Recycling of Thermoset Materials

The potential impact on reducing fossil-based plastic waste

PRESCOUTER

The covalently cross-linked networks of thermosets make them an attractive material, particularly for structural applications, but limit their recyclability.

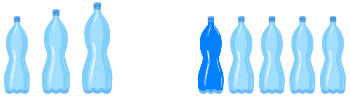
The shift from a fossil- to renewable-based society is crucial for our next generations. But what is the role of recycling in reducing already existing plastic waste? Are all plastics suitable for recycling? **According to Plastics Europe, worldwide plastic production in 2020 was 367 million tonnes. The fraction that is recycled is only 10%-18%.** The majority is wasted but has the potential to be recycled by conventional routes. **Around 11% of plastic production volume (42 million tonnes) are thermosets**, and this is where part of the challenge lies.

Generally, plastic materials are classified as thermoplastics and thermosets, according to their chemical composition. From a technological point of view, thermoplastics are easily recycled and reprocessed by conventional methods, while **thermosets have long been considered thermally unprocessable** as a result of the presence of covalent intermolecular cross-links. Major thermoset resin classes are isocyanates, unsaturated polyesters, formaldehydes, epoxies, and alkyds, which are widely used as strong, lightweight materials.

Currently, most thermoset polymers are landfilled or incinerated after their useful lifetimes, the least preferred waste management approach. **In this Intelligence Brief, we highlight some examples of current options for recycling thermosets and some that are close to being fully developed**.

Executive Summary

Based on the projections of 5%-6% compounded annual growth rate on world plastic production (thermosets included) and the small fraction of 10%-20% that is actually recycled,



5%-6%
annual growth

only **10%-20%**
is recycled

new solutions can be explored to increase the volume of recycled materials and, potentially, reduce waste and increase income.

According to a Subject Matter Expert (SME), the thermosets for which recycling solutions exist and are currently available are composed of mainly **polyurethanes**, **epoxies**, and **silicones**, since either valuable material can be recovered or the output material can be used as building blocks in the manufacturing process of the original plastic material.

This report presents **9 commercially available** solutions for the recycling of two important thermoset materials (polyurethane foams and reinforced epoxy thermoset composites) and mixtures of plastic materials that are considered to be difficult to recycle.

PreScouter highlights recent investments by **Dow and BASF** in the polyurethane foam recycling technologies **RENUVA Polyol and ChemCycling**, respectively, and by the **Aditya Birla Group** in the **Recyclamine** technology for epoxy fiber reinforced composites recycling, which may start commercial operations in 2022 through a major partnership with Siemens Gamesa Renewable Energy for a recyclable wind turbine blade project.

Current scenario and forecasts of recycling of plastic waste: Thermosets versus Thermoplastics

Volume of global thermosets production

In 2020, the global volume of thermosets produced was around **42 million tonnes** [PRNewswire]. According to SME insight, although polyurethanes are the most recycled thermosets, **no more than 20% of the world's production of polyurethane foam is actually recycled**.

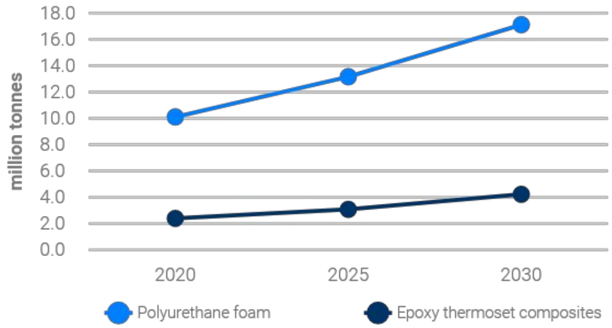


Figure. World production estimates of polyurethane foam and epoxy thermoset composites. Source: Markets and Markets.

Volume of global thermoplastics production

In 2020, the global volume of thermoplastics produced was around **400 million tonnes** [Statista]. The main thermoplastic that is recycled is polyethylene terephthalate (**PET). Up to 68% of PET is recycled, corresponding to 30% of all recycled thermoplastics** (MarketsandMarkets, SME insight).

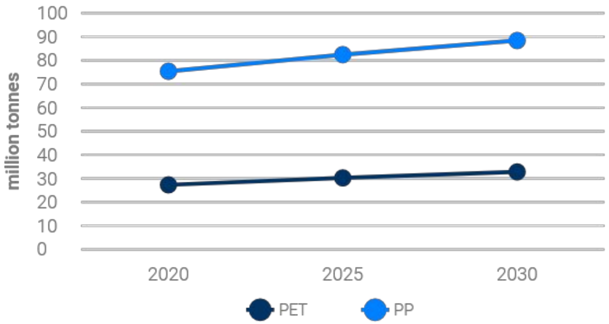


Figure. World production estimates of PET and PP. Source: Statista.

Polymer recycling operations present a hierarchy of preference in ascending order that goes from primary to quaternary.

Polymer recycling operations

Primary recycling or reuse:

Reprocessing operations of industrial polymeric residues from the production process itself to obtaining products with a performance similar to those products made with pristine polymers

Secondary or mechanical recycling:

Transformation of polymeric residues into a new product with satisfactory performance for its respective application using mechanical and thermomechanical processing

Tertiary or chemical recycling:

Processes in which the polymer residues are chemically modified or transformed into small molecules (such as oils or hydrocarbons, in the case of polyolefins), monomers, or oligomers

Quaternary recycling or energy recovery:

Technological solutions that involve the incineration of polymer waste to generate heat, steam, and electricity

Current routes of thermoset material recycling

- ✔ The most widely studied method is pyrolysis, that is, breaking down the thermoset network in the presence of heat, sometimes promoted by catalysts and even solvents.
- ✔ Though most thermosets can effectively be thermally degraded, these processes are typically very energy-intensive and costly, often requiring temperatures over 400°C.
- ✔ Photodegradation presents an alternative approach, but degradation kinetics are too slow to be of practical use for managing thermoset waste.
- ✔ Most attention is given to the recycling of fiber-reinforced composites, since the fibers are generally more valuable than the matrix material, especially when carbon fibers are used. Therefore, a first consideration in the recycling of high-quality-demanding thermoset products should always be to verify the possibility of direct reuse in applications where a lower quality is acceptable.
- ✔ The direct reuse of thermoset products will most likely remain a specific niche market.

Current routes of thermoset material recycling

The presently available techniques that are already commercial or are approaching a commercial status can be divided into mechanical, thermal, and chemical processing.

