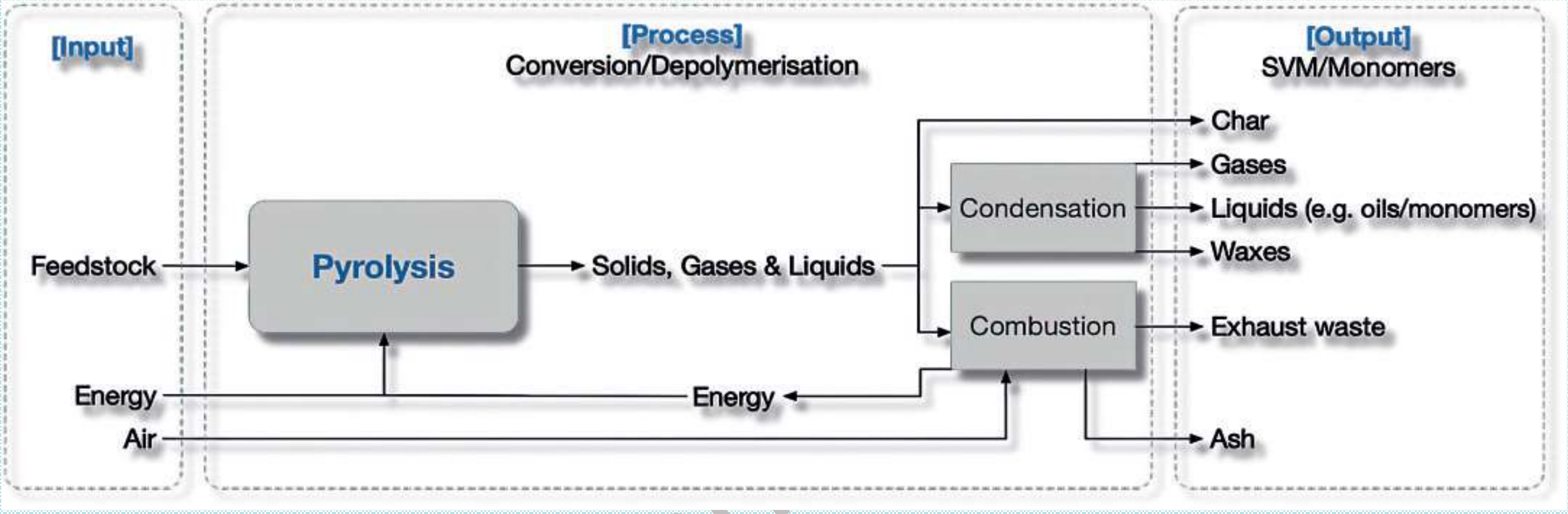


Source: LCA summary report for Eastman methanolysis technology (North America) Jan 5, 2022

Pyrolysis - thermochemical recycling process that converts or depolymerizes mixed plastic wastes (mainly polyolefins) and biomass into liquids, solids, and gases in presence of heat (400-600°C) and absence of oxygen.

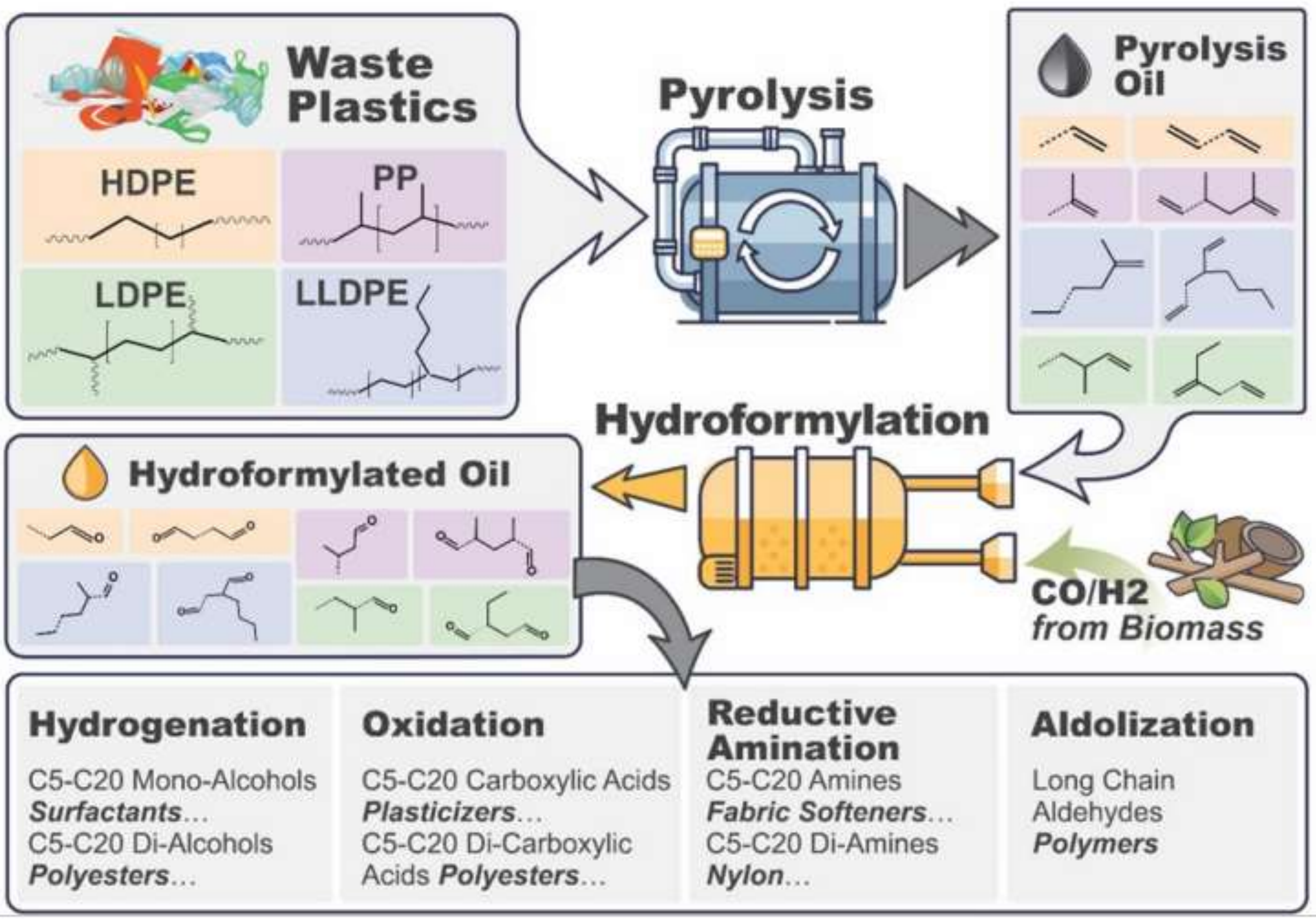
Obtained products can be for instance different fractions of liquids including oils, diesel, naphtha, and monomers as well as syngas, char, and waxes. Depending on the obtained products new polymers can be produced from these renewable feedstocks.

