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Advancing a Circular Economy for Upcycling PET/PUR wastes

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Abstract:

The inevitability to shift to a closed-loop or a circular economic model has never been more critical as the present time. The linear economic system that held sway for almost a century, casting off valuable resources to languish in landfills is rapidly running out its practicality. The concept of implementing a circular economy perhaps represents the most meaningful reform for global commerce; arguably similar in importance and impact that the industrial revolution had in the 19th century. Rampf Group and others have developed pragmatic technological solutions to address this challenge. The Rampf technique can effectively upcycle waste feedstocks by efficiently converting them to polyols that are comparable in performance to those obtained from virgin feedstocks. The technique essentially eliminates the concept of waste and keeps materials in circulation at their optimal and highest use. Several real-world case studies are presented. These include the upcycling of our in-house polyurethane (PUR) tooling board wastes, TPU elastomers, as well discarded PIR/PUR foams and polyethylene terephthalate (PET) fibers received from Tier-One suppliers. The goal has been to demonstrate how this technology might assist the successful conversion of waste feedstocks and upcycling them to form polyols for use in formulations to produce products, preventing their journey to a landfill.

Introduction

Rampf Eco-Solutions (REC) in Germany has established a cost-effective and efficient technology whereby waste plastics (especially PET and its derivatives) and foams (recycled Post-Industrial and Post-Consumer PUR) can be efficiently upcycled into novel materials enabling prevention of these wastes from occupying valuable space and languishing in landfills. The success of this technology in Europe is gathering momentum, most likely because of the stringent measures put in place by the European Union precluding both post-consumer as well as post-industrial wastes from being disposed of in landfills[1]. Furthermore, leading guidelines acknowledging the changing environmental conditions, in particular with regard to the growing awareness about climate change is apparently becoming a driving force in the implementation of this technology. Additionally, resource availability is also becoming an increasingly discernable benchmark. For Rampf, a greater cognizance of environmental factors regarding products and manufacturing processes is immensely vital, predominantly when dealing with the USMCA (formerly called NAFTA) and European trade regulations. These standards explicitly affect the foundry industry, an important clientele in Rampf's business portfolio. Changes in the legal framework with compliance mandates such as REACH, RoHS, TSCA, and CA Prop 65 are also pivotal component factors necessitating judicious consideration.

The aforementioned central principles are now being seriously deliberated for enactment in the United States, with California spearheading the implementation of the European model[2]. Increasingly, as the number of states in the US, begin to embrace these mandates as a prudent way to address the issues related to wastes with no alternative but a one-way trip to the landfills, the timing seems appropriate to take a closer look at the Rampf model and explore its feasibility and operation for any organization where traditionally unrecyclable waste generation is part of conducting business.

In North America, many of the key Tier-One auto suppliers of polyurethane foams used for example to produce seats, headrests, armrests, steering wheel covers, and headliners for the US Big-Three automakers, as well as the Japanese auto manufacturers are major producers of PUR (polyurethane) and PIR (polyisocyanurate) foams. The largest of these, Magna Corporation and Woodbridge Foam Corporation in Canada as well as Adient (formerly Johnson Controls) and Lear Corporation in the US are global giants. These enterprises, in conjunction with producers of materials that employ PET, PET-glycolyzed (PETG), and poly tri-methylene terephthalate (PTT) as starting materials for manufacturing products like water bottles, fabrics, carpets, medical accessories, trunk liners, and dunnage trays are also seriously exploring technologies that would permit them to circumvent transporting most of their wastes to recycling centers and landfills.

Major manufacturers of PET and PTT products used for carpet and flooring auxiliaries like Shaw Inc., The Mohawk Group, and Milliken Industries are actively collaborating with the Carpet America Recovery Effort (CARE) – a joint industry-government non-profit organization whose mission is to develop market-based solutions for recovering value from discarded carpet, to address this challenge. These industries have also been very sensitive to this situation, as they experience legislative and NGO pressure to reach viable resolutions to address their waste generation and disposal, and are therefore open to the concept of chemical conversion of carpet waste to achieve sustainability.

