Plastics Recycling and the Circular Economy:
Catalytic and Compatibilization Solutions

Updated Multi-Client Study Proposal

September 2019
Plastics Recycling and the Circular Economy: Catalytic and Compatibilization Solutions

I. ABSTRACT

There is an intense R&D effort being undertaken by plastics producers, industry consortia and academia globally to understand and appreciate the hurdles to be overcome and to economically resolve a serious improvement in the recyclability of plastics, which has taken a center stage in a global debate (Circular Economy Action Plan, 2018). It is hoped that this will transform the way plastic products are designed, used, produced and recycled in the EU and other industrial countries. China, the U.S. and Western Europe and other regions are pressing for sustainable solutions to plastic recycling and a drastic reduction of plastic waste to the marine environment (AzocleanTech, 2017). This proposed study is to assist the plastics and polyolefin industries to identify new pipeline technologies and strategic commercial directions which will help speed up their resolutions to these challenges in an economical way. It will address current state-of-art (SoA) in technology and commercial development, identify and address progress towards viability in two (2) promising approaches — notably catalytic and compatibilization and provide strategic guidance on the competitive landscape and future investment. It is a “must have,” industrially-sourced assessment for addressing the current industry need from resin producers, process licensors and catalyst/compatibilizer suppliers from a practical perspective.

II. BACKGROUND

All open literature and related studies to date do an adequate job of defining “the challenge” from both a market statistical basis, as well as defining the current plastics industry recycling status, i.e. the state-of-art (SoA) in recycling technologies. What is clearly missing is a visionary industrial oriented Technology Roadmap for the next 5-10 years that will concentrate R&D and commercial development efforts to speed up deployment, improving both efficiency and effectiveness of implementation, particularly in mixed plastics waste.

The missing factors to be addressed more fully are:

- What new pipeline technologies for different segments, e.g. PET, polyolefins, mixed plastics, etc., are likely to be the best directions for producers and industry to pursue economically?
- What do plastic producers currently think about this challenge, and what are their plans to address the issue? Without their support and input, the process will undoubtedly be slower.
- What likely country, regional and global regulations will impact each company’s decision making?
No one disputes this is a decade long challenge! The issues to be resolved go beyond technical to include economic ones, based on the commercial understanding that currently the collection, separation of physical plastics streams, and the conversion back to monomers or recyclable technologies as they stand to date, are not yet ready for “prime time.” In this proposed multiclient study, TCGR will take a lead in providing viable technological directions from both pipeline R&D and commercial strategy perspectives.

Our leading networks from within the plastics industries, as well as from our Dialog Group®, industrially and from academia, provide us with unique resources to interface on a global basis, to provide insights that would not be readily available elsewhere. We are also very operations focused; therefore we can include production insights unavailable from others.

The challenge is, of course, currently diverse and fragmented, so in this visionary report we can offer a consolidation of current knowledge, along with direct field interviews with the developers of next generation solutions. We believe the timeliness and vision will assist resin producers, process licensors, catalyst manufacturers and the logistics systems in improving the rate of recycling in a faster manner. There is much rhetoric and confusion that needs to be uncoiled to create a solid pathway forward. If we are to collectively resolve this issue together, then some sound thinking and minds must prevail. By consolidating this global information, with the best scientific and commercial minds, we have the opportunity to make some better investment and R&D investment decisions.

Industry has taken significant steps recently:

- On January 16, 2019 The Alliance to End Plastic Waste (AEPW) was launched, which has committed over $1BIL, with the goal of investing $1.5 BIL over the next five years. The founding members of this consortium include; BASF, Berry Global, Braskem, Chevron Phillips, Clariant, Covestro, Dow, DSM, ExxonMobil, Formosa Plastics, Henkel, LyondellBasell, Mitsubishi Chemical, Mitsui Chemical, NOVA Chemicals, Oxychem, Polyone, Procter & Gamble, Reliance, SABIC, Suez, Shell, SCG Chemicals, Sumitomo Chemical, TOTAL, Veolia, and Versalis (ENI).