Gasification represents another thermochemical process that is capable to convert mixed plastics wastes and biomass in presence of heat and oxygen into syngas (a gaseous mixture of CO, CO_2, H_2 and CH_4) and CO_2.



Process diagram showing the inputs and outputs of different secondary valuable materials (SVM) from the pyrolysis process. The main products are usually pyrolysis oil (via thermal-/catalytic-/hydro-cracking) or monomers (via thermal depolymerisation) Adapted from Stapf et al. (2019)

Hydroformylation of Olefin fraction from Pyrolysis Oil



Proposed routes to produce alcohols, carboxylic acids, and amines from waste polyolefins.

Hydroformylation of Olefin fraction from Pyrolysis Oil

Pyrolysis of PE & PP produces olefin mixtures that can be directly subjected to hydroformylation. Hydroformylation ("oxo" process) coverts olefins (alkenes) into aldehydes by reacting them with carbon monoxide and hydrogen in the presence of a catalyst.

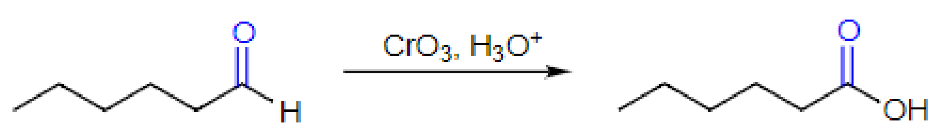
(Alkene) $R_2C = CR_2 \xrightarrow{CO / H_2 / \text{Catalyst}}$ R--CH=O (Aldehyde)

Reduction or Hydrogenation of Aldehydes to Alcohols or Diols

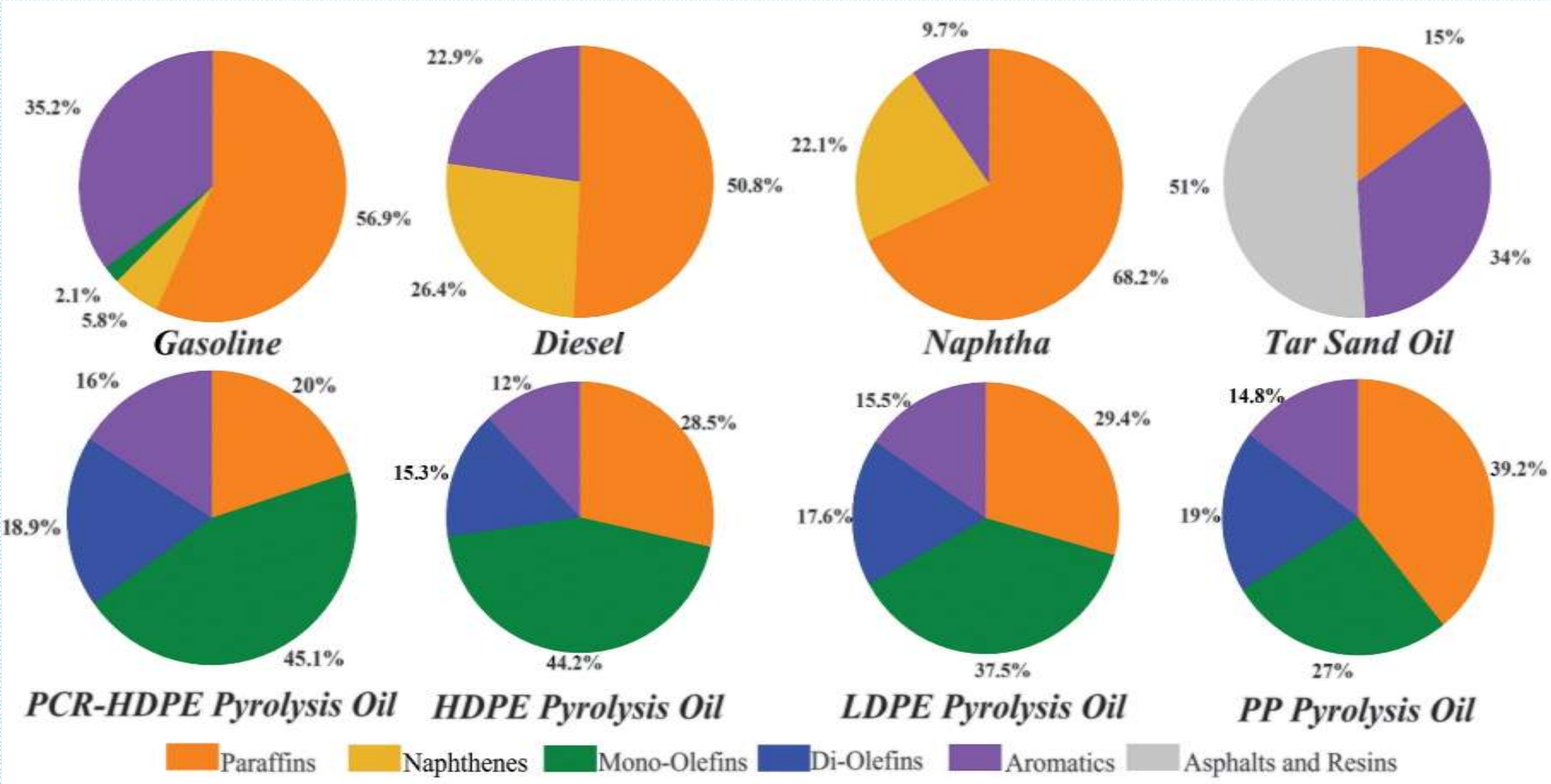
R-CH=O (Aldehyde) $\xrightarrow{H_2 / \text{Catalyst}}$ R – C -- OH (Alcohol)

