Healthcare Plastics Recycling Council

Advanced Recycling Pilot Project White Paper | January 24, 2022

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Executive Summary

About the Healthcare Plastics Recycling Council

The **Healthcare Plastics Recycling Council** (HPRC) is a private technical coalition of industry peers across the healthcare, recycling, and waste management industries seeking to improve recyclability of plastic products and packaging in healthcare, while recognizing that reduction and reuse initiatives have a higher priority in the waste hierarchy and efforts in these areas must continue.

HPRC's Vision for Advanced Recycling and Circularity

HPRC's mission is to collaborate across the value network to inspire and enable the healthcare community to implement viable, safe, and cost-effective recycling solutions for plastic products and packaging used in the delivery of healthcare. HPRC is committed to advancing a circular economy where recycled materials are used to create like or better products.

2021 Advanced Recycling Pilot Project

Building on insights from the 2020 Advanced Recycling initiatives and the 2019 Flexibles Recyclability Assessment Pilot project, HPRC embarked on the **2021 Advanced Recycling Pilot Project** to better understand the suitability of a mixed stream of healthcare plastics as a feedstock for different advanced recycling technologies. The goal of this work is to uncover new recycling opportunities that will reduce landfill waste, carbon emissions associated with creating virgin plastic, and reliance on fossil fuels — ultimately enabling greater material circularity. Identifying opportunities for circularity is especially important at this time when the use of plastic is critical to being able to deliver cost-effective global healthcare.

Through this project, advanced recyclers that participated in HPRC's earlier research conducted a hands-on assessment of clean healthcare plastic packaging to determine compatibility with their technologies. Also included in this project were bioprocessing containers used in the biopharma industry that generate a plastic waste stream. These containers were included in this project given their similarity to healthcare plastic packaging materials and the increased usage of these containers for vaccine production in response to the COVID-19 pandemic. The project incorporated a variety of advanced recycling technologies and demonstrates the complementary nature of the different technologies, as well as the opportunities for material circularity within the healthcare industry and across related sectors such as the biopharma industry.

This white paper is intended for hospitals, medical product manufacturers, and advanced recyclers; its findings represent a significant step forward in understanding opportunities and challenges associated with recycling plastic materials commonly found in real-world healthcare settings. Based on this research, HPRC concludes that healthcare plastics are a viable and valuable feedstock for a variety of advanced recycling technologies. Because of advanced recycling's ability to handle material streams that are incompatible or difficult to handle with mechanical recycling, HPRC continues to view advanced recycling as a complementary solution to mechanical recycling.

Summary of Takeaways by Stakeholder

Hospitals

- Plastics provide unique benefits and are essential for delivering cost-effective, successful outcomes in healthcare settings; a robust recycling strategy is critical to helping reduce the environmental impacts of healthcare plastics.
- Ninety percent of the healthcare plastics evaluated in this study can be processed using one or more advanced recycling technologies.

- Possible barriers to advanced recycling in healthcare settings are expected to be similar to those found with mechanical recycling and include space limitations for collection, competing staff priorities, and education required to enable effective collection of materials.

Medical Product Manufacturers

- Plastic healthcare packaging plays an essential role in delivering a safe, sterile, and effective product to the customer in a cost-effective manner.
- “Designing for recyclability” includes avoiding the use of materials that negatively impact yields of advanced recycling processes. For example, nylon and paper reduce the yield of output for the advanced recycling processes examined in this white paper, which increases recycling costs and makes circularity more expensive.
- Use of PVC, which provides uniquely beneficial functionality in healthcare settings, should be limited when possible, as it contaminates materials outputs and most advanced recycling technologies can only tolerate it at low levels in mixed waste streams due to its corrosive properties.

Advanced Recyclers

- A typical mixed stream of healthcare plastic packaging materials is an acceptable feedstock for many advanced recycling technologies. Bioprocessing container plastic waste is a similar material and would be a compatible feedstock when combined with healthcare plastic packaging materials.
- Advanced recyclers can help promote and drive viability of processing real-world mixed plastic waste streams from hospitals by focusing on the impact of various materials on yield, communicating about acceptable levels of difficult-to-recycle materials in a mixed stream, and providing guidance for medical manufacturing and healthcare industries.
- Innovations that expand the range of acceptable feedstocks for advanced recycling should aim to increase yields and circularity while maintaining safety and performance imperatives.
- Advanced recycling processes should seek to maximize material circularity in order to reduce landfill waste, reduce carbon emissions associated with creating virgin plastic, and reduce reliance on fossil fuels.

I. Introduction

A. Healthcare Plastics Market

i. Broader Market Drivers for Plastics

Demand for plastics, including consumer products made from recycled plastic materials, continues to increase. With large global brands, retailers, and manufacturers making commitments around plastics circularity, the use of recycled materials, recyclable content, and the recovery of plastic materials is expected to continue rising. Worldwide demand for chemicals, including petrochemicals used to make plastics, is expected to rise by approximately 40 percent by 2030 (ExxonMobil 2020 Annual Report n.d.), and current projections suggest that by 2030, there will be demand for 5 to 7.5 million metric tons of recycled plastic content for use in creating new products (Closed Loop Partners 2021). Market growth may be also be influenced by future legislation requiring manufacturers to pay for waste or incorporate recycled materials into their products.

Growing demand for plastic feedstock, combined with increasing public pressure to reduce dependency on fossil fuels and waste that goes to landfills or incinerators, has prompted more focused efforts to promote plastics recycling. Public attention to climate issues has intensified accountability of the fossil fuel industry — the source of virgin plastic feedstock. For example, in 2021, Harvard University, whose endowment tops U.S. universities at $41 billion, joined other prestigious learning institutions committed to ending all investments in fossil fuels, while shareholders of Chevron, ExxonMobil, and Shell took bold steps to hold those companies responsible for their climate impacts (Meredith 2021). A few months later, ExxonMobil announced plans to build its first large-scale plastic waste advanced recycling facility, expected to be among the largest in North America (ExxonMobil to build its first large-scale plastic waste advanced recycling facility 2021).