Statistical Data to Support the Model

Based on the US EPA's latest statistics available from their website[3] with regard to plastics wastes being diverted to landfills, the most recent information accessible in the public domain is for calendar year 2017. Figure 1 mirrors the information published by the EPA and indicates approximately 9 billion metric tons of plastic wastes being discarded annually. The percentage of this measure being redirected to landfills varies anywhere from 52.5% (or 4.7 billion tons – EPA estimate) to 80% (or 7.2 billion tons – Waste Management estimate)[4]. Regardless, of the varied estimates, the amount is staggeringly and unsustainably enormous. Even if one follows the more conservative EPA assessment, the reported quantity of wastes that are recycled is a paltry 25%, with the rest being used for either composting, pyrolysis or combustion.

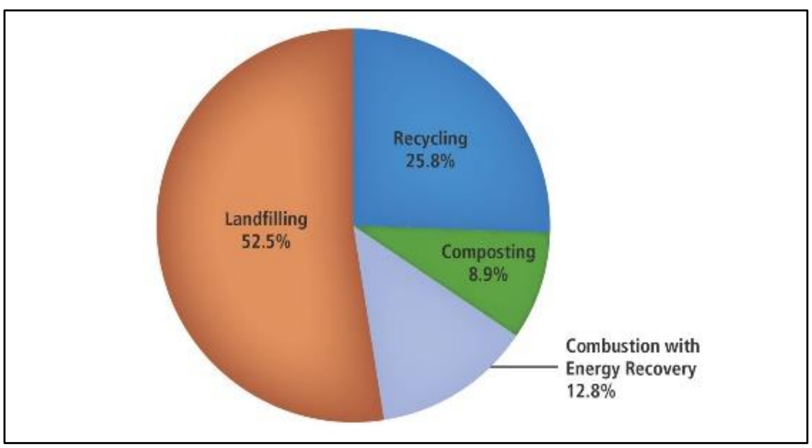

Fig 1: Breakdown of methods of disposal for the 9 billion metric tons of waste generated every year – Courtesy Environmental Protection Agency website (www.epa.gov).

These numbers justify both economic and environmental risk mitigation motivations for pursuing this endeavor, particularly since Rampf Eco-Solutions has the background and knowledge for developing and ensuring success for such an effort.

Wide-ranging Benefits for Waste Generators

Implementing an on-site capability of turning waste into liquid base chemicals for the manufacture of a variety of coatings and products at the point of generation could undeniably benefit generators of the waste plastics. A self-sustaining program as defined by the Ellen MacArthur Foundation that states "*A circular economy based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems*"[5] would be appealing to any manufacturer since such a system would contribute to a reduction in CO_2 emissions while providing a method to repurpose the discarded materials. In the Rampf model, the wastes generated by a producer of polyurethane foam or PET related article, is fragmented (i.e., chemically depolymerized) employing one of the well-known techniques, viz. glycolysis, polyolysis or acidolysis (Figure 2). Subsequent conversion of the mixture to a polyol for future applications in CASE related products that might perhaps find application in an entirely different field certainly becomes an option.

Fig. 2: Unit for the production of polyols from waste PUR and PET – Picture Courtesy from Rampf Eco-Solutions

Polyurethanes are generally produced by employing liquid raw materials – a polyol and an isocyanate. After the two components are mixed (in various proportions), the viscosity of the blend begins to increase. The propagation of this reaction can result in cross-linking giving rise to the PUR-polymer. By adding reagents, also known as hydrophobes numerous PUR foams with myriad properties can be achieved. The polyurethane, in the form of flexible foams (mattresses, seats), insulation foams, integral foams (car parts, shoe soles) are some examples. Although plastics of the thermoplastic type, such as polypropylene, polyethylene, PET or PVC can be simply recycled by melting or depolymerizing them, the possibilities of recycling PUR foams have been restricted, particularly because of their duroplastic nature. This is the reason, PUR had long been thought to be non-recyclable or that it might be very problematical to recycle. With greater consideration being directed towards the environment, the ecological requirements of materials that do not have a method to be recycled are increasingly becoming more stringent. Therefore, in order not to restrict the use of the plastic PUR due to inadequate recyclability, research on numerous processes are currently being pursued. The objective is to apply a practical method to upcycle this duroplastic type of material.