Oxidation of Aldehydes to Carboxylic Acids

R-CH=O (Aldehyde) $\xrightarrow{H_2 / \text{Catalyst}}$ R – COOH (Alcohol)



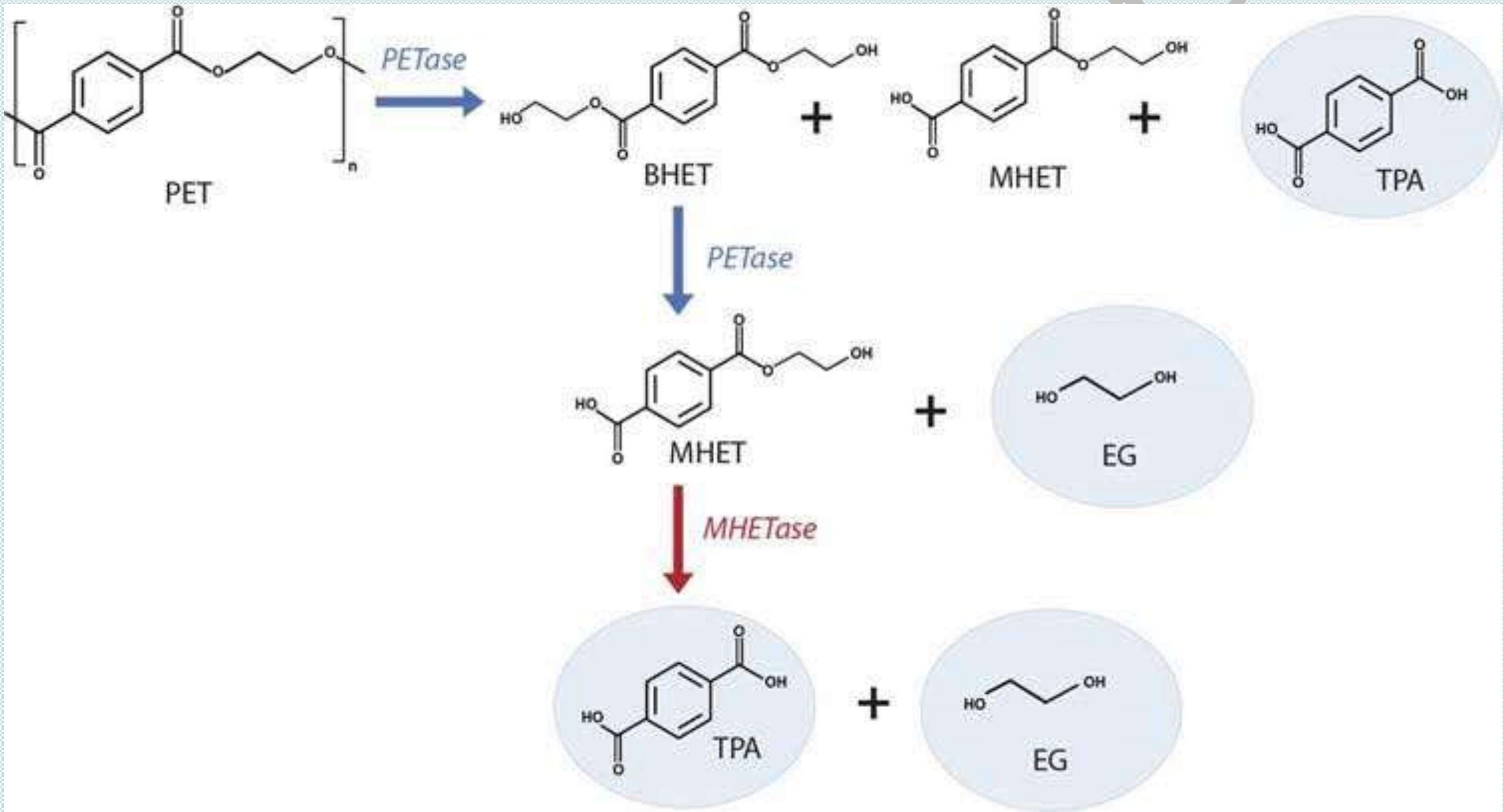
Oxidation of hexanal to form hexanoic acid using Jones Reagent



Chemical composition of petroleum products and plastic oils derived from pyrolysis of PCR HDPE, HDPE, LDPE, and PP.

Ref: Hydroformylation of pyrolysis oils to aldehydes and alcohols from polyolefin waste
SCIENCE 10 Aug 2023 Vol 381, Issue 6658

Enzymolysis represents a technology based on biochemical processes utilizing different kinds of biocatalysts to depolymerize a polymer into its building units.



In 2016 the discovery and characterization of the soil bacterium strain, *Ideonella sakaiensis* 201-F6 was reported. This gram-negative, aerobic, rod-shaped bacterium has the remarkable ability to use PET as its major carbon and energy source for growth.

I.sakaiensis employs a two-enzyme system to depolymerize PET to its building blocks, TPA and EG, which are further catabolized to a carbon and energy source. One of the two enzymes, ISF6_4831 protein, hydrolyzes and breaks ester linkages. With a preference for aromatic rather than aliphatic esters, and a specific inclination towards PET, it is designated as a **PET hydrolase (PETase)**.

The PETase enzyme is a cutinase-like serine hydrolase that attacks the PET polymer, releasing bis(2-hydroxyethyl) terephthalate (BHET), mono(2-hydroxyethyl) terephthalate (MHET) and TPA. PETase further cleaves BHET to MHET and EG. The second enzyme, ISF6_0224 protein, MHET hydrolase (**MHETase**), further hydrolyzes the soluble MHET to produce TPA and EG. Both enzymes are used synergistically, to enzymatically convert PET into its two monomers, TPA and EG4, making it possible to fully recycle PET.