Thermal recycling (aerobic and anaerobic combustion)

Aerobic

- ✔ The fluidized-bed combustion process developed by Pickering et al. is an example of an aerobic composite recycling process for glass fiber reinforced plastics (GFRPs) that is capable of fiber recovery, while the thermoset matrix is broken down in CO_2 and water vapor that is converted into energy. A second promising example of aerobic thermal recycling is the use of scrap GFR thermosets as feedstock for cement processing in cement kilns.

Anaerobic (pyrolysis)

- ✔ Compared to aerobic combustion, pyrolysis will break down the thermoset matrix into lower molecular weight organic compounds, of which the chemical nature is correlated to the original material.
- ✔ Compared to processing into cement kilns, pyrolysis gives rise to the option of reusing the thermoset product components more than once. With the assistance of specific catalysts, the thermoset pyrolysis recycling output can be enhanced.

Current routes of thermoset material recycling

The presently available techniques that are already commercial or are approaching a commercial status can be divided into mechanical, thermal, and chemical processing.

Chemical recycling (solvolysis)

- ✔ Similar to thermal recycling, the main driver for the development of solvolysis for thermosets is the potential to regain carbon fibers from thermoset composites. Additionally, as with pyrolysis, the degraded and dissolved organic compounds originating from the matrix can be reclaimed from the solvent and be reused as molecular building blocks. A recent trend is the use of (near) supercritical fluids as a recycling medium.

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2. *Pickering, S. J.; Kelly, R. M.; Kennerley, J. R.; Rudd, C. D.; Fenwick, N. J. A Fluidised-Bed Process for the Recovery of Glass Fibres from Scrap Thermoset Composites. Compos. Sci.Technol. 2000, 60, 509–523. DOI: 10.1016/S0266-3538(99)00154-2.*
3. *Current options for characterizing, sorting, and recycling polymeric waste (2020)* https://journals.sagepub.com/doi/abs/10.1177/1477760620918603?journalCode=prpa
4. *Hydrolysis and Solvolysis as Benign Routes for the End-of-Life Management of Thermoset Polymer Waste (2020)* https://doi.org/10.1146/annurev-chembioeng-120919-012253

Summary of technologies profiled

	# of employees	Headquarters	Recycled Material	Technology Name	Case Study	Scale
GMR	11-50	USA	Polyurethane foam (pre-consumer)	Polyurethane foam recycling	N/A	Commercial scale
Dow	>10,000	USA	Polyurethane foam	RENUVA Polyol	N/A	20,000 end-of-life mattress in 2021
BASF We create chemistry	>10,000	Germany	Polyurethane foam (post-consumer)	ChemCycling	N/A	Pilot scale
covestro	>10,000	Germany	Polyurethane foam	Polyurethane foam recycling	PUReSmart research project	Pilot scale
ADITYA BIRLA GROUP	>10,000	India	Epoxy thermoset composites	Recyclamine	Siemens Gamesa Renewable Energy - Recyclable blades.	Commercial operations in 2022
Adherent Technologies, Inc.	unspecified	USA	Epoxy fiber reinforced composites	Wet chemical breakdown	N/A	2 tonnes/day if received $4 M investment
Recycling Technologies	51-200	UK	Plastics that are not routinely recycled	RT700 - Fluidized bed thermal cracker	Bin Group - Scotland	Commercial scale
MURA TECHNOLOGY	51-200	UK	Waste plastic (clean and shred)	HydroPRS (hydrothermal recycling system)	ReNew ELP (England)	800,000 tonnes/year under construction
Braven	51-200	USA	Difficult to recycle waste plastic	Braven PyChem	Chevron Phillips Chemical (Virginia)	12,000 tons/year

RECYCLING OF THERMOSET MATERIALS | **GEOGRAPHICAL DISTRIBUTION OF PROFILED COMPANIES**

Braven Environmental

- Develop waste plastics solutions
- Technology provider in the advanced plastics recycling sector
- 2010

Mura Technology

- Recycle plastics through HydroPRS process
- Hydrothermal upgrading
- 2019

Recycling Technologies

- Chemical recycling
- Accelerating the evolution of plastic into a more sustainable material through innovation, reducing carbon footprint
- 2011

Dow Polyurethanes

- Chemical, plastic, and agricultural products corporation
- Contribute to a more sustainable society working on a path to achieve carbon neutrality and eliminate plastic waste
- 1897

Generated Materials Recovery

- Find solutions for manufacturing and industrial operations to achieve sustainability goals by offering industrial recycling services.
- GMR offers industrial recycling services
- 2003

Adherent Technologies, Inc.

- Surface science, composites, coatings, sensors, and polymer science
- Adherent Technologies, Inc. solves demanding materials problems by developing cutting-edge technologies and the processes to produce them.
- 1990

Aditya Birla Group

- Aditya Birla is majorly engaged in the businesses of non-ferrous metals, viscose filament yarn, viscose staple fiber, cement, fertilizers, chemicals, branded apparel, carbon black, sponge iron, telecom, IT services, financial services, insulators, and business process outsourcing.
- Multinational conglomerate
- 1857

Covestro AG

- Manufacture of high-tech polymer materials and the development of innovative, sustainable solutions for products used in many areas of daily life
- Supplier of diverse innovative, sustainable polymer materials
- 2015

BASF

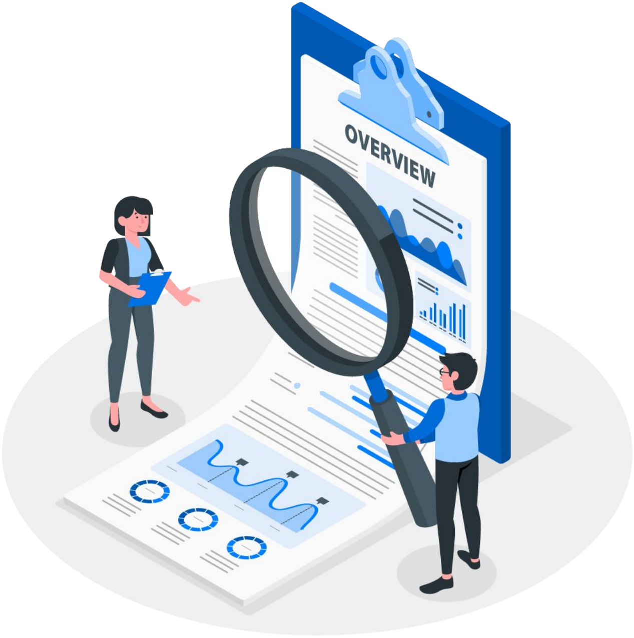
- Chemicals, materials, industry solutions, surface technologies, nutrition and care, and agricultural solutions industries
- Sustainability
- 1865

KEY MAP

- Main GMR focus
- Key differentiator
- Founded
- Polyurethane foam solutions
- Epoxy composite solutions
- All plastics – Difficult to recycle solutions

PRESCOUTER

Technology overview



Polyurethane foam solutions

Generated Materials Recovery

Generated Materials Recovery (GMR) was founded in 2003 and is focused on comprehensive waste and recycling services for industry. It is located in Arizona, United States, with 11-50 employees.