Specific Cases Highlighting Implementation of the Rampf Technology

Polyols from waste carpet and waste foams generated by Global Tier-One Carpet and Foam Suppliers:

Glycolysis and/or acidolysis has long been known as a process for the depolymerization of high molecular weight polymers like rPET (recycled PET), rPTT (recycled PTT), PETG, as well as rigid and integral PUR foams[6]. After their depolymerization and retrieval in their oligomeric forms – comprising a mixture ranging from dimers to hexamers – the products are re-formulated by subsequent reactions with hydrophobes to make polyester polyols exhibiting physical and chemical properties suitable for novel applications. In the present situation, employing the Rampf Eco-Solutions' technology – wherein all of the above-mentioned waste feedstocks were effectively incorporated in the recycling process – the polyols generated were employed for several upcycled industrial applications.

The polyol produced at the Rampf Eco-Solutions' facility employing recycled rPET has been commercialized; and is presently being sold under the registered name (Petol®). Additional polyols produced by this technology (Table 1) have been carried out using discarded PUR (commercially sold under the registered name Recypol®) or NP polyols i.e., those that comprise bio-based components in their formulation.

Waste Resource	Commercial Name	OH Value (mg KOH/gm)	Viscosity (cP)	Acid Value (mg KOH/gm)	Functionality
PET	Petol®240/02	235 – 265	1000 – 4000	<3	~2.0
	Petol®320/02	305 – 335	800 – 2000	<3	~2.0
	Petol®380/10	375 – 405	300 – 1100	<3	~2.3
PUR	Recypol®903	480 – 540	2600 – 6600	<2	~3.7
	Recypol®SC60	330 – 390	2500 – 6000	<2	~2.7
	Recypol®201	35 – 65	4500 – 9500	<1	~2.0
	Recypol®SW904	490 – 550	4500 – 9500	<2	~2.7
Bio-based/Natural	NP®260	250 – 280	50 – 350	<2	~2.5
	NP®350	330 – 360	20 – 100	<2	~2.0

Table 1: Commercial Polyols manufactured by Rampf Eco-Solutions from waste PET and PUR Feedstocks

Any of the above-mentioned polyols can become the base polyol that is used for subsequent transformations (Figure 3). This technology is earnestly being considered for implementation in the US, as many of the largest PET carpet manufacturer encounter this enormous challenge for sustainable disposal of both their post-industrial and post-consumer PET (and PTT) carpets and mixed polymer waste

As mentioned previously, Shaw and similar companies like Mohawk Industries and Milliken – all of whom are large flooring and carpet manufacturers – would benefit from employing this technology particularly, if the polyol obtained from the waste PET can be upcycled to produce a product looped back into their products or made ready for marketing and resale. For instance, the polyol could be used to manufacture an adhesive that might find application in the production of rebond foam that is commonly used as an underlay for new carpets.

Fig. 3: Formation of Recypol® – Courtesy Rampf Eco-Solutions

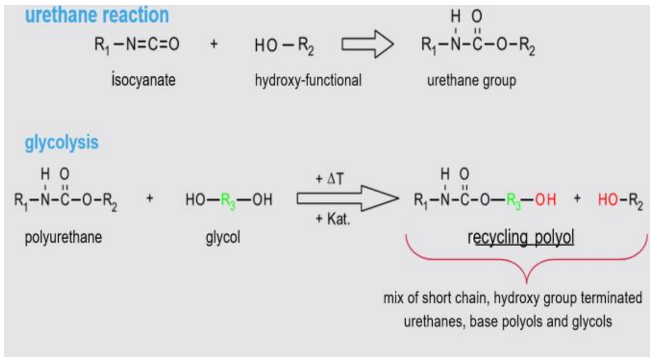

Fig. 4: Reaction Steps showing Glycolysis

To substantiate this technology, several tier-one suppliers of scrap PET carpet were contacted and submitted post-industrial PET samples reported as 95% pure. This scrap PET was converted to a polyol with the following properties:

Samples	Hydroxyl Value (mg KOH/gm)	Acid Value (mg KOH/gm)	Viscosity (cP)	Foreign Substances(gm)	Foreign Substances (content %)
Sample F1	267	3.32	1,900	18.95	4.39
Sample F2	263	3.35	1,955	19.32	4.47

Table 2: Physical properties of rPET polyol obtained from upcycling scrap PET waste carpet

The information presented in Table 2 was communicated to the manufacturers[7]. The objective of this exercise was essentially to demonstrate the value present in the discarded waste PET and that the polyol synthesized from it was capable of being employed in additional applications. In this case, the polyol was used in an adhesive formulation at our facility in the US. The intention essentially was to communicate to the OEM that they could avail of a similar application.

A similar undertaking was carried out with a Tier-One supplier to the OEMs of waste PUR foam. Two separate kinds of foam were shipped to our facility in Germany, one of which (identified as Type 1) a semi-rigid MDI foam containing HDPE as an additive and the other batch (identified as Type 2) that did not contain this additive. Both the foams were depolymerized and converted to a polyol with the following properties (Table 3a and 3b).

Polyol from scrap PUR Foam (Type 1)	Units	Values
Color	Visual	Light Yellow
OH Value	mg/gm KOH	500
Viscosity	cP @ 25°C	3090
Acid Value	mg KOH/gm	N/A

Table 3a: Physical properties polyol obtained from Type 1 PUR foam obtained from Tier-One Foam manufacturer

Polyol from scrap PUR Foam (Type 2)	Units	Values
Color	Visual	Brown
OH Value	mg/gm KOH	330
Viscosity	cP @ 25°C	45,540
Acid Value	mg KOH/gm	0.71

Table 3b: Physical properties polyol obtained from Type 1 PUR foam obtained from Tier-One Foam manufacturer

The information obtained from REC was shared with both the suppliers of the waste feedstocks. At REC all of the recycling processes have been tailor-made for the customers and hence the resultant polyols typically are satisfactory from the customer's viewpoint[8]. As mentioned previously, the rPET polyols, which are called Recypols® are particularly well suited for selling to customers who may want to create their own formulae or for that matter to system-houses that are in a position to raise these recycling-polyols to the level at which these become systems. In our case, the main objective was to connect with OEMs and Tier suppliers in North America to see whether or not this concept would be feasible as a business opportunity for REC, and by extrapolation if a similar outfit were to be implemented in our plant in Wixom, Michigan

Thus far, two corporations that have communicated with us and supplied with their waste streams are those mentioned in this manuscript. The same principle will be applied to the other organizations listed in Scheme 1 to ensure the validity of this model. Otto Bock, for instance, indicated they could benefit from recycling approximately 50 tons of waste PUR generated in their facilities annually. Similarly, the other organizations mentioned they have large amounts of waste feedstocks where a plant could utilize this waste and divert it from being transported to a landfill can avail this opportunity. The ultimate goal for this endeavor would be to construct the plant co-located at the customer site, so that the waste feedstocks could be directly transferred to the hopper and subsequently into the reactor where the polyols could be synthesized via glycolysis or acidolysis and avoid costly handling and freight

Fig 5. A schematic displaying a proto type plant at a customer (a Tier One supplier) site

An additional objective (for the ***Plant at the Customer Site*** as shown in Figure 5) would include "industrial polyurethane recycling", which has been effectively demonstrated at REC, which the engineers foresaw as a possibility for PUR producers, who only deal with ready-to-use systems. This additional feature ought to enable the recycling of residual material, and thereby reintegrate them as polyols in the current production.

As a consequence of specific formulations involving the addition of cross-linking agents, extenders, catalysts, stabilizers and propellants, it would be feasible to achieve specifications required by particular customers who are focused on a very narrow range of properties. Moreover, within the scope of foam-production, new PUR systems can be manufactured based on these recycling polyols and sold under the brand name of Recypurs®. The afore-mentioned recycling polyols that are based on PUR residual materials already contain stabilizers and catalysts. The subsequent formulations are therefore less complex in addition to being inexpensive. Since recycling polyols are in fact high-grade liquid polyols, not only can these be added in small quantities to the new synthetic-polyol, but they can also be used as the main polyol. When using recycling polyols, no additional investments are required, nor does a potential customer using PUR require a refitting of machines.