Depolymerization (solvolysis) & Conversion (pyrolysis)

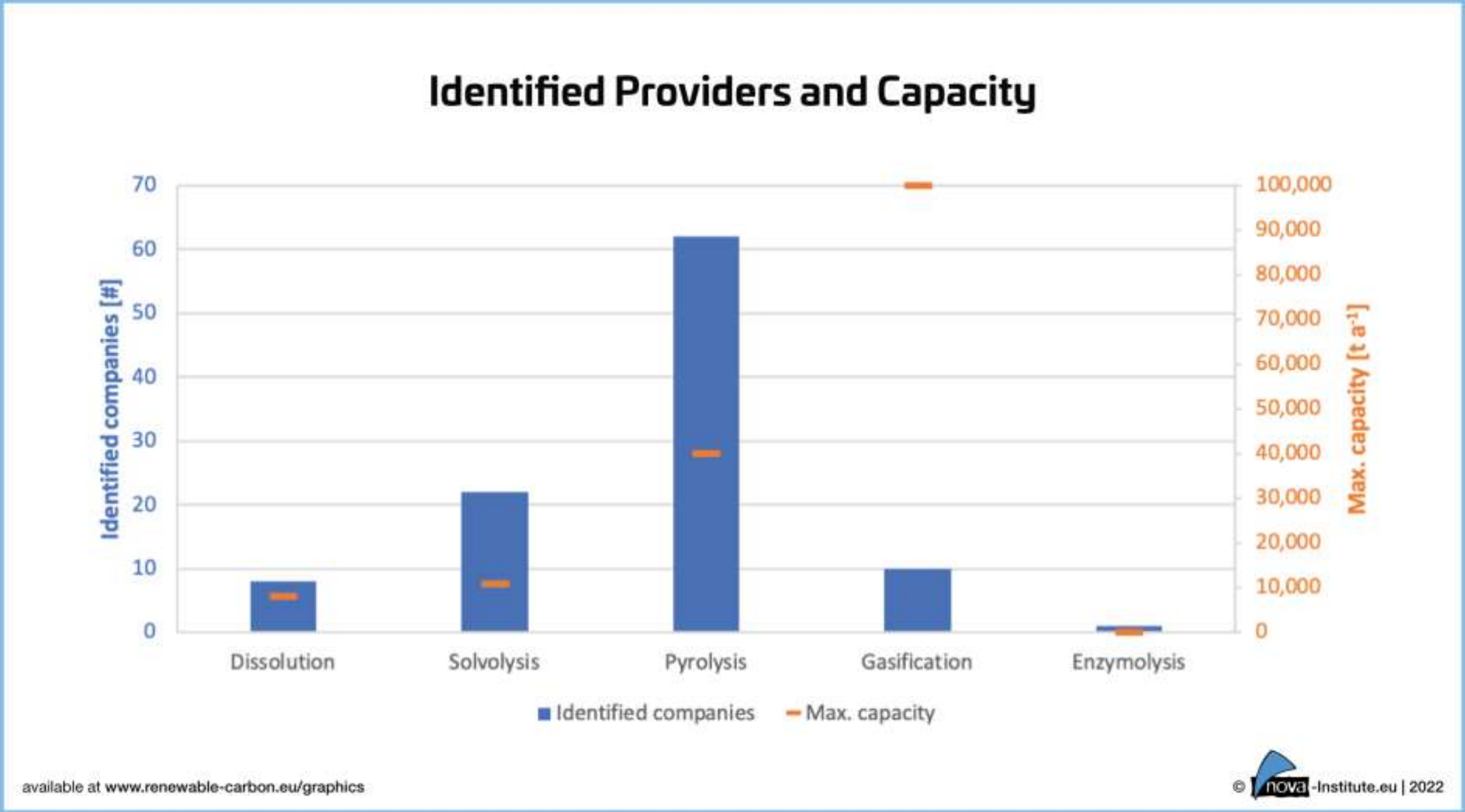
- Eastman Chemicals (US) – glycolysis & methanolysis
- **Rewind – PET™ by Axens, IFPEN and JEPLAN - Japan 22 KT (glycolysis)**
- Revalyu Resources GmbH (Germany) – glycolysis
- IONIQA & KOCH Technology – glycolysis plant 5KT Netherlands
- Loop Industries (Canada) methanolysis of rPET into DMT & MEG
  Ester Industries (Infinite Loop)
- Trinseo (Italy) --- PMMA pilot depolymerization plant
- Mura and WMG (UK) --- hydro-PRT recycling technology
- IKV (NL) --- LOOPCYCLING – entire process chain of mechanical recycling: sorting, shredding, washing, de-inking, compounding with stabilizers, decontamination and odour removal
- Ineos Styrolution – styrene monomer from PS

Depolymerization (solvolysis) & Conversion (pyrolysis)

- Carboliq™ Tech., Recenso – catalytic tribo-chemical process
- **Agilyx & Technip Energies – styrene monomer from PS**
- Encina (US) – plastic waste to aromatics
- Altera Energy, Neste & Ravago – liquefaction technology

Enzymatic Depolymerization of PET

- Carbios (France)
- Carbios & FCC Environment (UK), Zhink Group (China), SASA Polyester (Turkiye)