Company has the following expertises and focus:

- Helping industrial facilities improve financial performance
- Provides comprehensive and operationally integrated waste and recycling services to large industrial facilities
- Seeks to minimize waste and disposal costs and maximize the value of recyclable products
- Focused on service for a client, not commodity sector

Website: generated.com
Contact: info@generated.com

HQ: United States
Company size: 11-50

Main GMR focus

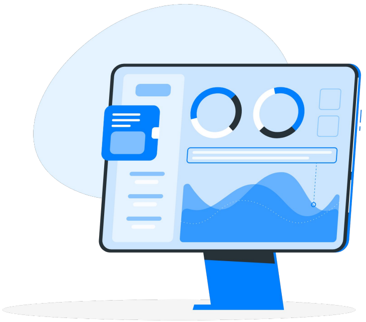
Find solutions for manufacturing and industrial operations to achieve sustainability goals by offering industrial recycling services.

Key differentiator

GMR offers industrial recycling services

Founded

2003



Polyurethane foam recycling

TECHNICAL DATA

GMR provides a reliable and efficient polyurethane foam recycling solution based on the needs of each client. Polyurethane foam can be found in a variety of products and materials, such as:

- Mattresses
- Furniture
- Packaging

Solution: Polyurethane Foam Recycling Consultancy

Input material: Pre-consumer polyurethane foam

Output material: Product is sold to companies looking for carpet underlayment or pillow filling.

Steps: Discuss what the client expects, propose a detailed process plan, implement equipment, recycling service, search for additional improvements.

Efficiency: N/A

Advantages: Recycling solution will be fully customized according to the needs of each customer and the material available for recycling.

Disadvantages: Few data available on the recycling process itself.

Figure. Polyurethane foam. Source: GMR.

Generated Materials Recovery

ADDITIONAL INFORMATION

The recycling process begins with the classification of materials, identifying the company's main types of recyclables. From this, the best solution is proposed and the foam materials are prepared for recycling. In the case of polyurethane foam, it needs to be compressed before recycling to reduce the cost of the process.

GMR works by collecting all types of mattresses to be discarded for recycling, and according to the company's CFO, the search for recycled memory foam is on the rise.

After recycling, GMR sells the product to companies looking for carpet underlayment or pillow filling, for example.

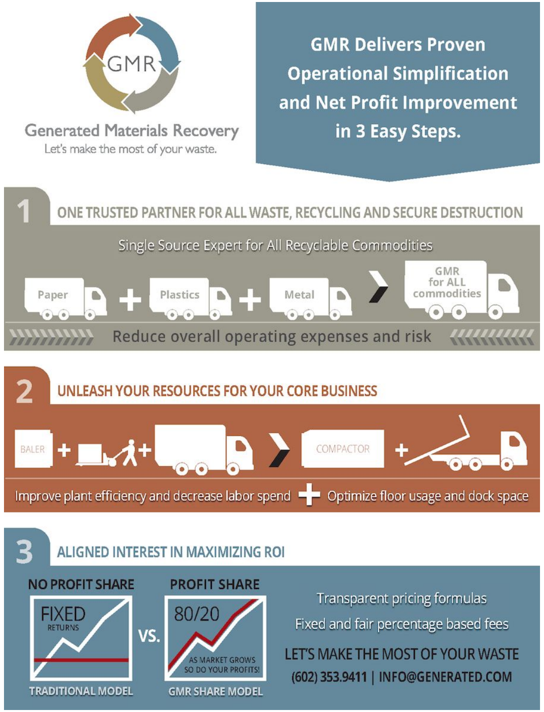


Figure. Commercial foam recycling services. Source: GMR.

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3. https://generated.com/why-gmr/foam-fabrication-plant-recycling/
4. https://generated.com/commercial-foam-recycling-services/
5. https://www.linkedin.com/company/gmr-generated-materials-recovery/
6. https://www.plasticstoday.com/sitemap/articlepermonth/7/2020?page=8

Dow Polyurethanes

Dow Polyurethanes is a segment of the DOW company focused solely on polyurethane solutions, applications, and development. Dow was founded in 1897 in the United States and now has more than 10,001 employees.

Company has the following expertises:

- Provides innovative polyurethane solutions
- Custom solutions on polyurethane according to customer application
- Portfolio in polyurethane systems, additives, surfactants, polyols, and isocyanates

Website: dow.com
Contact: Form

HQ: United States
Company size: >10,001

Main Dow Polyurethanes focus

Chemical, plastic, and agricultural products corporation

Key differentiator

Contribute to a more sustainable society working on a path to achieve carbon neutrality and eliminate plastic waste

Founded

1897

RENUVA Polyol

TECHNICAL DATA

Through the RENUVA Mattress Recycling Program, Dow is recycling polyurethane foam from mattresses and turning it into polyols for use in new mattresses and other applications like building insulation boards.

Solution: RENUVA Polyol

Input material: Polyurethane

Output material: Polyol

Steps: Polyurethane decomposition and conversion to a new product

Efficiency: Up to 50% replacement of standard polyol in rigid foam and up to 30% replacement of standard polyol in flex foam

Advantages: Reduces collective carbon emissions and energy consumption

Disadvantages: Technology is not fully commercial, pilot plant opened in 2021.

Figure. RENUVA circular chain. Source: Dow.

Dow Polyurethanes

ADDITIONAL INFORMATION

In the RENUVA Mattress Recycling Program, purpose polyurethane foam from end-of-life mattresses can be converted back to its raw material ingredient, the polyol.

Dow promises that this recycled polyol, the RENUVA Polyol, will offer exceptional performance with no loss in quality, making it suitable for a range of rigid and flexible foam applications.

In 2021, Dow, Orrion Chemicals Orgaform, and Eco-Mobilier (responsible for the collection of the mattresses), together with H&S Anlagentechnik and the Vita Group have inaugurated a pilot mattress recycling plant. When operating at full capacity, the industrial-scale reactor will recycle polyurethane foam from up to 200,000 mattresses per year.

Figure. Discarded mattresses. Source: Dow.