Despite powerful market factors, supply of recycled plastics is lagging, with the available supply of recycled plastics currently meeting just six percent of real demand —and apparently stuck at that level (Closed Loop Partners 2021).

ii. Healthcare Plastics Market Dynamics

Over the past 150 years, an increasing variety of plastics has been developed to meet the exacting standards of healthcare applications. The global medical plastics market is currently worth U.S. $22.26 billion, or 2 percent of total plastics production by value, and is growing by 6.1 percent per year. The U.S. consumes around 40 percent of medical devices manufactured globally, followed by Europe at around 30 percent and Japan at around 10 percent (Weeda 2021).

Figure 1: Medical Supplies Packaged in Sterile Plastic Pouches

The healthcare industry is uniquely dependent on specialized single-use plastic products and packaging to cost-effectively ensure sterile environments and prevent the spread of disease and infection (**Figure 1**). While the recycling process is considered less complex and more ubiquitous for materials such as paper, metal, glass, and widely recycled plastics such as beverage bottles and food containers, it is more challenging where healthcare plastics are concerned due to the composition of those materials.

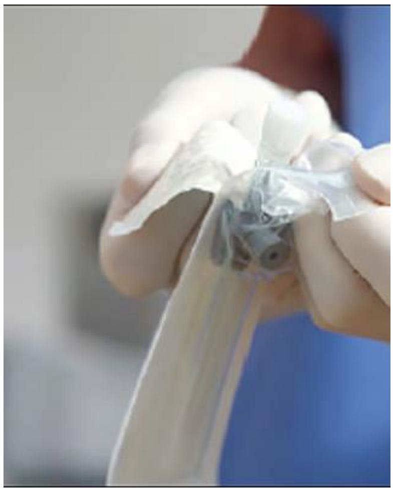

Figure 2: Healthcare Worker Opening Sterile Plastic Packaging

In response to growing awareness of the environmental impacts of plastics and associated market drivers, plastic products are increasingly being designed with recyclability in mind. HPRC has published Design Guidelines for Optimal Hospital Plastics Recycling to aid manufacturers in using materials and adopting practices that enhance recyclability of their products and packaging.
HPRC has also worked to help hospitals set up plastics recycling programs through its HospiCycle program, a free online resource specifically developed for healthcare professionals. The program includes tools and guidance that outline how to establish a hospital plastics recycling program and address associated logistical challenges.

However, the plastics recycling industry has been experiencing great changes since 2018 when China enacted its National Sword policy banning the importation of certain types of solid waste and setting strict contamination limits on recyclable materials (Center for EcoTechnology 2018). In addition, recent oil price fluctuations have created greater complexity with changing virgin plastic prices. Changes in the recycling market challenge recycling programs with frequently changing requirements in response to a changing market. In addition, there continue to be gaps in the knowledge of hospital staff. For example, hospital staff may not be aware that uncontaminated plastic waste from sterile operating room set-up **(Figure 2)** is often recyclable. These knowledge barriers, along with the rapidly changing recycling industry, have limited the amount of healthcare plastics currently being recycled.

iii. Impact of COVID-19 on Plastics Usage

In 2020, the emergence of COVID-19 caused a global spike in the healthcare industry's already heavy use of plastics, including personal protective equipment (PPE) such as masks, gloves, and gowns made with plastic materials. The United Nations Environment Program estimates the pandemic has generated about 7.5 pounds of COVID-related medical waste per person per day worldwide (Ives 2021). Prior to the pandemic, plastics have been estimated to account for 30 percent of all healthcare waste, or about 1.7 million tons annually (Rizan, et al. 2020).

Figure 3: Sterile Syringes

In addition to continued demand for PPE in response to the pandemic, the development and delivery of tests and vaccines has relied on single-use plastics for pharmaceutical and bioprocessing needs. Nearly ten billion COVID-19 vaccine doses had been manufactured and administered worldwide by the end of 2021 (More Than 9.94 Billion Shots Given: Covid-19 Tracker n.d.), with individual doses using a syringe and multiple doses using vials and packaging (Barndollar 2021) **(Figure 3)**. Some experts estimated pre-COVID that 30,000 tons of biopharma single-use products were disposed to landfill or incineration every year (Macdonald 2019). A key component of that waste stream is bioprocess containers **(Figure 4)** used in vaccine production. These containers are multi-layer plastic film container systems, very similar to the multi-layer plastic materials used for healthcare packaging. Due to the complex composition and single-use application of bioprocessing containers, advanced recycling will be essential for managing this type of waste.

Figure 4: Thermo Scientific™2D and 3D BioProcess Containers

Single-use bioprocessing systems are favored in many processes due to numerous benefits including scalability and ease of integration with other systems. They can be cost-effective alternatives to conventional stainless-steel systems. They also bolster operational efficiencies leading to reduction in water consumption, cross-contamination; and time required for setup, maintenance, and validation. Industry associations such as the Bio-Process Systems Alliance continue to research and drive initiatives related to sustainable engineering; circularity; and lifecycle management in the biopharma industry.

B. Advanced Recycling Technology Landscape

While recycling in various forms dates back to ancient times, modern recycling gained acceptance in the 1970s as an extension of the environmental movement and anti-pollution campaigns (Eschner 2017). Today, the most common types of recycling are mechanical processes that pelletize recyclable materials, with pellets then reconstituted into new products. The efficiency of these processes varies by material, but for plastics this process generally degrades the performance of the material due to the shortening of polymer chains and introduction of contaminants. Mechanical recycling processes require relatively pure streams of materials, creating logistical challenges in collecting and sorting materials in a way that is efficient and economical.