Identified Providers and Capacity
70
60
50
40
30
20
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Identified companies [#]
100,000
90,000
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Dissolution
Solvolysis
Pyrolysis
Gasification
Enzymolysis
Identified companies
Max. capacity
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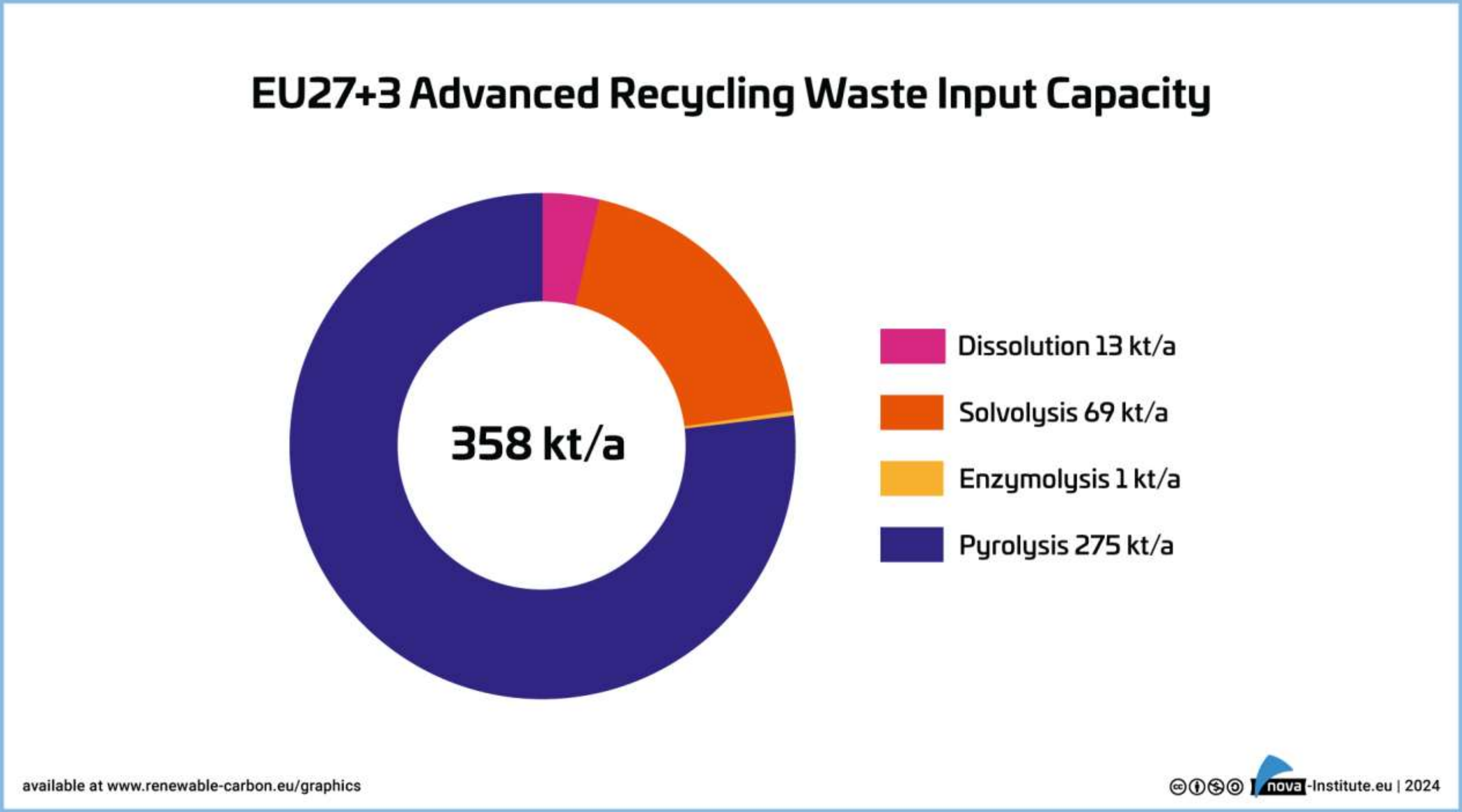
EU27+3 Advanced Recycling Waste Input Capacity
358 kt/a
Dissolution 13 kt/a
Solvolysis 69 kt/a
Enzymolysis 1 kt/a
Pyrolysis 275 kt/a
available at www.renewable-carbon.eu/graphics
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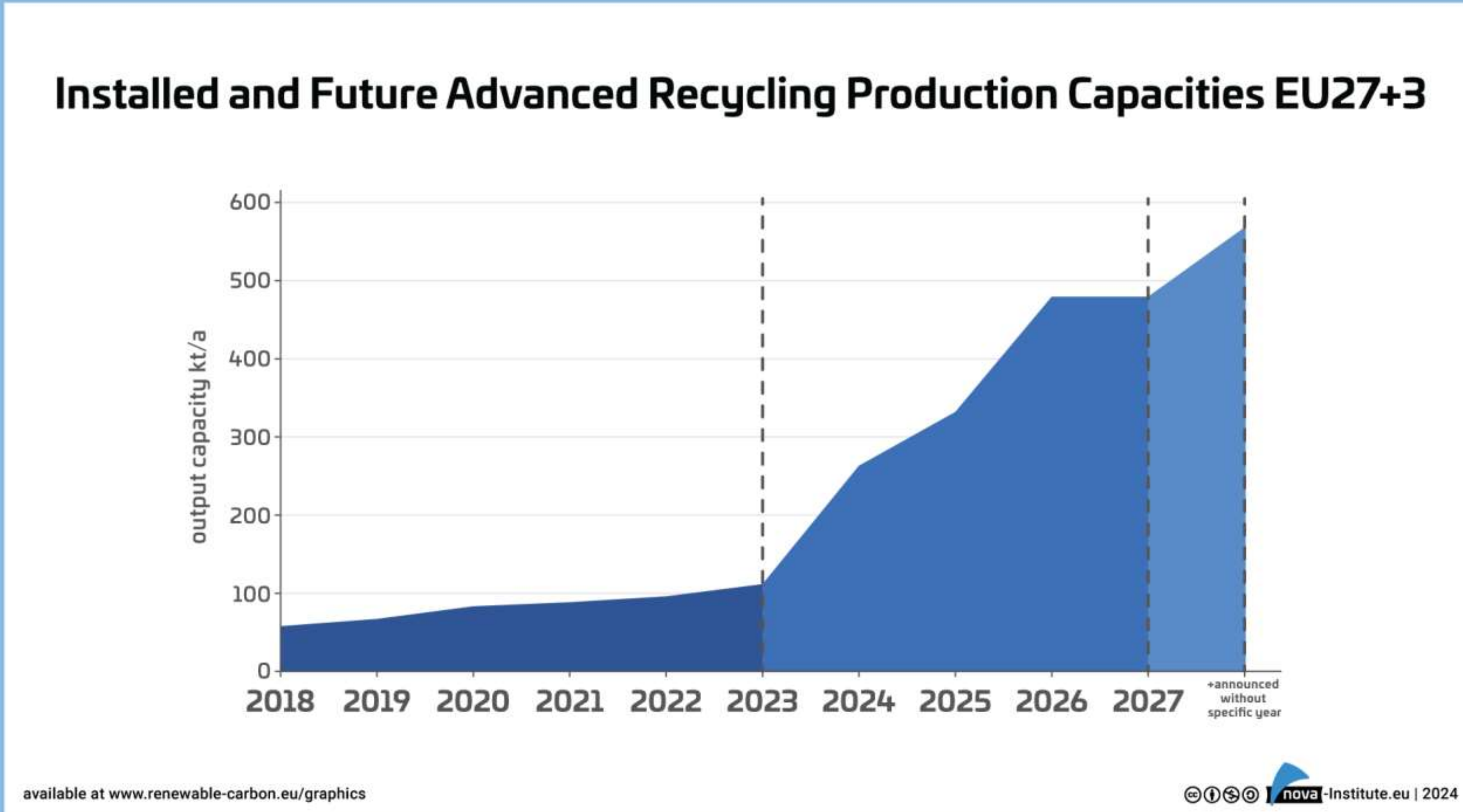
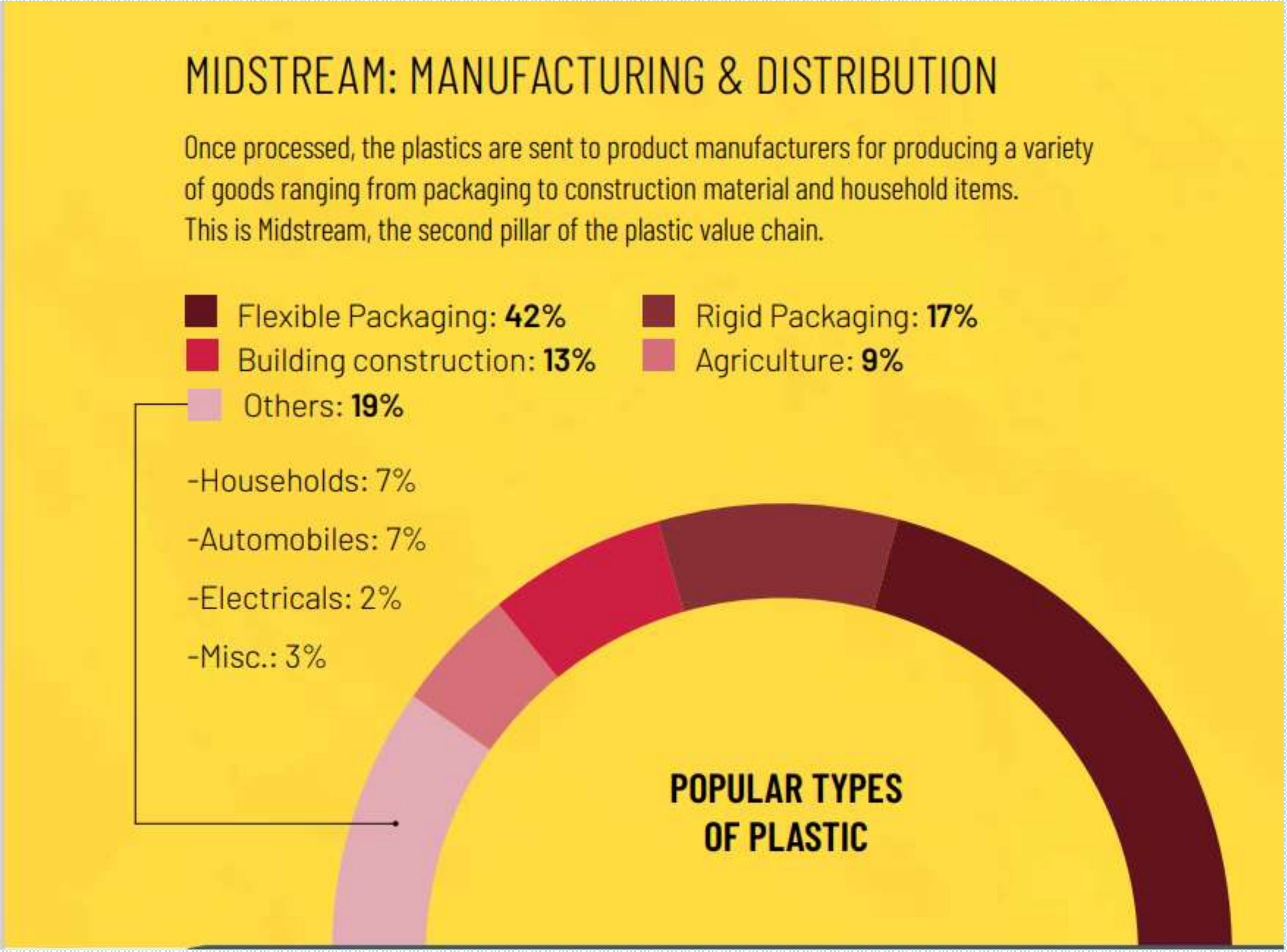