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2. https://corporate.dow.com/en-us/science-and-sustainability/2025-goals/renuva-program.html
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4. https://www.sustainableplastics.com/news/start-renuva-plant-mattress-recycling-project-renuva-now-reality
5. https://www.linkedin.com/showcase/dow-polyurethanes/
6. https://dowcircles.nl/en/sustainability/recycling/recycling-discarded-mattresses
7. https://everchem.com/dow-is-bringing-back-the-renuva-name/

BASF

BASF was founded in 1865 and is the world leader in the chemical sector. It has locations in more than 90 countries, with about 110,000 employees and generated sales of around €59 billion in 2020.

Company has the following action areas in sustainability:

- Aims to achieve net-zero CO_2 emissions
- Efficiency in production and energy usage
- Creation of accelerator solution for customers
- Circular economy program
- Responsibility in the supply chain
- Engagement in the alliance to end plastic waste

Main BASF focus

Chemicals, materials, industry solutions, surface technologies, nutrition and care, and agricultural solutions industries

Key differentiator

Sustainability

Founded

1865

Website: basf.com
Contact: Form

HQ: Germany
Company size: >10,001

ChemCycling - BASF

TECHNICAL DATA

BASF has developed a chemical recycling process for used mattresses made from polyurethane and is starting pilot tests. BASF's process breaks down the flexible polyurethane and delivers the initially used polyol.

Solution: ChemCycling

Input material: Post-consumer polyurethane foam

Output material: Polyol

Steps: Wet chemical recycling

Efficiency: N/A

Advantages: Significantly lower carbon footprint for the production of new foam

Disadvantages: Technology currently at pilot scale

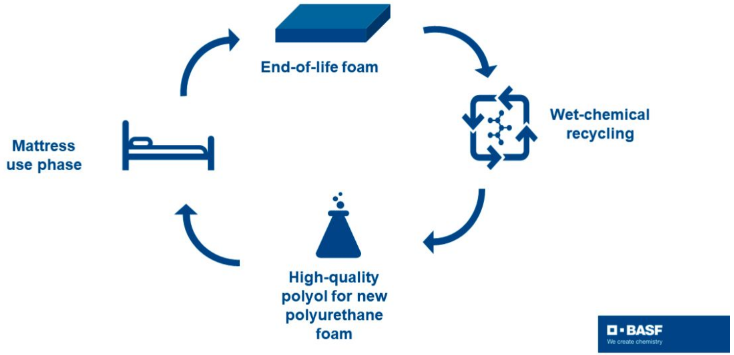

Figure. BASF process for mattress recycling. Source: BASF.

BASF

ADDITIONAL INFORMATION

Benefits of mattress recycling

- Mattresses are easy to collect and sort out
- Post-consumer material that has so far been landfilled or incinerated is recovered
- The recycled materials can be used for the production of new mattresses
- Production of new foam with a significantly lower carbon footprint because, in total, fewer fossil resources are used
- Quality comparable to that of non-recycled raw materials

Figure. BASF's process breaks down the flexible polyurethane and delivers the initially used polyol. Source: BASF.

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5. https://www.linkedin.com/company/basf/
6. https://www.basf.com/global/en/who-we-are/sustainability.html

Covestro AG

Covestro is a Bayer spinoff formed in 2015 that is fully committed to the circular economy. It has locations worldwide, with more than 10,001 employees, and had sales of €10.7 billion in 2020.

Company has the following expertises:

- Experience in 3D printing, adhesives, coatings, composites, elastomers, films, foams, plastics, and thermoplastic polyurethane
- Polymer production (polyurethane- and polycarbonate-based raw materials)

Website: covestro.com
Contact: Form

HQ: Germany
Company size: >10,001

Main Covestro focus

Manufacture of high-tech polymer materials and the development of innovative, sustainable solutions for products used in many areas of daily life

Key differentiator

Supplier of diverse innovative, sustainable polymer materials

Founded

2015

Polyurethane foam recycling

TECHNICAL DATA

Covestro has a pilot plant for flexible foam recycling at its Leverkusen, Germany, site. Polyurethane flexible foam recycling/recovery can be done in a few ways:

1. Rebonding (mechanical recycling) - Molding and adding binder to hold together. Applications include carpet padding, flooring, athletic mats, cushioning, packaging, and acoustical materials
2. Regrinding (mechanical recycling) - Grinding and blending with polyol. Applications in seating materials
3. Glycolysis (chemical recycling)
4. Energy recovery - Recommended when recycling is not technically or economically feasible

Solution: N/A

Input material: Polyurethane flexible foam from used mattresses

Output material: Polyols

Steps: Glycolysis (chemical recycling): Reaction with diols at temperatures greater than 200°C

Efficiency: N/A

Advantages: Reduces the carbon footprint

Disadvantages: Currently at pilot scale

Figure. Polyurethane recycling tests. Source: Covestro.

Covestro AG

ADDITIONAL INFORMATION

Covestro's products include isocyanates and polyols for cellular foams, thermoplastic polyurethane and polycarbonate pellets, and polyurethane-based additives used in the formulation of coatings and adhesives.

Covestro polyurethane was used in the 2014 official FIFA World Cup football.

In cooperation with the companies Recticel and Redwave, a division of Wolfgang Binder GmbH, and as part of the PUReSmart research project, Covestro has also developed an intelligent sorting solution for separating the different polyurethane foams from post-consumer mattresses.

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Epoxy composite solutions

Aditya Birla Group

The Aditya Birla Group was founded in 1857 and is a global powerhouse in a wide range of sectors. It is from India and operates in 36 countries in North and South America, Africa, and Asia, with more than 140,000 employees.

Company has the following expertises:

- Aluminum rolling, viscose staple fiber, and carbon black
- Experience in the metals, pulp and fiber, chemicals, textiles, carbon black, telecom, and cement fields
- Provides help to customers in achieving technological excellence and enhancing their market positions

Main Aditya Birla Group focus

Aditya Birla is majorly engaged in the businesses of non-ferrous metals, viscose filament yarn, viscose staple fiber, cement, fertilizers, chemicals, branded apparel, carbon black, sponge iron, telecom, IT services, financial services, insulators, and business process outsourcing.

Key differentiator

Multinational conglomerate

Founded

1857

Website: adityabirla.com
Contact: Form

HQ: India
Company size: >10,001

Recyclamine

TECHNICAL DATA

Recyclamine is a technology platform that uses novel polyamine curing agents that contain specifically engineered cleavage points at cross-linking sites, which convert thermosetting epoxies into recyclable thermoplastics under a specific set of conditions. It was developed in partnership with Cobra International for manufacturing surfboards that can be recycled.