In contrast, advanced recycling technologies use more complex processes to solve the two primary problems associated with mechanical recycling of plastics: (1) reduced yield due to incorrect sorting and (2) degradation of the performance of material output. Advanced recycling is defined as a broad range of processes that use primarily chemical rather than mechanical means to transform materials from a finished state back into more basic raw materials (Baca 2021). This not only allows for more options to achieve material circularity, but also enables higher control of finished product quality such that outputs can be indistinguishable from virgin plastics derived from fossil fuels.

The ability to create recycled materials that perform like virgin materials widens the potential market for products made with recycled content. The collective vision of the advanced recycling industry is to ensure that valuable materials that cannot currently be recovered in mechanical recycling processes can be recovered by other means, rather than ending up in landfills, in incinerators, or as environmental pollutants.

i. Growing Opportunity for Advanced Recycling Applications

Over the past year, brands, retailers, and manufacturers around the world have made commitments to source substantial portions of their plastic demand from recycled sources. Collectively, this demand will far exceed the existing supply of recycled material, driving the need for new investment (Closed Loop Partners 2021). By 2030, as much as one-third of total plastics demand could be met by recycled plastics rather than plastics created from virgin oil and gas feedstocks, with half of that coming from recycled materials generated by advanced recycling processes (Hundertmark, et al. 2018).

To meet this demand, advanced recyclers need access to high-quality plastic feedstock. If it could be collected and sorted economically, the high-quality plastic materials used in healthcare products and packaging would provide a rich source of advanced recycling feedstock. In 2021, numerous advanced recycling leaders including Alterra Energy, Eastman, and Freepoint Eco-Systems made announcements regarding new facilities and increased reach of their offerings.

ii. Advanced Recycling Conversion Processes

Advanced recycling conversion processes are generally divided into three categories:

Purification

Purification is a process that uses solvents to separate plastic polymers from additives, colorant, odor, and other resins. Purified polymers can then be turned into new plastics. This technology generally requires segregated and single streams of specific plastic types. For example, PureCycle Technologies uses purification technology to convert polypropylene (PP) plastic waste into a recycled polypropylene product.

Decomposition/Depolymerization

Decomposition/depolymerization involves chemical processes that break the molecular bonds of plastics into monomers and intermediates. Similar to purification, the inputs are generally single plastic types, and the end products can be used to make new plastics.

There are three methods of decomposition: biological, chemical, and thermal. Eastman uses glycolysis, a form of decomposition, to take polyester plastic waste derived from polyethylene terephthalate (PET) bottles and textiles and turn it into monomers that can be used to manufacture new plastic products. Starting in 2023, Eastman will use another type of decomposition called methanolysis to do the same with a much broader range of polyesters.

Thermal Conversion

Thermal conversion returns plastics to their most basic petrochemical building blocks by applying high temperatures to break molecular bonds. The resulting products from these processes are liquid and gaseous hydrocarbons that can be used for fuels and as raw materials for the circular repolymerization of new plastics.

Pyrolysis and gasification are two types of thermal conversion technologies commonly used in advanced recycling processes. These technologies use heat in a precisely controlled environment to break chemical bonds and convert plastic waste into liquid and gaseous products. A rich mixture of gaseous hydrocarbons and carbon oxides, commonly called syngas, is a common output from both of these technologies. Although syngas is often used as a combustible fuel, many companies use syngas for the production of durable materials.

Thermal conversion can process more complex mixtures of plastic/polymer types, which is an advantage over purification and decomposition/depolymerization technologies. Alterra Energy recycles using a process called thermochemical liquefaction to produce plastics, waxes, and fuels. Brightmark, Freepoint, Alterra, and Nexus Circular all employ pyrolysis technologies that enable them to produce a similar output. Sierra Energy and Eastman process mixed plastic waste by gasification into syngas. Eastman uses this feedstock to produce cellulosic materials used in products like eyewear, apparel, and cosmetic packaging. Sierra Energy uses syngas to produce recycled fuels.

More background on the advanced recycling technology landscape can be found in HPRC's 2020 white paper, Advanced Recycling of Healthcare Plastics: An Opportunity for Circularity.

iii. Optimizing the Waste Management Hierarchy

With promising opportunities to dramatically reduce plastic waste sent to landfill, advanced recycling technologies should be evaluated in the context of other methods of raw material production. Focusing on the recycling process alone, traditional mechanical recycling technologies are typically more energy efficient than advanced recycling processes. However, resins produced from advanced recycling generally have lower environmental impacts than corresponding virgin resins, as measured by natural resource and water consumption (Closed Loop Partners 2021). They also recycle a wider range of inputs than mechanical recycling processes, allowing them to process materials that would have been landfilled or incinerated if there was only a mechanical recycling option available. When compared to the alternative of incineration, a recent independent study concluded that advanced recycling of mixed plastic waste emits 50 percent less carbon dioxide (Closed Loop Partners 2021, 67), (Closed Loop Partners 2021). In each case, the relative quality of outputs and the emissions related to the transport of waste to the point of recycling, landfill, or incineration should also be considered, as this will contribute to the total impact of each process (Jeswani, et al. 2021).

Based on HPRC's stated goal of advancing circular outputs where recycled materials are used to create like or better products, non-circular outputs of advanced recycling such as fuels are considered less preferable. That being said, in certain cases the production of fuels using waste plastic may generate an overall environmental benefit compared to extracting those fuels from the earth. The availability and impact of these technologies ought to be considered in developing an environmentally optimal waste management strategy.

Due to the many variables involved in calculating carbon impacts, it's not possible to create a single waste management hierarchy that applies to every situation. However, given the energy efficiency and prevalence of existing infrastructure, mechanical recycling solutions should typically be given priority for easily sortable materials to minimize emissions impact. Given the high level of investment in recycling technology, waste hierarchies should be regularly revisited to ensure they account for the latest advances in process efficiency.