Based on AMI's research, global installed input capacity for chemical recycling in 2022 was 1.2m tons, forecast to increase to 8.7m tonnes by 2030. Pyrolysis is forecast to account for 46% of installed input capacity by 2030.

Plastic End Use Products / Sectors

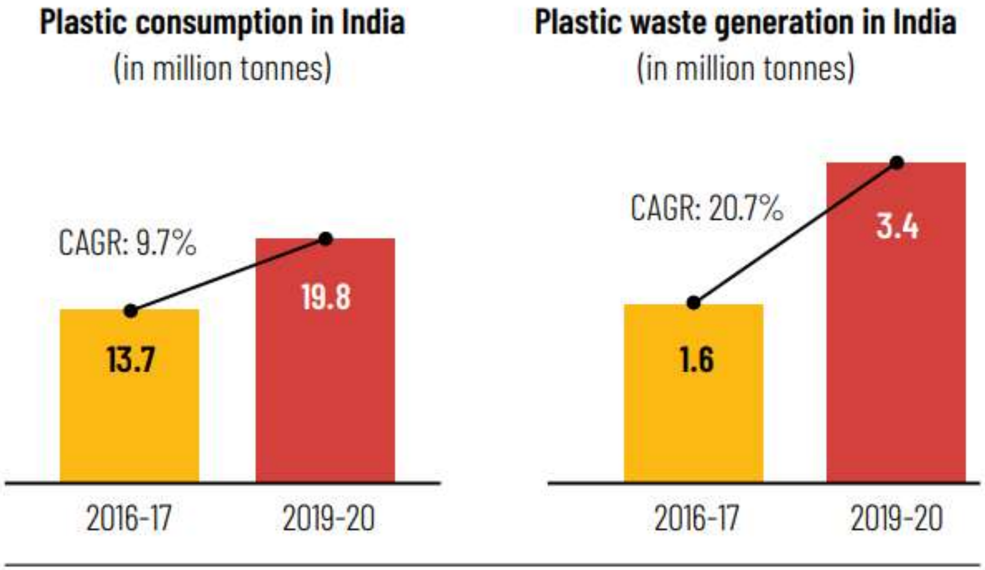


Source: Innovation in Plastics (2022) – Marico Innovation Foundation

HOW INDIA USES PLASTIC

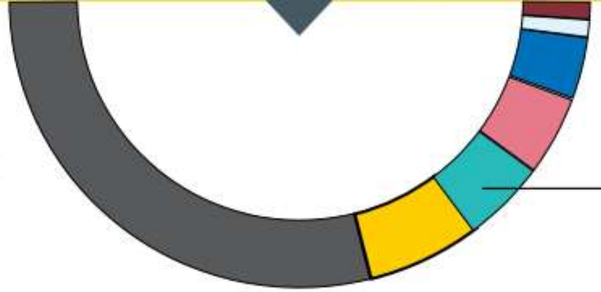
Plastic waste generation more than doubled between 2016-17 & 2019-20