Plant at a Central Location:

A second model for this business would be to construct the same type of plant in a central location, for example near our US headquarters in Wixom, Michigan. This processing center would essentially perform the same functions as that described for the plant co-located at the customer site. However, in this case the feedstreams would include PU waste generated in-house, as well as those generated from companies within a radius of approximately 200 miles of Wixom. In this radius are many major producers of PUR as well as collection facilities whose sole purpose is to collect discarded plastic wastes (Great Lakes Recycling, in Livonia, Michigan for example,). These facilities normally accumulate these discarded plastics and convert them for use at ski resorts for snowboarding, skiing, and other winter sports activities.

Fig. 6: Rampf Eco-Solutions facility in Pirmasens, Germany

Other organizations within the 200 mile radius involved in pelletizing plastic wastes include Midland Recycling in Midland, Michigan and IRR in Howell, Michigan. These facilities specialize in shredding, granulating and pelletizing all types of plastic wastes which adds efficiency, for the glycolysis reaction to be carried out, the manufacturer of polyols benefits from being able to charge a higher load of the starting materials in the reactor.

Besides producing polyols for CASE applications, other functions that the reactors could find utility would be for blending chemicals at elevated temperatures for several hours. This particular activity has been explored previously to be carried out at toll manufacturing facilities, which could be expensive particularly when we consider volumes that might annually range anywhere from 20 to 40 tons.

The auto industry has been actively engaged in promoting sustainability initiatives with most of their tier suppliers. Ford Motor Company for example, has arguably been at the forefront of this endeavor; and is serious about implementing bio-based feedstocks in most of the foam related parts that go into their automobiles. One of the most dominant raw material being promoted in this regard is the use of rapeseed oil in many of their formulations. Other bio-based feedstocks that are prominent with some of the OEMs and Tier manufacturers are soybean and castor oils. The latter has an advantage as it provides flexibility to the foams by virtue of the ricinoleic components (double bonds) present in its structure. These hydrophobes besides being relatively inexpensive are also abundantly available, and can impart salient features to the finished goods being produced.

Promoting a Closed Loop Value-Chain:

Figure 7a and 7b provide another example for utilizing our model to assist the OEMs and the Tier manufacturers in terms of assisting them to reclaim their wastes for upcycling and preventing them from being transported to a landfill. In these cases, the scraps from the auto manufacturers that are either PET based (dunnage trays and trunk liners, for example) can be retrieved and depolymerized via glycolysis, and re-converted using the bio-based feedstocks mentioned earlier to produce foams that can find utility in headliner and head rest applications.

Likewise, the same principle can be applied with the PUR foams from seat cushions and headliners. In this case, the scrap material can be granulated, and subsequently depolymerized via acidolysis. The polyol produced from this can either be used as-is in a novel formulation or can be used as a component (once the physical properties are ascertained) in a formulation that is employed for the production of current articles used in the auto manufacturing process.