Advanced recycling technologies focused on producing new product feedstocks can be factored in to address waste streams that are impractical or impossible to effectively sort to the level of purity required for mechanical recycling. This includes methanolysis to manage polyester waste streams, as well as pyrolysis and gasification to handle olefin-rich mixed streams.

iv. Integrating Recycling Technologies

Given that advanced recycling outputs can be used to produce materials with qualities indistinguishable from virgin sourced materials, these technologies can dramatically expand the applications in which recycled content materials can be used (Jeswani, et al. 2021) (Introducing chemical recycling: Plastic waste becoming a resource n.d.). In light of rapidly growing demand for recycled materials, an optimal solution for scaling advanced recycling technologies is to position them to recycle materials not already being addressed by mechanical recycling processes. This ensures growing demand can be met while also ensuring new recycling capacity makes progress against overall waste and emissions reduction goals. Therefore, advanced recycling should be viewed as a complementary solution to mechanical recycling, rather than a replacement.

While some predict that recycling technologies will inevitably scale to meet the market's needs, others have expressed concern that the rise of advanced recycling solutions could reduce motivation for the plastics industry to address its role in plastic pollution head-on. It is imperative that the plastics industry continues not only to scale to meet market demand, but also to invest in minimizing their environmental impacts including continuous carbon emissions reduction strategies. Clear and transparent measurement and disclosure of the impacts of these processes, as well as ongoing analysis of the possibility of a continual "closed loop" where recycled materials are made into new products, will help foster the credibility and long-term viability of these technologies as circular solutions.

II. Healthcare Industry Plastics Packaging Survey

A. Survey Intent

In 2021, HPRC conducted the Healthcare Industry Plastics Packaging Survey, aimed at identifying potential compositional barriers to the advanced recycling of mixed healthcare plastics packaging. The results of this survey, detailed below, provides insight into the materials used in healthcare plastic packaging and the make-up of a hypothetical waste stream of mixed healthcare packaging materials. The Healthcare Industry Plastics Survey involved nine leading healthcare packaging manufacturers. The purpose of the survey was to gather information about the general composition of various types of plastic packaging, with the primary focus on flexible and multilaminate packaging, which are the most difficult to recycle using mechanical recycling processes. The survey focused on roll stock, pouches and bags such as chevron-peel pouches, header bags, vent bags, and linear tear bags, die-cut lids, rigid trays and lids, and other healthcare packaging materials.

B. Survey Results and Conclusions

Information from participating manufacturers was aggregated to create a generic profile of healthcare packaging materials. Based on survey responses, 58 percent of healthcare packaging was composed of polyolefins **(Figure 5),** which includes polyethylene (PE), high-density polyethylene (HDPE), low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), and polypropylene (PP). High-density polyethylene (HDPE) **(Figure 6)** represented approximately 30 percent of total surveyed materials.

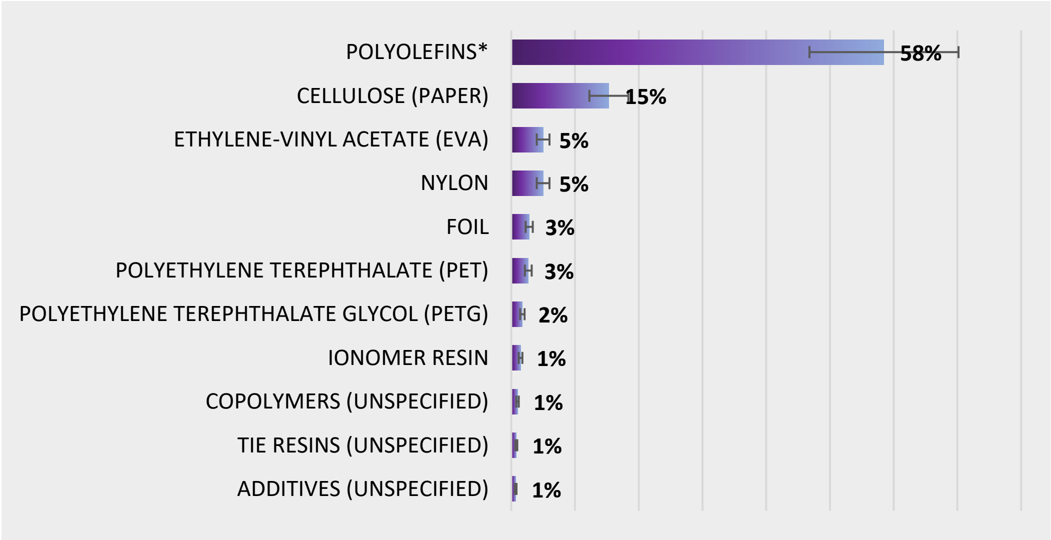

Figure 5: Mixed Stream Plastic Packaging Volume by Material – Top 95 Percent
** Polyolefins include: PE, HDPE, LDPE, LLDPE, and PP. HDPE comprises ~30% of surveyed materials*

Polyolefins play a major role in healthcare packaging materials and are quite versatile in terms of their ability to serve as the primary component of a package. The majority of polyolefins used in healthcare packaging can be further split into polypropylene and polyethylene. Polypropylene is favored for rigid applications like pitchers and basins as well as in some forming film applications and blue wrap.

Polyethylene is most prominently used in sterile barrier systems as a flexible film layer or as the sealant or "adhesive" layer that is sealed to itself or other materials in many flexible film laminations.