Solution: Recyclamine

Input material: Epoxy thermoset composites (carbon fiber, glass fiber)

Output material: Recyclable thermoplastic and recovered fibers

Steps: The matrix composed of epoxy resin and Recyclamine hardeners in polymer composites can be cleaved by solvolysis under specific conditions (not disclosed).

Efficiency: N/A

Advantages: Maintains or exceeds the process and performance characteristics of epoxy matrix used in composites. Recovered fibers are in near virgin form, with nominally reduced mechanical strength.

Disadvantages: Recycling process steps are not disclosed.

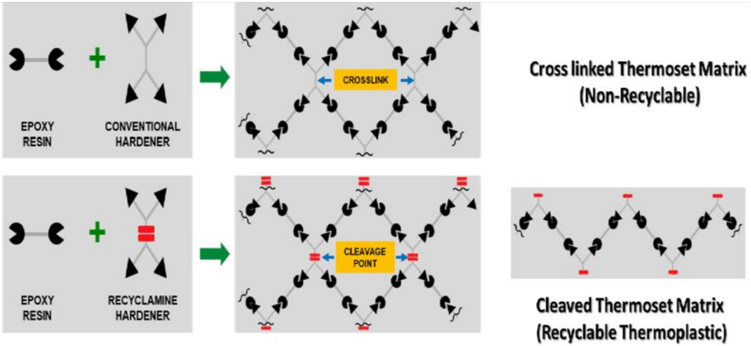

Figure. Schematic depicting curing of epoxy resin systems (non-recyclable vs recyclable). Source: Dubey et al., 2020.

Recyclamine

CASE STUDY

The first industrial-scale implementation of Recyclamine was performed by Siemens Gamesa Renewable Energy, and commercial operations are expected to commence in 2022.

Companies: Siemens Gamesa Renewable Energy

Location: German North Sea

Input material: A mixture of resin and materials including balsa wood, glass fiber, and carbon fiber

Output material: A combination of materials (balsa wood, glass and carbon fiber) cast together with resin to form a strong and flexible lightweight structure

Objective: Recyclable wind turbine blade

Methods: Heating the material in a mildly acidic solution

Results: The chemical structure of this new resin type makes it possible to efficiently separate the resin from the other components at the end of the blade's working life. This mild process protects the properties of the materials in the blade, in contrast to other existing ways of recycling conventional wind turbine blades. The materials can then be reused in new applications after separation.

Figure. The first six 81-meter long recyclable blades. Source: FT.

Aditya Birla Group

ADDITIONAL INFORMATION

ADITYA BIRLA GROUP

Wind turbine blades have been produced using epoxy systems. With Recyclamine, the blades are recyclable, as are the fiber and epoxy, closing the loop and allowing for a circular economy. This helps solve the difficult issue of disposal of the blades, making the wind turbines truly 100% recyclable, as well as creating value through the reuse of recovered materials.

In the vehicle industry, thermoset composite structural elements like the doors, chassis, and panels can have improved end-of-life characteristics with Recyclamine.

Recyclamine was developed by Connora Technologies, and Aditya Birla acquired the product and technology rights. Connora's co-founder and CTO is now the CEO of Thintronics.

This technology is protected by patent number US20130245204A1.

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Adherent Technologies, Inc.

Adherent Technologies Inc. (ATI) develops polymers and processes for use in the high-performance composites, adhesives, coatings, foams, and recycling process markets. The company provides composite, recycling, and space technologies as well as light-curing resin systems, testing, and consulting.

Company has the following expertises:

- Finish for carbon fiber to improve adhesion
- Composite repair primers
- Surface treatments for nanomaterials
- Powder towpregs for out-of-autoclave processing
- Recycling technology for composite materials
- Specialty foams for space and defense applications

Website: adherent-tech.com
Contact: inquiries@adherent-tech.com

HQ: United States
Company size: unspecified

Main ATI focus

Surface science, composites, coatings, sensors, and polymer science

Key differentiator

Adherent Technologies, Inc. solves demanding materials problems by developing cutting-edge technologies and the processes to produce them.

Founded

1990

Wet chemical breakdown

TECHNICAL DATA

This technology is a wet-chemical treatment, in which the matrix resin of the carbon fiber-reinforced composite is broken down in a liquid, producing a very clean fiber under much milder conditions than those found in pyrolysis processes. ATI has a pilot plant capable of processing 100 lb of composite scrap per batch.

Solution: Carbon fiber wet chemical breakdown

Input material: Most fiber-reinforced composites, in particular, carbon fiber

Output material: Short carbon fibers of variable length

Steps: Wet chemical degradation of the polymer matrix

Efficiency: Over 99% clean fiber retaining

Advantages: Resale value of reclaimed fiber, does not rely on extensive pre-sorting or disassembly, no volatile solvents

Disadvantages: Materials need to be reduced in size beforehand

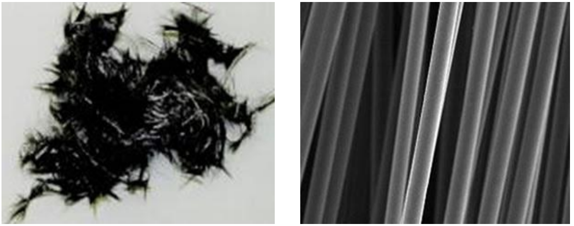

Figure. Reclaimed fibers (left). SEM micrograph of reclaimed carbon fiber (right). Source: ATI.

Adherent Technologies, Inc.

ADDITIONAL INFORMATION

Adherent Technologies markets to defense, aerospace, and government entities throughout the United States.

Little information is available, and the company may have been purchased or invested by AMTII Corp.

ATI is a research and development company, not a waste processor.

According to ATI, a 2-ton-per-day standalone facility would require a $4 million investment.

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All plastics – Difficult to recycle solutions

Recycling Technologies

Recycling Technologies was founded in 2011 and is a global recycling solution company. It has two locations in the United Kingdom, with 51-200 employees.

Company has the following expertises:

- Experience in technology to recycle plastic waste
- Experience in chemical recycling
- Circular economy solutions

Main Recycling Technologies focus

Chemical recycling

Key differentiator

Accelerating the evolution of plastic into a more sustainable material through innovation, reducing carbon footprint

Founded

2011

Website: recyclingtechnologies.co.uk
Contact: Form

HQ: England
Company size: 51-200

RT7000

TECHNICAL DATA

RT7000 is a technology that transforms plastic waste into chemical feedstock for plastic production. The machine uses a process called “thermal cracking” that breaks down the long chains of polymers into shorter chains through the use of heat in the absence of oxygen. The output material, Plaxx, produces far less sulfur dioxide (SO_2) than heavy fuel oil when burned, with emissions of 0.09-0.5kg of SO_2 compared with 20.5kg SO_2.