  Just as of July 10th, 2019 this now consists of 12 new companies; Equate Petrochemical, Gemini, Grupo Phenix, Mondi, Novolex, Pepsi Co, Sealed Air Corporation, Sinopec, SKC, Storopak, TOMRA and Westlake. In announcing this expansion, AEPW stated by advancing a global coordinated effort focused on recovering, recycling and reusing plastics, we will develop a global business model that creates value from waste.

- In the polystyrene segment “Styrenics Circular Solutions (SCS)” was formed in December, 2018 with four founding members INEOS Styrolution, TOTAL, Trinseo, and Versalis (Eni); in June, 2019 Repsol joined. This consortium has teamed up with Agilyx to develop depolymerization back to monomers.
In the PET segment, commercial operations are already underway, to depolymerize using hydrolysis or glycolysis processes. Eastman just announced conversion of their Kingsport, TN to recycle waste PET into new products. Others, including Dow, Shell and even Kodak have chosen directions, as PET is already the most recycled plastic globally, enhanced by the ability to convert PET into yarns and fabrics for the clothing industries. These processes are enhanced using Zn acetate (and other) catalysts. We will benchmark these alternatives.

Because Styrenics and PET are so well developed, although we will have cameo developments, our intent is to focus on the largest challenge involving polyolefins (PO) and mixed plastics wastes (PET/PO, PVC, nylon and other mixtures) which will represent about 75-80% of this report, where a better and deeper understanding is needed.

A. New Advanced Catalytic Solutions

The use of heteroatom titanates in this application is not new; in fact, Salvatore Monte of Kenrich Petrochemicals first published in 1973 and many papers have been widely circulated up to the present. Much evidence exists that both titanate and zirconate coupling agents act as a repolymerization catalyst in the unfilled or filled macromolecular melt to increase mechanical properties.

1. Neoalkoxy Heteroatom Titanates/Zirconates do not need hydrolysis, surface hydroxyls, or pH control as with silanes.
2. Water of condensation is not left on the interface as with silanes.
3. Promote adhesion via in situ proton coordination directly in the dry, polymer melt or solvent phase. They are water insoluble.

Figure 1. Points to the SIX FUNCTIONS of a neopentyl (diallyl) oxy, tri(diocyl)phosphato zirconate and why Function 1 COUPLING is different than silanes (Kenrich Petrochemicals, 2019).
Figure 2. Illustrates FUNCTION 1 coordination coupling of a neoalkoxy titanate to non-silane reactive 3-micron CaCO₃ (Kenrich Petrochemicals, 2019).

The difference today, is that more advanced chemistry is available from organometallics since the metallocene revolution, back in the late 1980-1990’s. We intend to explore new catalytic chemistries, that can be even more compatible with today’s producer resins.

Figure 3. Reactive compounding shear needed in the melt. A common mistake is run tests under the same conditions (Kenrich Petrochemicals, 2019).
As you can see from papers at the forefront of this approach in its early years (Chien et al., 1997) and ExxonMobil (Baugh and Canich, 2008), homogeneous catalysts of new generations hold a high promise for more cost/performance advanced techniques. With TCGR’s long history in single-site catalysis and monitoring new advanced techniques, we are planning to add considerable value to polyolefin and mixed plastics compatibilization in this field. No one within industry is more qualified to investigate these forward-looking cost/performance alternatives.

Figure 4. Catalytic Approaches for Specific Comonomer Incorporation (Chien et al., 1997)

B. New Advanced Compatibilizer Solutions

Many industry papers have summarized commercially available compatibilizers including those from The Society of Plastics Industry or SPI (SPI, 2015). The current challenge is not available solutions but rather cost/performance ones for commercial recyclers. Also, one of the challenges is that each batch of mixed plastics has a different composition and most recyclers are not sophisticated to be able to understand the chemistry to adjust to these moving targets within the field. No “one-size-fits-all” is a common phrase within the industry.