Figure 6: High-density Polyethylene Pouch

Another common use of polyethylene in medical packaging is nonwoven, spun-bound high-density polyethylene (commonly seen in DuPont™ Tyvek®) and favored for its breathability and durability, which is required for some sterilization techniques and demanding products. Medical-grade or coated paper is another common material option used to achieve breathability necessary for sterilization processes. Ethylene vinyl acetate (EVA) is an additional type of polyolefin similar to polyethylene, providing a glue-like layer for binding different materials in a multilayer film and sealing different materials together to form pouches, blisters, and bags.

Foil is commonly used in multi-layer laminations for products that have higher moisture and/or oxygen barrier requirements. Polyesters like polyethylene terephthalate (PET) and polyethylene terephthalate glycol (PETG) are used in rigid bottles and high-performing rigid trays for sensitive medical devices and equipment. As a flexible film, PET is favored for its resistance to heat and printability, often used as the outer layer of laminations to ensure a good seal is achieved.

Nylon film offers heat-resistance benefits similar to PET, in addition to excellent puncture and scuff resistance during shipment. These can be crucial qualities for medical devices packaged in pouches and blisters that are made primarily of metal or hard plastics, especially those that are uniquely shaped such as syringes. Additional materials that make up a smaller quantity of the overall volume are sometimes used to enhance some of the qualities mentioned above or as a less costly option that provides similar performance.

Halogenated polymers — most notably polyvinyl chloride (PVC) — are present in plastic packaging materials for the healthcare market, though in small amounts. One-third of participating manufacturers reported producing packaging materials that contain halogenated polymers, though not in general applications such as commonly used header bags or pouches. Rather, certain types of form-filled sealed packaging containing PVC may be used when there are specific pharmaceutical requirements for high-barrier materials. Along with PVC, typical halogenated polymers may include polyvinylidene chloride (PVDC), PVDC-coated film, and fluorinated materials. Manufacturers involved in the survey expect a transition away from halogenated polymers over time as suitable alternatives are developed and tested.

The healthcare packaging materials survey responses indicated the presence of less than 0.5 percent of each of the following:

- hydrocarbons,
- polychloroprene,
- adhesive (unspecified),
- wax,
- polyurethane adhesive,
- silicone,
- polyethylene co-methacrylic acid (EMAA) polybutene,
- resins,
- polyvinylchloride (PVC),
- halogenated polymers, and
- unknown materials.

III. Advanced Recycling Pilot Project

A. Scope

The 2021 Advanced Recycling Pilot Project is a continuation of the healthcare plastics recycling initiatives previously undertaken by HPRC. HPRC's 2019 Flexibles Recyclability Assessment Pilot Project demonstrated that mixed-material streams of flexible plastic packaging from multiple sources **(Figure 7)** — such as plastic bags, film, wrap, pouches, and other sterile device packaging — could be successfully processed and pelletized into a resin via mechanical recycling for use in secondary applications. The work was expanded upon in 2020 with the HPRC Advanced Recycling Project which considered a healthcare plastic waste stream beyond just flexible packaging and looked at how advanced recycling technologies could address this waste stream in a broader way.

The research conducted by HPRC in 2019 and 2020 revealed opportunities and barriers associated with recycling plastic derived from healthcare settings. Building on the findings from these earlier projects, the 2021 Advanced Recycling Pilot Project sought to test samples from a representative plastics waste stream (see Appendix 1) both within the healthcare industry and across related sectors using a variety of advanced recycling technologies. Participating advanced recyclers were called on to demonstrate their respective recycling capabilities; the breadth of those capabilities in serving broader markets; and their success in achieving material circularity in their outputs.

The goals of the 2021 Advanced Recycling Pilot Project were:

- to generate a "mock" waste stream of uncontaminated healthcare packaging plastics and similar plastic films used for bioprocessing containers based on the material characterization from the Healthcare Industry Plastics Packaging Survey, and;
- to determine compatibility of the mock waste stream with a range of advanced recycling technologies.

Figure 7: Package Types Found in a Typical Mixed Plastic Healthcare Waste Stream

B. Project Participants

To meet the goals of this project, HPRC engaged medical device manufacturers; hospitals; advanced recycler partners (including HPRC members and non-members); and environmental sustainability professionals. As a health and safety precaution and because of COVID restrictions, unused sample materials were sent directly from participating manufacturers to advanced recycling companies for analysis of chemical composition. These samples are representative of sterile plastic packaging waste and healthcare-related plastic films found in many bioprocessing containers.

Five advanced recyclers evaluated the uncontaminated mock waste samples to provide data on which the project's findings and conclusions are based.

i. Brightmark

Global waste solutions company Brightmark has invested in two advanced recycling facilities to divert plastic waste from landfills, waterways, and incinerators. Its Ashley, Indiana, facility, scheduled to launch in 2022, will divert 100,000 tons of post-consumer and post-industrial plastic waste each year and has achieved International Sustainability and Carbon Certification PLUS (ISCC PLUS) certification. Brightmark has entered into an offtake agreement with BP for the finished products produced at Ashley. Brightmark's advanced plastics recycling and renewal facility in Macon-Bibb County, Georgia, billed as the world's largest facility of its kind, will sit on a 5.3 million square-foot site and will have the ability to divert a minimum of 400,000 tons of plastic waste each year. In addition to North America, Brightmark is developing plastic renewal projects in Asia and Europe.

Brightmark's state-of-the-art, proprietary plastics renewal process enables its plants to process all types of plastic, including plastics numbered 1 (PET) and 2 (HDPE), and difficult-to-recycle types 3 (PVC), 4 (LDPE), 5 (PP), 6 (PS), and 7 (miscellaneous others). Brightmark produces ultra-low sulfur diesel, naphtha blend stocks, and commercial grade wax ,which ultimately will be converted into plastics creating a fully circular solution.