Solution: RT7000

Input material: Plastics that are not routinely recycled

Output material: Plaxx, an ultra low-sulfur liquid hydrocarbon product

Steps: Residual plastic waste is first inserted into a fluidized bed thermal cracker. The product goes to a fluidized bed regenerator and back to the fluidized bed thermal cracker in a cyclical process. During the cycles, the gas of interest is collected. This goes through a refining process and is then stored.

Efficiency: 85% according to Solar Impulse Foundation [5]

Advantages: Reduces emissions, recycles residual plastic that are not currently recycled

Disadvantages: High cost

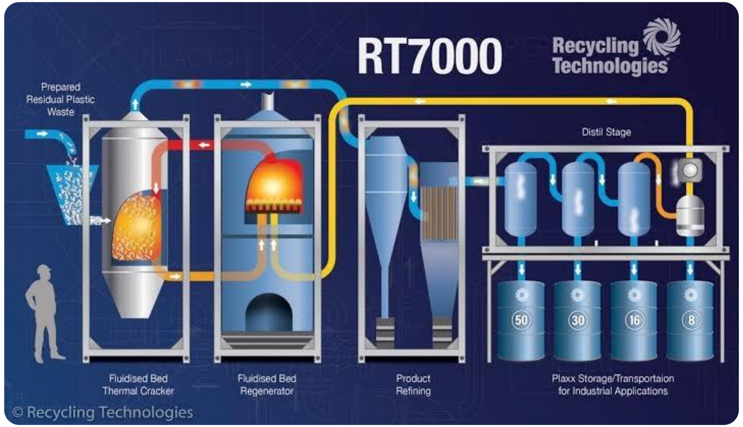

Figure. RT7000 recycling process. Source: Recycling Technologies.

RT7000

CASE STUDY

Recycling Technologies

In 2018, the Bin Group announced that through Project Beacon, Recycling Technologies would begin installing its first commercial chemical recycling RT7000 machine at Binn Eco Park to recycle plastic back into oil.

Companies: Bin Group

Location: Binn Eco Park, Perthshire, Scotland

Input material: Plastics that are not routinely recycled

Output material: Plaxx, an oil used to make new polymers

Objective: Boosts the local economy and enables household and large rigid plastics to be recycled instead of incinerated

Methods: Commercial-scale unit

Results: The combined mechanical and chemical recycling processes will enable a recycling level of around 90% of all received plastics. Chemical outputs will provide manufacturing feedstocks for industry. No information was found about the inauguration of the unit.

Figure. Plaxx oil produced is stored in these containers. Source: Recycling Technologies.

Recycling Technologies

ADDITIONAL INFORMATION

The RT7000 can process most types of plastics that are not routinely recycled.

Plaxx is a liquid hydrocarbon feedstock that is produced from the waste plastic processed through the RT7000. It is a valuable chemical feedstock that, after refinement, can be used in the manufacturing of new virgin quality plastic.

The company has had a demonstration test plant in operation since 2018 that allows for small input and upgrade testing before carrying out the procedure on a large scale. This test unit is located in a Swindon Borough Council recycling facility.

This solution can be installed at existing waste sites anywhere in the world to help divert plastic waste away from landfills, incineration, and leakage into the environment.

Looking for investors, waste handlers, partners, and governments to accelerate the deployment of the technology.

The global fleet of RT7000s could save a total of 17 million tonnes of carbon equivalent, equating to almost 16,000 wind turbines, or enough electricity for 6.7 million houses per year.

This technology is protected by patent number WO2014128430A1.

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Mura Technology

Mura Technology was founded in 2019 and was formed to commercialize an advanced recycling process. It is located in England and has 51-200 employees, but their portfolio includes sites within USA, Germany, and Asia.

Company has the following expertises:

- Provides an end-to-end solution to convert mixed waste plastic.
- Developed the HydroPRS process.

Main Mura Technology focus

Recycle plastics through HydroPRS process

Key differentiator

Hydrothermal upgrading

Founded

2019

Website: muratechnology.com
Contact: enquiries@muratechnology.com

HQ: England
Company size: 51-200

HydroPRS

TECHNICAL DATA

The Hydrothermal Plastic Recycling System (HydroPRS) is a process developed by Mura Technology that utilizes the Cat-HTR technology, which employs supercritical water, heat, and pressure to convert waste plastics into valuable chemicals and oil. This chemical recycling process targets plastics deemed unrecyclable.

Solution: HydroPRS

Input material: All kinds of end-of-life plastics

Output material: Naphtha, distillate gas oil, heavy gas oil, heavy wax residue

Steps: 1) Waste plastic cleaned and shredded; 2) Melting and pressurization; 3) Mix with steam; 4) Heat; 5) Cat-HTR reactor; 6) Depressurize; 7) Product separation; 8) Product storage

Efficiency: Over 85% of the mass of plastic converted to hydrocarbon product

Advantages: High conversion efficiency, the technology is scalable, controllable reaction, process flexibility, and does not generate toxic products.

Disadvantages: Does not mention specifically thermoset materials

Figure. Obtained products after plastic recycling through HydroPRS process. Source: Bioenergy International.

HydroPRS

CASE STUDY

ReNew ELP is the first commercial-scale HydroPRS site, already under construction, with an annual capacity of 80,000 tonnes on completion.

Companies: ReNew ELP

Location: Teesside, North East England

Input material: End-of-life plastic

Output material: Naphtha, distillate gas oil, heavy gas oil, heavy wax residue

Objective: Recycle all kinds of plastics

Methods: N/A

Results: N/A

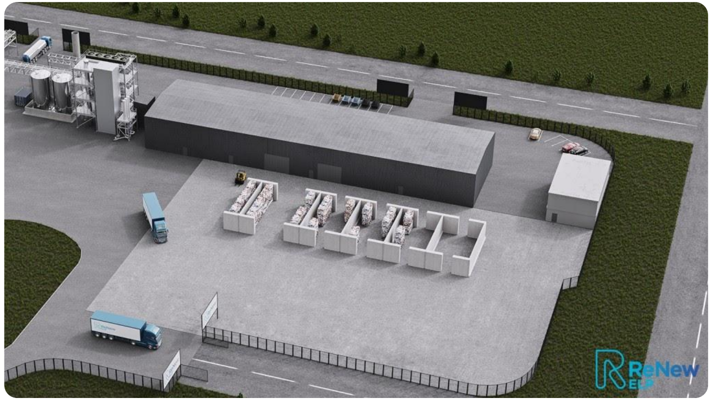

Figure. ReNew ELP pilot-scale site project.
Source: Recycling Product News.