One of the objectives of this study is to provide industry guidance to resin producers, technology developers and ultimately to recyclers on how to better anticipate these mix changes, to reduce rejected waste. We would encourage subscribers to support the education needs in the market place, needed to bridge these gaps.

In order to focus the content of this well researched document, we also propose more direct discussions with our project team. Specifically, with sufficient “charter subscriber” ToC inputs (a practice always followed by TCGR multi-clients) we expect to tailor the scope/content for subscribers to make it a study, “by the industry, for the industry.” This is a unique hallmark of our operations.
References
Azocleantech, 2017
Circular Economy Action Plan, January 2018
James C. W. Chien, Yasumasa Iwamoto, Marvin D. Rausch, Wolfgang Wedler and Henning H. Winter
The Alliance to End Plastic Waste, https://endplasticwaste.org/

III. THE NEED FOR THIS STUDY

The case for choosing this subject has never been clearer. Due to increasing environmental drivers, the need for such a study has never been more timely. Major plastics producers are now committed to significant reductions in plastic landfill, and the reduction of waste plastics finding their way into our oceans. The older methods of disposal like incineration or even pyrolysis are no longer acceptable due to tightening emissions and CO$_2$ regulations.

One of the key issues is that different plastics waste streams do not mix when thermally heated, like oil and water. So new compatibilizer technologies are an R&D direction that needs to be better explored. It is also clear that pyrolysis approaches are not an economic solution. This study will reveal more advanced approaches being undertaken on a global basis. There are opportunities in catalysis, in determining the molecular structure of the resin (including co-monomer incorporation containing functional groups) to design-in re-use/recycle functionality.

The benefits of aggregating the multiple approaches into one study creates an opportunity to extract and determine which approaches or pathways are most beneficial given the local circumstances, providing value to chemical (olefins and other monomer) producers and suppliers of different types of plastics.

Critical topics this study will address include:

1. State-of Art (SoA) in industry investments and partnerships in existence.
2. New pipeline technologies in for the next 5-10 years, including benchmarking economics where available, key players, pilots and R&D investments.
3. Regional outlooks based on market opportunities and regulatory drivers.
4. Strategies for implementation.
This study also complements other studies undertaken by The Catalyst Group Resources, demonstrating TCGR’s unique capability and resources to deliver exceptional insight. Recent multi-client studies can be seen on http://www.catalystgrp.com for more detail.

- **Polyolefin (PO) Catalysts and Processes: Competitive Implications of Industry Consolidation** (completed in July 2018)
- **Progress in Technology for Polyolefin Production: Quantifying the Value-Added of Advanced Catalysts, Co-catalysts/Activators and Stereoregulators** (completed in December 2011)

### IV. SCOPE AND METHODOLOGY

As seen in the report’s preliminary Table of Contents (TofC) that appears on page 8, TCGR’s proposed study will focus on new technologies in pilot and in the R&D pipeline, that enhance the economics through catalysis and compatibilizers which retain or enhance virgin resin properties, so that we can find pathways beyond lower value reuses such as road asphalt and park benches. There is already considerable work being undertaken by Borealis Everminds™ and LyondellBasell in these directions. At the latest Society of Plastics Engineers (SPE) “Polyolefins Conference” in Houston (February 2019), we also conducted interviews with a number of companies developing interesting new compatibilization technologies.

**SECTION III** will summarize the current State-of-Art (SOA) for all key resins including PET, Styrenics, Polyolefins and Thermoplastics in general.

**SECTION IV** will document pipeline technologies from both patent analyses and field interviews with producers and pilot companies.

**SECTION V** will interview resin producers and converters to obtain a better clarity on the industry needs and wants moving forward during the next 5-10 years.

**SECTION VI** will document pending regional regulations, as well as access the likely costs on non-compliance.

**SECTION VII** will document existing and pending regulations globally, regional and country specific e.g. bags and other single use plastics used by consumers and being regulated.