Brightmark is working toward a goal of diverting 8.4 million metric tons of plastic from landfills or the environment by 2025 and incorporating that waste into a truly circular process to produce 1.7 million tons of feedstocks.

ii. Eastman (HPRC member)

Global advanced materials and specialty additives company Eastman is focused on advancing its molecular recycling capabilities by leveraging existing manufacturing facilities. It began commercial operation of its molecular recycling technology in late 2019 and has announced a $250 million expansion of its recycling capacity to be complete in 2023. The company has committed to recycling 250 million pounds of plastic waste annually by 2025 and more than 500 million pounds annually by 2030.
Using its two Advanced Circular Recycling technologies, carbon renewal technology (CRT) and polyester renewal technology (PRT), Eastman can break down hard-to-recycle waste plastic to its basic building blocks and use them to create new materials an infinite number of times. Eastman's ISCC PLUS certification ensures an unbroken chain of custody for recycled content from the point it is recycled all the way to the end consumer.

Eastman's recycling processes produce molecules that are indistinguishable from those created using traditional processes. Eastman's Renew materials are made using up to 100 percent ISCC-certified recycled content. Currently available products made with their molecular recycling technologies include Eastman Tritan™ Renew, a copolyester used to make water bottles, food storage containers, and large appliances; Eastman Acetate Renew, used for premium eyewear; Eastman Trēva™ Renew, an engineering bioplastic; Eastman Cristal™ Renew copolyester, used for cosmetics packaging; and Naia™ Renew, a fabric made from sustainably sourced wood pulp and mixed plastic waste to serve the sustainable fashion industry.

iii. Freepoint Eco-Systems (HPRC member)

Freepoint Eco-Systems, a wholly owned subsidiary of Freepoint Commodities, is a developer and owner of advanced recycling systems for diverting plastic waste produced by the healthcare packaging industry and other sources from landfill or incineration. Over the past two years, Freepoint has worked to develop advanced recycling systems throughout the United States and has begun construction of its first advanced recycling facility in Hebron, Ohio. Each Freepoint advanced recycling facility will process 170 million pounds of waste plastic per year, reducing greenhouse gas emissions equivalent to taking 450,000 cars off the road.

Freepoint's innovative recycling technology employs proven pyrolysis technology to process plastic that is not currently recycled. Freepoint's advanced recycling system itself is also self-sustaining in that it uses a portion of the waste plastic it processes to power the facility, dramatically reducing usage of other forms of energy.

Freepoint aims to create 26 million pounds of new plastic per facility per year by converting plastic waste into new products. The company has already begun receiving mixed material waste containing Tyvek and a variety of packaging films supplied by PAXXUS and Technipaq, enabling diversion of nearly all their mixed material waste from incineration.

iv. Nexus Circular, LLC

Nexus is an operational, commercially scaled converter of waste-to-virgin plastics from waste sources with global partners and brands including Royal Dutch Shell, Chevron Phillips, and others. Nexus is currently rolling out plants in the U.S., Europe, and other global locations through joint partner relationships. Nexus is located in Atlanta, Georgia.

Nexus' environmentally friendly process is 100 percent circular and ISCC PLUS-certified, creating an infinite loop. The company's end-to-end business spans engineering, software, and front-end sorting, meeting all regulatory, training, and safety requirements (EPA, state, and local).

Operational and economically proven Nexus has produced and shipped consistent, on-spec tanker loads of offtake to large global partners who blend it into their current streams and convert it into virgin plastics. Through Nexus' processes, more than 500,000 gallons have been produced and sold and more than 4 million lbs. of waste plastics diverted from landfills to make virgin recycled-content plastics.

v. Sierra Energy

California-based Sierra Energy is the maker of the Pathfinder FastOx®, a commercial system that turns trash into energy without burning. The complete system has a maximum height of 40 feet, requires less than a half-acre of land, and processes up to 50 metric tons of mixed waste per day. Sierra Energy has also partnered with federal, state, and local agencies to build its facility at Fort Hunter Liggett in Monterey County, California, positioning the base to be one of the first military installations to reach net-zero energy and waste goals.

Sierra Energy's FastOx system uses heat, steam, and oxygen to break down waste at the molecular level. The FastOx gasifier is engineered for continuous operation. The internal temperature reaches 4000°F, which is achieved by introducing steam and oxygen into the vessel through Sierra Energy's patented lances. This high heat turns the organic material in waste into an energy-dense syngas. The inorganic materials melt into a non-leaching stone. The gasifier can handle mixed waste with minimal processing including municipal solid waste, biomass, tires, medical waste, hazardous waste and industrial waste. The FastOx system converts waste into products including clean syngas; hydrogen fuel; and sulfur-free, aromatic-free, renewable diesel. Waste undergoes complete conversion into high-value products with no toxic byproducts and no process emissions.

Additional advanced recycling companies who contributed to HPRC research include:

vi. Alterra Energy

Alterra Energy (Alterra) is Solving Plastic Pollution® on a global scale with the deployment of an advanced recycling technology. Alterra has developed and continuously operates this technology on a commercial scale at its 60-ton-per-day Akron, Ohio, facility. Alterra licenses its technology to entities looking to recycle more challenging plastics or seeking more sustainable products. Currently, there are two publicly announced industrial facilities in Europe that will be licensing Alterra's technology to recycle more challenging plastics.

At its Akron plant, Alterra uses a scalable, patented thermochemical liquefaction technology to process hard-to-recycle plastic. These plastics are heated in the absence of oxygen until they break down into a hydrocarbon vapor and non-condensable gas. The hydrocarbon vapor is then cooled into circular pyoil, a petrochemical product that can be further refined into feedstocks for new plastic production. The facility ISCC PLUS-certified as a pyrolysis plant and collection point for mixed plastic waste.