Mura Technology

ADDITIONAL INFORMATION

HydroPRS process breaks down the long-chain hydrocarbons and donates hydrogen to produce shorter-chain, stable hydrocarbon products for sale to the petrochemical industry for use in the production of new plastic and other materials.

The use of supercritical water provides an organic solvent, a source of hydrogen to complete the broken chemical chains, a means of rapid heating, avoiding excessive temperatures that would lead to excessive cracking, and a scalable process.

This helps to create a circular economy for plastic by diverting those materials that cannot be recycled via traditional means away from landfills and incineration and into recycling, thus reducing unnecessary single-use plastics and reducing carbon emissions.

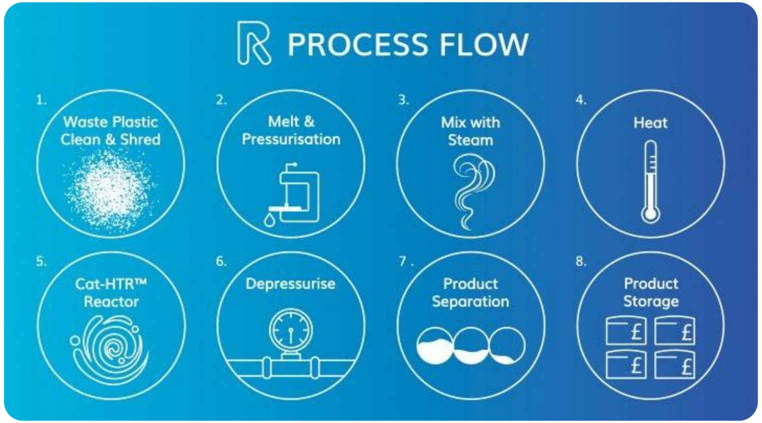

Figure. ReNew ELP process flow. Source: ReNew ELP.

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8. https://www.linkedin.com/company/mura-technology/
9. https://renewelp.co.uk/

Braven Environmental

Braven Environmental was founded in 2010 and is trying to find solutions to eliminate plastic waste. It is located in the United States, with 51-200 employees.

Company has the following expertises:

- Implementing plastic recycling process
- Localized facility ready for processing in a few months
- Experience in redirecting waste plastics away from landfills, oceans, and waterways
- Pyrolysis process

Main Braven Environmental focus

Develop waste plastics solutions

Key differentiator

Technology provider in the advanced plastics recycling sector

Founded

2010

Website: bravenenvironmental.com
Contact: info@bravenenvironmental.com

HQ: United States
Company size: 51-200

Braven PyChem

TECHNICAL DATA

The company's product, Braven PyChem, has two primary uses: as a building block for new plastic production, and as a substitute for traditional fuel products, generating second-life fuel. The process uses a catalyst cracking technique that depolymerizes the hydrocarbon chain.

Solution: Braven PyChem

Input material: Mixed, difficult-to-recycle waste plastics

Output material: PyChem oil

Steps: Pyrolysis process functions without water and oxygen and under pressure at temperatures that are above 430°C (800°F).

Efficiency: N/A

Advantages: The process used is not incineration

Disadvantages: Uses large rotating vessel and large kiln apparatuses. Difficulty of obtaining an environment entirely devoid of oxygen.

Figure. Pyrolysis of plastic to oil. Source: Braven.

Virginia Plant

CASE STUDY

Braven has a commercial facility in North Carolina, USA, where an average of 12,000 tons of waste plastic can be processed each year. In 2020, Braven announced that it would invest $31.7 million to establish a manufacturing operation in Virginia. With the pyrolysis method, it is possible to break down waste plastics with minimal emissions.

Companies: Chevron Phillips Chemical

Location: Virginia

Input material: Waste plastics

Output material: PyChem oil

Objective: Plastic recycling with minimal emissions and supply of its pyrolysis-derived feedstock.

Methods: Pyrolysis

Results: Braven is developing a network of facilities across the United States and abroad to offer this solution.

Figure. Braven's plant equipment. Source: Braven.

Braven Environmental

ADDITIONAL INFORMATION

Braven facilities are capable of processing mixed waste categories 1, 2, 4, 5, 6, and 7, including plastic film and bags.

The first step of Braven's procedure is to find a solution with zero ocean and landfill impact in a modular, local facility, using a comprehensive processing with minimal emissions to discover valuable second-life uses.

With one ton of plastic processed, Braven can produce approximately 200 gallons of Braven PyChem.

In 2021, Braven announced an agreement with Chevron Phillips Chemical to supply its pyrolysis-derived feedstock.

The PyChem system and process for converting waste plastic into fuel is a patented technology (Pub. No. US 2018 / 0010049 A1) published in 2018.

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Expert Interview

Expert Interview

Sudhin Datta, PhD

Consultant on Polymers
Retired Senior Research Associate, ExxonMobil Chemical

Expert consultant on polymers with almost 40 years of experience at ExxonMobil Chemical, in the polymers business. He holds a PhD in organometallic chemistry from Harvard University and postdoctoral engagements at the University of Toronto and the University of Chicago. His work on polyolefin elastomers has been honored in both 2011 and 2014 by ExxonMobil Chemical Outstanding Patent awards, which recognizes technology commercialization with widespread utility. In addition, he has been honored with the 2015 Charles Goodyear award of the Rubber Division of the American Chemical Society. Dr. Sudhin can speak with authority on the topic of recycling of thermosets.

The most important classical thermosets that are recyclable are polyurethanes, epoxies, and silicones. Additionally, there are materials which behave like thermosets in the recycling process, such as PVC, Teflon, and PEX, cross-linked polyethylene.

The three classical thermosets are recycled for different purposes:

- ✔ **Polyurethanes** are recycled because there is a very large volume in the world in the low-density form. There is inherent value in the materials that come out of polyurethane recycling, and the process only takes a couple of hours. It is not being done in North America and Western Europe, as the companies in such regions would much rather export that waste polyurethane foam to lower cost countries in Asia.
- ✔ **Epoxies** have inherently no value, but reinforced epoxies are recycled for carbon fiber recovery, which are 10 times more expensive than the epoxy itself.
- ✔ **Silicones** are recycled because silicone monomers are very expensive.