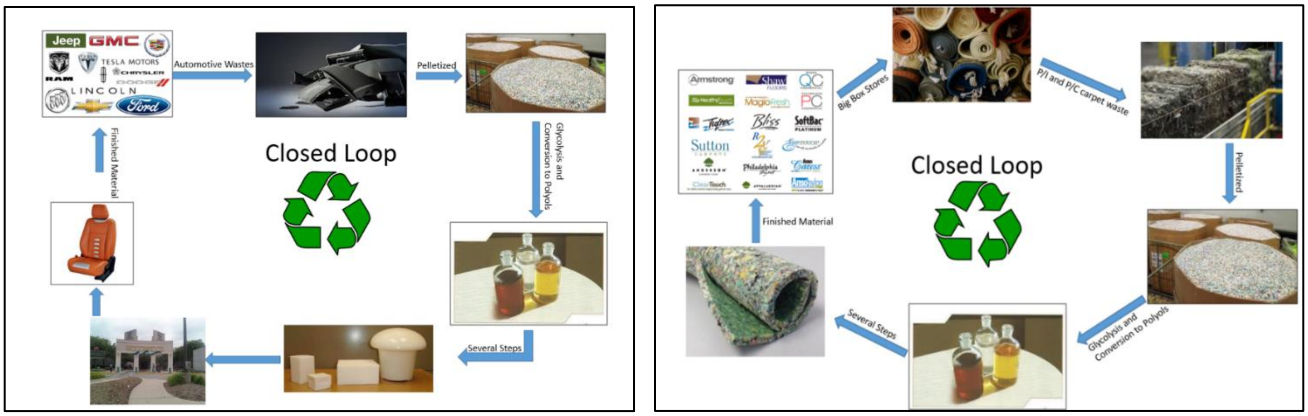

Fig 7. Closed Loop proposals for (a) auto and (b) carpet manufacturers utilizing and upcycling wastes generated

Figure 7a provides a general idea of how a closed loop could be created based on our technology as we partner with the auto manufacturers and employ our technology to assist them in achieving their targets.

Similarly, for the carpet manufacturers like Shaw and Mohawk both unused post-industrial or heavily used post-consumer PET, PTT carpets and flooring related articles can be utilized by shredding, granulating, and pelletizing them to enable their depolymerization via a glycolysis process. In this instance, either the polyols produced could be re-sold to the carpet manufacturers or they could be formulated as adhesives that can find applications for the OEM’s utility. For example, as adhesives for adhering floorboards or the polyols via reaction with isocyanates can be re-formulated to produce rebond carpeting that is applied on the baseboards prior to the installation of carpets.

Polyol Applications:

One needs to be aware that a great deal of engineering and technology is invested in the finished polymeric articles, whether they be PET plastic water bottles, carpets, or any of the foam articles mentioned in the manuscript. When these articles undergo conversion to polyols for example, many of the salient features of these engineered materials are transferred, and consequently provide inherent benefits to the polyols. Figure 8 shows some of the many benefits that can be obtained from a coatings perspective as a result of using these polyols made from these engineered articles.

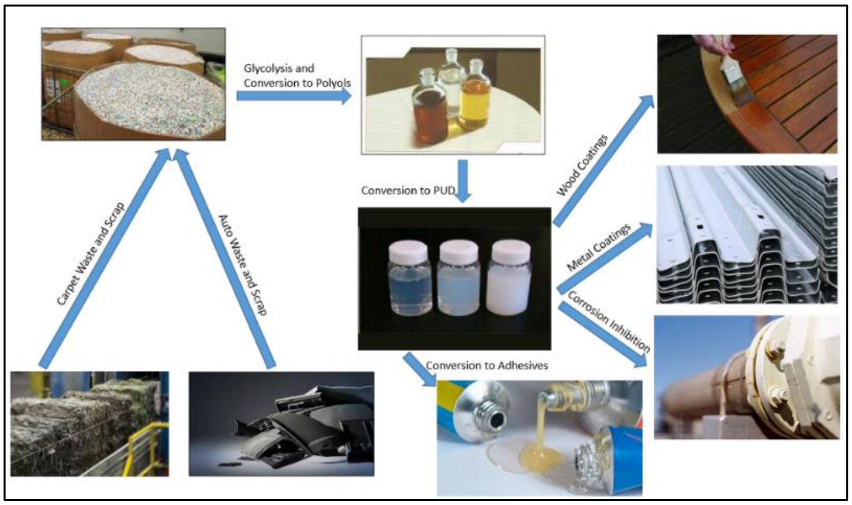

Fig 8. Additional uses of polyols obtained from auto and carpet waste

Conversion of polyols to PUDs, and their subsequent conversion to wood coating, metal coating, or corrosion inhibitor coatings is yet another avenue with the use of the polyols. Presently, the trend towards water-based systems is also obvious in the field of polyurethane adhesives.

Apart from sustainability and positive ecological facets, polyurethane dispersions have the added advantage, which is absent in non-aqueous PU systems, i.e., the water borne systems can be applied in a way that combines high solids content with low viscosity regardless of the molecular weight of the polymer. Moreover, the adhesion range and superior stability values make the polyurethane dispersions an optimal raw material for a variety of challenging adhesive and primer applications.