Alterra transforms end-of-life plastics destined for landfills into petrochemical products that can be further refined into high-quality feedstock for new plastic production, enabling the circular economy.

vii. PureCycle Technologies (HPRC member)

PureCycle Technologies™ uses a unique patented technology, developed by the Procter & Gamble Company, that produces Ultra-Pure Recycled (UPR) resin while using dramatically less energy than first-use plastic production. A PureCycle facility is under construction that will be the first commercial purification plant in Ironton, Ohio. This flagship facility will convert 119 million pounds of polypropylene waste to more than 107 million pounds of UPR resin. The Ironton facility is expected to be operational in Q4 of 2022. PureCycle has announced its second purification facility will be located in Augusta, Georgia. This site is expected to have a total capacity of 650 million pounds of UPR when all lines come online. The first two lines are expected to be operational in the second quarter of 2023.

PureCycle's unique technology separates color, odor, and contaminants from polypropylene waste feedstock, producing renewable resources that can be used infinitely. Its process includes two steps, Feed Pre-Processing (Feed PreP) and Purification. The Feed PreP step collects, sorts, and prepares the feedstock for purification. The Purification step removes molecular contaminates from the feedstock and returns UPR polypropylene resin. The PureCycle purification technology uses a solvent-based physical separation process to return waste stream polypropylene to near near-virgin conditions. Because no chemical reactions are performed, the PureCycle process can be reused many times on the same polypropylene. The first Feed PreP is located in Winter Garden, Florida, and has processing capabilities of more than 100 million pounds.

PureCycle Technologies recycling converts plastic waste into a like-new plastic resin, fully closing the loop on the reuse of recycled plastics while making recycled polypropylene more accessible at scale to companies wanting to use a sustainable, recycled resin.

C. Development of the Mock Waste Stream

The mock waste stream of healthcare plastic packaging materials evaluated by advanced recyclers for this project was designed to be representative of the variety of packaging materials that are most likely to be present in a hospital's plastic waste stream. Based on past work indicating that flexible and multilaminate packaging materials are most difficult to recycle through mechanical recycling processes, this project focused on these types of materials. Additionally, a handful of bioprocessing containers with similar recycling challenges were included in the assessment. In total, the project included testing 28 distinct plastic materials falling into nine general material categories (see Appendix 1 for a detailed list of products composed of these materials). The samples were provided by six leading global manufacturers of medical devices, medical packaging, hospital supplies, and bioprocessing products.

The recyclers provided feedback on whether the materials contained sufficient volumes of plastics compatible with their processes and on acceptable levels of contaminating plastics and additives. Contaminants in this case are defined as materials that harm the advanced recyclers' equipment, that would contaminate the output, or that do not conform to an advanced recycling process that could generate useable output, thereby reducing yields. Taking this approach gave an understanding of the capability of advanced recycling technologies to recycle common medical packaging materials, provided those materials could be collected, sorted, and routed to a compatible recycling facility.

One material known to be underrepresented in our sample set is polyvinyl chloride (PVC). This was due to learnings from HPRC's 2020 work indicating complications posed by this material in advanced recycling processes; halogenated materials such as PVC manifest as corrosive agents within most advanced recycling processes. Recyclers carefully screen incoming waste streams to ensure they do not contain unacceptable levels of PVC. Therefore, the project team focused on collecting only samples that had low levels of halogenated materials.

D. Findings

Based on the samples provided in the mock waste streams compiled for this project, the five participating advanced recyclers evaluated the 28 distinct plastic materials (as detailed in Appendix 1) and provided feedback on recycling success, compatibility with specific recycling technologies, negative effects of specific materials, and other observations. Findings are summarized below.

i. Advanced Recycling Success Rate

Feedback from participating advanced recyclers confirmed that pyrolysis, gasification, and methanolysis are highly complementary technologies, together capable of accepting more than 90% of product and packaging samples examined in this study. The tables below summarize the materials present in the sample set **(Figure 8)** and the frequency with which these materials were accepted for recycling into new products **(Figure 9)**. As noted above, the sample set of materials did not contain significant levels of PVC, a material known as a process contaminant across all advanced recycling technologies.

Based on feedback from participating recyclers, it can be concluded that the healthcare plastics packaging waste stream and bioprocessing containers appear to be compatible with advanced recycling in general, assuming that most of the PVC can be separated from the rest of the waste stream. To achieve optimal yields using advanced recycling processes, manufacturers should reduce the use of materials that negatively impact yield while advanced recyclers work to increase their capacity to process challenging materials.

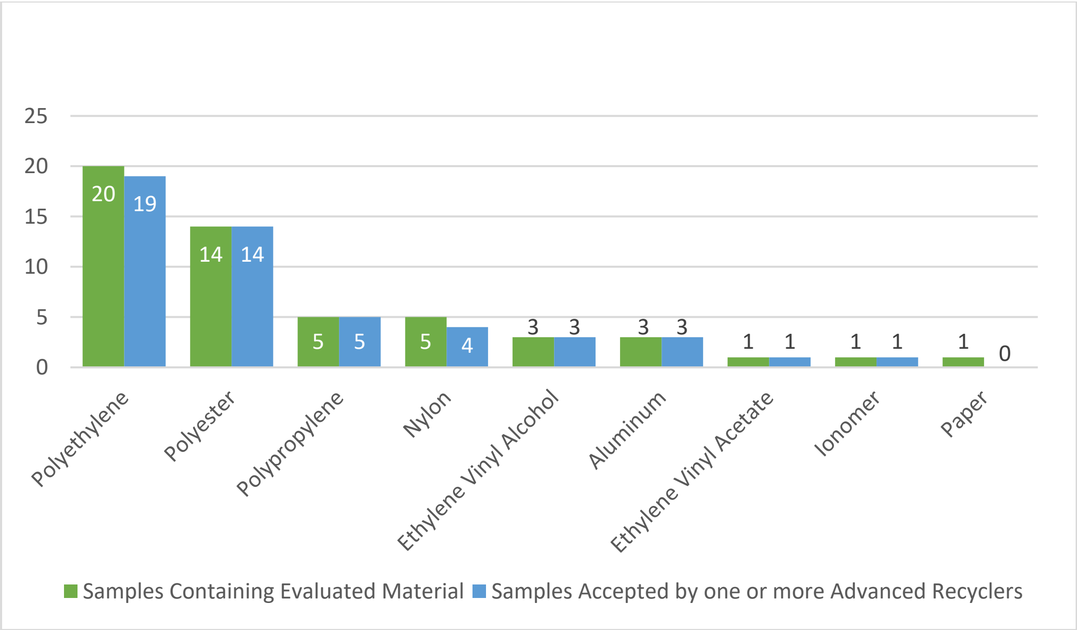

Figure 8: Number of Samples Containing Evaluated Materials and Number of Samples Accepted by Advanced Recyclers