The plastic consumption in India has grown at a significant pace over the past five years, and so has its waste output. The country consumed 14 million tonnes of plastic in 2016-17. This figure rose to 20 million tonnes in 2019-20, growing at a compounded annual growth rate (CAGR) of 10%. India's plastic waste output also doubled between 2016-20. Among all states, Maharashtra, Gujarat and Tamil Nadu generate the most amount of plastic waste, occupying 38% of the total waste output.



Source: Innovation in Plastics (2022) – Marico Innovation Foundation

APPLICATION AREAS FOR PLASTICS ACROSS VARIOUS INDUSTRIES



MISCELLANEOUS:
1.9 MN TONNES

PACKAGING
11.5 MN TONNES

Multilayer films | BOPP films | Shrink & Stretch wraps | Thin wall moulding | Thermoforming | Blow moulded containers

BUILDING & CONSTRUCTION
2.6 MN TONNES

Pipes | Storage tanks | Profiles | Geotextiles | Geomembrane | Wire and Cable

AGRICULTURE
1.8 MN TONNES

Greenhouse films | Low tunnels | Micro irrigation: Drip/Sprinkler | Mulch films | Crates | Pallets

AUTOMOTIVE
1.4 MN TONNES

Bumper | Seats | Dashboard | Fuel system | Body panels | Lighting

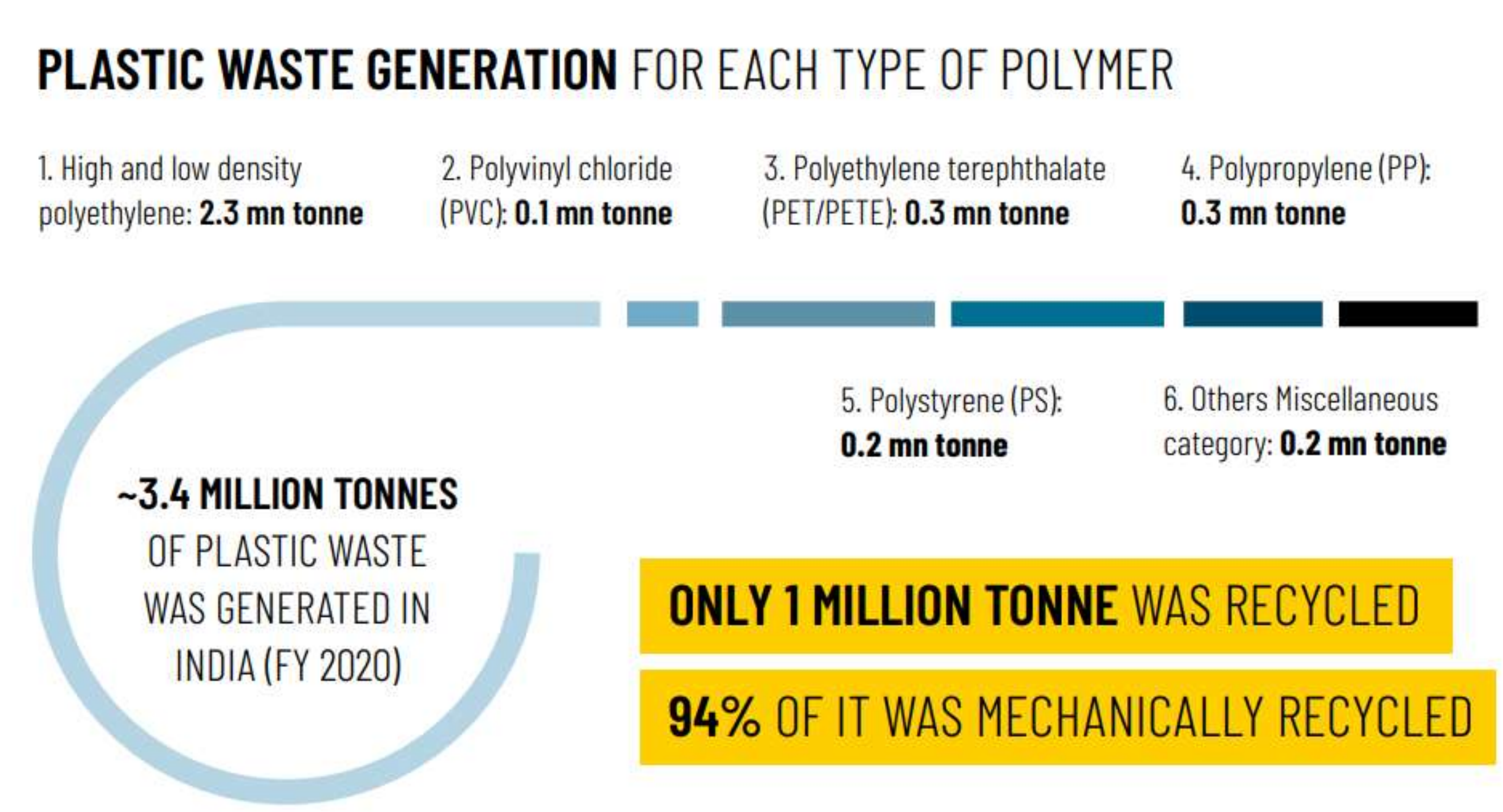
ELECTRICALS & ELECTRONICS
0.4 MN TONNES

Circuit breakers | Switch | Lighting fixtures | Cable & wire insulation | Refrigerator trays/linings | TV cabinet, etc.