**SECTION VIII** is where TCGR’s assessment will collective congregate the most value form existing technologies, the road-map and where to best to congregate investments.
PRELIMINARY TABLE OF CONTENTS*

I. Introduction/Background/Environment

II. Executive Summary

III. Recycling of Plastics - State of Art
   - This will provide the status of the mixed plastic (including polyolefins), PET and Styrenics recycled plastics market but focused on the current cost/performance hurdles faced by producers and recyclers.

IV. New Mixed Plastics Catalytic Technologies
   - Numerous organizations are investigating these directions both in academia and industry these include Dow Chemical, BASF, ExxonMobil, CP Chem, Borelais, TOTAL, LyondellBasell, Mitsubishi, Mitsui and others, including those by the 37 members of the Alliance to End Plastics Waste.

V. New Compatibilization Technologies
   - Resins and combined mixed resin opportunities
   - Compatibilizations is not new. Most PO and specialty companies offer solutions, including DuPont, Arkema, ExxonMobil, Dow, BASF, Kraton, Eastman and others. We will examine and rank existing vs. new offerings in cost/performance based on application.

VI. R&D Pipelines and Directional Investment for the Next 5-10 Years
   - Primarily patent analyses and announced strategies by producers, including promising R&D in academia, consortia, etc.

VII. Voice of Customer – What Producers Are Saying and Doing
   - What producers and also recyclers want; expectations for practical solutions and timing

VIII. Regulations and Pending Issues
   - Looks into single use plastics bans, as well as from consumer intensions
   - e.g., P&G, Unilever, and others

IX. Recommendations and Conclusions

*Charter subscribers (those who sign up for the study before launch) will have the opportunity to work with TCGR to further refine the scope of the report by nominating specific voice of customer and/or study content as well as delineating areas of particular interest for inclusion in the assessment.
V. QUALIFICATIONS

The Catalyst Group Resources, a member of The Catalyst Group, works with clients to develop sustainable competitive advantage in technology-driven industries such as chemicals, refining, petrochemicals, polymers, specialty/fine chemicals, biotechnology, pharmaceuticals, and environmental protection. We provide concrete proven solutions based on our understanding of how technology impacts business.

Using our in-depth knowledge of molecular structures, process systems, and commercial applications, we offer a unique combination of business solutions and technology skills through a range of client-focused services. Often working as a member of our clients' planning teams, we combine our knowledge of cutting-edge technology with commercial expertise to:

- Define the business and commercial impacts of leading-edge technologies
- Develop technology strategies that support business objectives.
- Assess technology options through strategy development, including:
  - Independent appraisals and valuations of technology/potential
  - Acquisition consulting, planning and due diligence
- Provide leading-edge financial methodology for shareholder value creation
- Lead and/or manage client-sponsored R&D programs targeted through our opportunity identification process.
- Provide leading information and knowledge through:
  - World-class seminars, conferences and courses
  - Timely technical publications

The client-confidential assignments conducted by The Catalyst Group include projects in:
- Reinventing R&D pipelines
- Technology alliances
- Technology acquisition
- Market strategy

We have built our consulting practice on long-term client relationships, dedication, and integrity. Our philosophy is clear and focused:

We Provide the "Catalysts" for Business Growth by Linking Technology and Leading-Edge Business Practices to Market Opportunities
VI. DELIVERABLES AND PRICING

This report is timely and strategically important to those industry participants and observers both monitoring and investing in the development and implementation of technologies for the conversion of waste mixed plastics recycling. TCGR’s report, based on technology evaluations, commercial/market assessments and interviews with key players goes beyond public domain information. As a result, subscribers are requested to complete and sign the “Order Form and Secrecy Agreement” on the following page.

The study, “Plastics Recycling and the Circular Economy: Catalytic and Compatibilization Solutions” is expected to be available in December 2019.

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<th>Participation</th>
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<th>Price</th>
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The Catalyst Group Resources, Inc. Tel: +1.215.628.4447
Gwynedd Office Park Fax: +1.215.628.2267
P.O. Box 680 e-mail: tcgr@catalystgrp.com
Spring House, PA 19477 - USA - website: www.catalystgrp.com

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