Other materials face more economic barriers, such as **Teflon and PVC**:

- ✔ Thermal recycling turns Teflon and PVC into dark intractable solids while releasing toxic acid gases which damage the equipment.
- ✔ **Teflon** recycling is hampered because typically it is present in small quantity by weight and recovering and recycling is economically unjustifiable.
- ✔ Typical **PVC** pipes for city water are composed of filled PVCs. So whatever recycling process should first remove the filler, which is a toxic waste that corresponds to around 40% of the volume.

> “There is a move to recycle or to reconstitute almost all the polyurethane foam insulation. My sense is no more than 20% of the world’s production of polyurethane foam is actually recycled.”

ADDITIONAL INSIGHT:

“Recycling of rubber products is a massive issue. By far, this is a blight of humanity, used tires which no one quite knows what to do with and is not widely discussed.”

- Sudhin Datta, PhD, Senior consultant on polymers

For thermosets, the recycling process is not mechanical, so is it always chemical? What about thermal recycling - pyrolysis?

Answer

That's correct. What is called "mechanical recycling" is actually a down cycling, basically just grinding it and feeding it into low-value products such as asphalt or something related. This is not recycling; it is just hiding the problem.

For thermosets, one would not go for pyrolysis. That is what thermosets are. If you heat them up by themselves, nothing happens, they just burn.

The processes are chemical catalyzed reactions (glycolysis and alcoholysis).

The recycling processes are usually not disclosed by the companies, but they can be understood based on their chemistries:

Polyurethanes

Polyurethanes are soaked, and then a glycolysis process is carried out by heating up ethylene glycol (at around 280°C) for about four or five hours and breaking the big molecules down to smaller molecules, which can be distilled and recovered. It is claimed a 95% efficiency of whatever output material as free monomers. The process is fairly well understood.

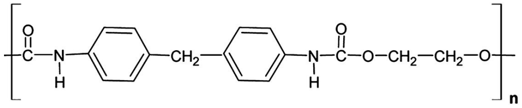

Figure. Chemical structure of polyurethanes.

Epoxies

Reinforced epoxies are recycled via alcoholysis, or there is typically a catalyzed degradation of the process. The epoxies come off and the catalyst is washed off, so the carbon fibers are recovered. The chemistry is well understood, but there is some work to be done to understand the catalyst.

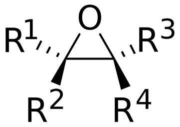

Figure. Chemical structure of the epoxide group, a reactive functional group present in all epoxy resins.

Silicones

Silicones are recycled in a similar way to polyurethanes, but the molecules are broken down to polydimethylsiloxane (PDMS).

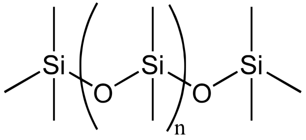

Figure. Chemical structure of silicones (PDMS).

When it comes to thermoplastic materials, there's a lot of discussion on post-consumer and post-industrial recycling. Is there a parallel for thermosets as well?

Answer

The recycling processes of polyurethanes, epoxies, and silicones are basically breaking them down into monomers. **So the sourcing of the material is not very important, as long as it has consistent composition**.

So thermoset recycling is more like break down the polymer and turn that back into **useful building blocks** which you can reuse in some other way or probably in a better way.

Silicones are a good example. After recycling, even if you don't make silicone products, you will make silicone liquids, which have actually **higher value** because they can be used in shampoo formulations as an anti-foam agent, for instance.

It looks like most of the silicone recycling is done on a small scale by silicone users, particularly in China and India.

Could you comment on societal hindrances and regulations in all plastics recycling?

Answer

There are two sets of societal customs and regulations which have to be considered. One is the **interest of the waste recyclers**. For waste recyclers or those who haul waste away, losing materials to side products is a loss of business and they oppose it vehemently. They oppose the classification of polyolefin or polyurethane, for instance, as a raw material rather than a waste.

In **in-kind recycling**, where you just take a waste plastic and put it back into its intended use — for example, a polyethylene foam going back into a polyethylene — that doesn't work very well because consumers are very concerned about odor, color, and history of the plastics used. So there is a huge amount of **consumer resistance** which always happens whenever you try to bring in in-kind recycling.

The one that seems to get around all these issues is breaking down into monomers, and sending to the process and reusing.

So for the regulations, there are politics, there is human psychology, and there are capital and economics. It is not a clean answer.

About the Authors

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Technical Director

Marija is the Technical Director for PreScouter's Chemical, Materials, and Packaging verticals. She has worked across topics such as product and process improvement and development and sustainability throughout the chemicals, materials, and packaging industry. Marija completed her Master's degree in Chemical Engineering from Belgrade University and her PhD in Organometallic Chemistry and Catalysis at the Swiss Federal Institute of Technology (ETH Zurich). Prior to her PhD, Marija worked in the chemical industry on the synthesis of new textile dyes.

Priscila Costa Carvalho

Project Architect

Priscila is one of PreScouter's Project Architects working primarily in the Chemicals, Materials, and Packaging verticals. She has a solid background in Chemistry and Chemical Engineering and holds an MSc in Chemistry and a PhD in Biochemical Engineering, both from the University of São Paulo (Brazil). Priscila brings to PreScouter years of experience in the research and development of new materials and bioprocesses, working in multidisciplinary teams and in collaboration with industry.

Gabriela Mattos

Researcher

Gabriela is a PhD student in the Chemical Engineering Program at COPPE at the Federal University of Rio de Janeiro (UFRJ, Brazil), with research focused on functionalized polymeric materials for biological applications. Gabriela holds an MSc in Nanotechnology Engineering from UFRJ, Brazil, and during this course, she was involved in parallel projects related to sustainability, circularity, reuse of plastic materials and replacement of oil by natural raw materials.

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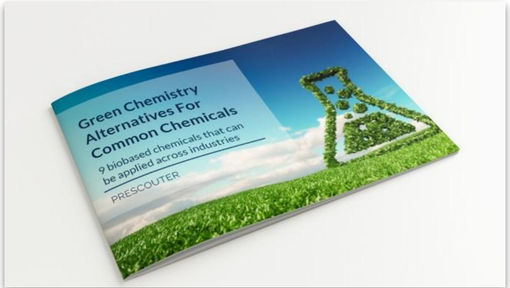

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Potential Next Steps

- PreScouter can look for more companies developing technological solutions for recycling of polymer materials based on your technical and business parameters
- PreScouter can conduct anonymous interviews with companies and researchers
- PreScouter can organize direct consultations between you and Subject Matter Experts (SMEs) in the space

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