HOUSEHOLDS
0.1 MN TONNES

FMCG products such as toiletries & cosmetics | Furniture | Toys | Luggage | Housewares and other lifestyle related products

TOTAL CONSUMPTION OF PLASTIC IN 2020: **19.8 MILLION TONNES**



Source: Innovation in Plastics (2022) – Marico Innovation Foundation

Examples of Food Grade PCR PE & PP

- Milk Pouch (PE) --- Deinking & caustic washing, tandem Extrusion with vacuum degassing & fine melt filtration, pelletization, hot air stripping for de-odourization.
- **Bread bags (PE or CPP) --- same a above**
- HDPE cap regrind (from PET washing lines) --- caustic washing, decontamination (vacuum & heat), extrusion with vacuum degassing & fine melt filtration, pelletization, hot air stripping for de-odourization.
- Five-liter edible oil jar --- de-labeling & wet grinding, same as above
- PP take away food containers --- caustic washing, decontamination (vacuum & heat), extrusion with vacuum degassing & fine melt filtration, pelletization, hot air stripping for de-odourization
- PET / PE --- dissolution to separate PET & poly, de-inking of PET extrusion, vacuum degassing, melt filtration, decontamination

Examples of Food Grade PCR PE & PP

- BOPP / PE --- dissolution to separate PP & PE, de-inking of PP extrusion, vacuum degassing, melt filtration, decontamination
- Aseptic packaging (paper / Al / PE) – hydro-pulping / enzymatic pulping, separation of Aluminium & PE by dissolution
- Recovery of PE and PP by dissolution from PE / Metalized PET or PE / Metallized BOPP
- **Recovery of PE from barrier films PE / Tie / PA or EVOH / Tie / PE (recovery of PA also possible)**
- PP Raffia Bags --- de-inking and dissolution to remove contaminants
- HDPE blow moulded contains --- de-labeling, deinking, dissolution to remove contaminants


Amul
Taaza
अमूल
ताज़ा

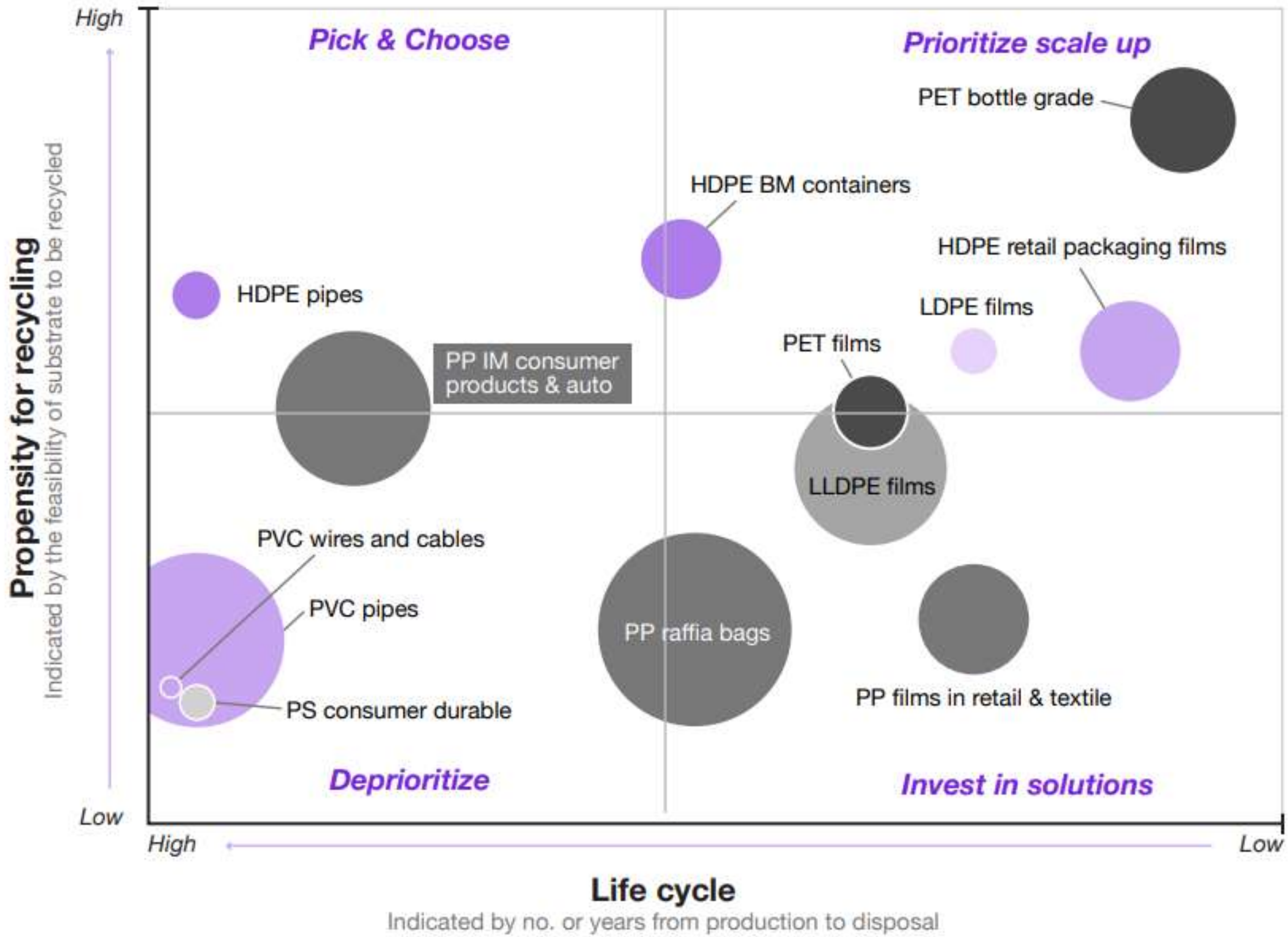

Schani
MOONG
SPLIT CHILKA
e 1kg


INDIA
GATE
BASMATI RICE
Super
5kg


SAMPURN
ORGANIC
Organic
Moong Dal
Product of India

Recycle Prioritization Matrix

Size of the bubble represents the demand of substrate (In MMTPA)



Ref: Solving Plastic Waste: Roadmap for a Sustainable Future Kearney & CII - 2024

THANK YOU

THE FUTURE BELONGS TO THOSE WHO SEE

POSSIBILITIES BEFORE THEY BECOME OBVIOUS

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