Figure 9 shows the global adhesive 2016 market by product type[9]. Polyurethane and epoxy adhesives are by far the two largest segments commanding nearly 90% share of the global sales in this segment. The polyols produced from waste engineered materials can certainly create a niché in this segment, particularly for their "green content" – green being defined as the combined total of the recycled and bio-renewable components in the formulation.

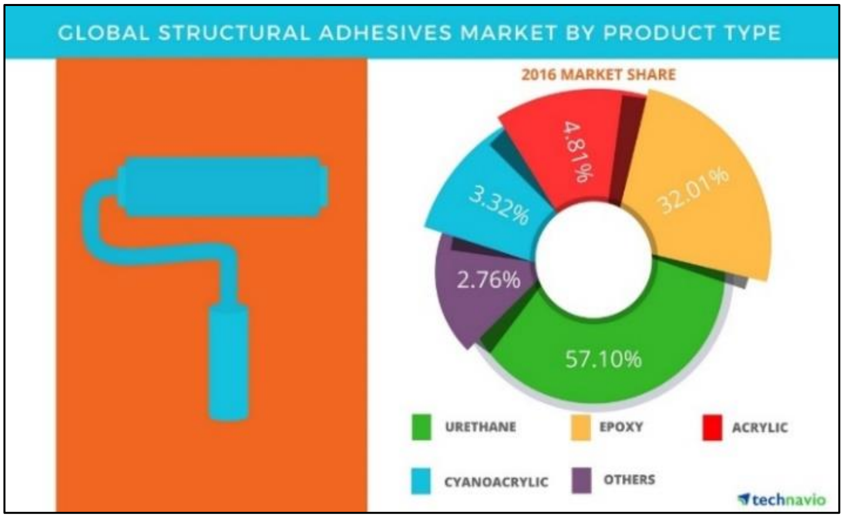

Fig 9. Data showing global adhesives market. A significant share is dominated by the polyurethane and epoxy adhesive segment – latest information available from 2016[8].

Competitive Landscape:

Although the concept presented in this manuscript is not new, since a number of organizations have implemented and actively exploring this idea, in their attempt to reduce greenhouse emissions by pursuing chemistry that would employ bio-based raw materials. From a literature and patent landscape scenario, Resinate Materials Group, Inc., of Plymouth, Michigan has filed a number of patents both on composition of matter as well as process development for using recycled and bio-renewable feedstocks and converting them to polyols[10]. However, it is this author's judgement that there are no companies, thus far, who have honed this technology to essentially procure waste and/or scrap feedstocks and upcycle them on a large manufacturing scale as has been demonstrated by Rampf Eco-Solutions in Germany. It is therefore critical for those in the business to take advantage of this technology and start pursuing opportunities to avail the benefits that this technology can provide.

Conclusions:

Although the trend towards a green initiative began more than a decade ago, the expediency of this vision has yet to materialize in a pragmatic way. It is true that in Europe and some of the countries in the Asia Pacific region, the seriousness with which this endeavor is being pursued needs to be acknowledged. However, in the Uinited States the urgency to deal with the looming plastic waste crisis has still not taken hold. The fact that Rampf Eco-Solutions in Germany has demonstrated the practicality of this program; and has correspondingly shown that not only can a plant be built to recycle wastes, but that the same plant can be built at a customer's site. This model completely resolves the inconvenience of having to transport the generated plastic wastes from one corner of the country to a specific location for upcycling.

Presently, most of these plastic articles are manufactured using raw materials that are normally obtained from fossil fuel derivatives. Furthermore, since a significant extent of engineering and quality control goes into the manufacture of these plastic articles, it behooves society to prohibit these materials from ending up in a landfill once they reach their end of life. The exceptional physical and chemical properties that are inherently built into in these designed materials ought to and should be harnessed to produce materials that could exhibit superior properties than their counterparts made by the conventional methods, and certainly not to go to waste. Therefore it is important that a system be developed whereby these discarded articles can be reused and recycled, to not only preclude the one-way journey from an oil refinery to a landfill, but to extend the life of these articles from a mere few months to several decades.

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