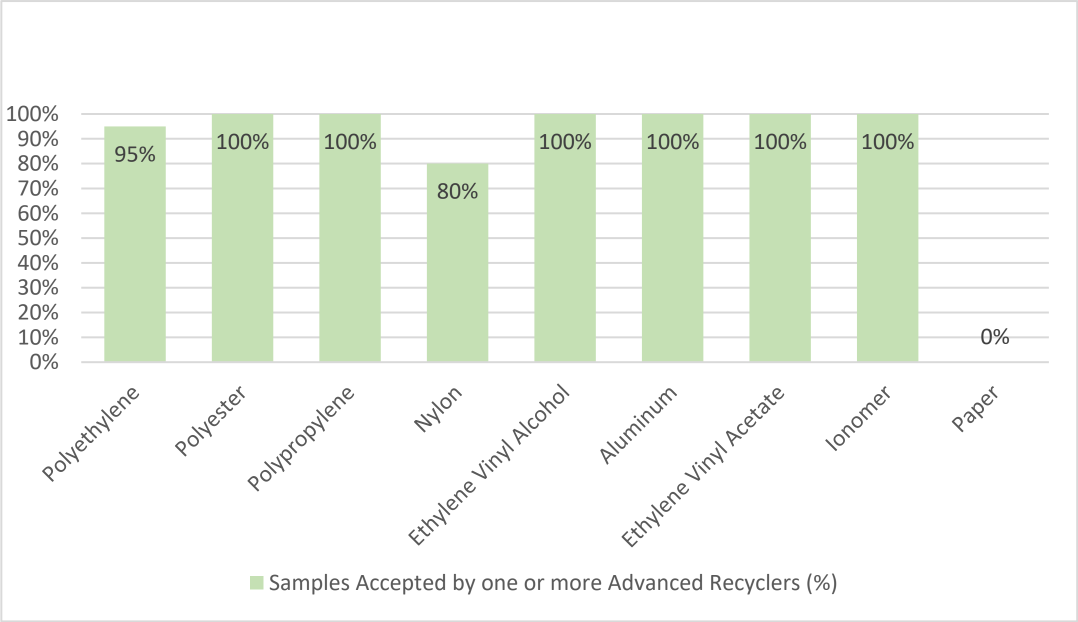

Figure 9: Percentage of Samples by Material Accepted by Advanced Recyclers

ii. Managing Challenging Materials

It should be noted that some products contained in the mock waste stream are almost entirely composed of a single material, while others may be composed of one primary material and one or more additional materials in lower amounts (see Appendix 1). Materials in the sample set were rejected by advanced recyclers when the sample was predominantly composed of a material that did not yield useful outputs in their recycling process. This resulted in the rejection of samples that mostly contained materials only acceptable in low levels.

The rejection of samples containing a high proportion of unacceptable materials — but probably making up a very low proportion of a mixed waste stream — revealed an important insight into how acceptance or rejection of a material component should be framed: The project was based on evaluation of individual samples for compatibility with advanced recycling technologies rather than with a mixed healthcare waste stream as would be expected to be generated in a hospital. Participating advanced recyclers indicated that the individual samples they rejected would likely be acceptable as low proportions of a mixed waste stream from a hospital.

A common statement among both mechanical and advanced recyclers is that "the solution to pollution is dilution." While this phrase often has negative connotations, the application in this specific situation is from a positive perspective: specific materials that are harmful or detrimental to a given recycling process can be managed at acceptable levels within a mixed stream of materials that will not significantly impact quality or yield of the final output. For example, the only samples rejected by all advanced recyclers in this project were those predominantly composed of nylon or paper. However, samples that contained small amounts of nylon or paper as a percentage of overall composition were accepted. This means that the rejected samples could be accepted by at least one advanced recycling technology if present in a stream that contained sufficient levels of desirable materials. It is useful to cross-reference the prevalence of various materials in medical packaging **(Figure 5)** for context on how much of each material type may be present in the waste stream and to what degree it would likely be diluted.

Materials that presented the greatest challenges and lowest yields for advanced recyclers included:

- halogens, nylon, and Ethylene Vinyl Alcohol (EVOH) – recycling yield is decreased as presence of these materials increases;
- PVC – corrosive in nature because it contains chlorine and is considered a contaminant to material outputs; manufacturers are increasingly seeking alternatives; and
- paper – commonly used for labels; decreases recycling yield.

Because rejection was typically a matter of high concentration rather than mere presence of challenging materials, most contaminants can be diluted to levels that would be accepted by advanced recyclers as part of a well-balanced mixed plastics waste stream. Moreover, based on the results of the Healthcare Plastics survey discussed earlier, the presence of challenging materials in the mixed waste stream appears to be minimal, assuming basic waste collection and sorting techniques are employed by healthcare Facilities.

IV. Advancing Healthcare Plastics Circularity

Researchers estimate that more than 8.3 billion metric tons of plastic have been produced since the early 1950s. About 60% of that plastic has ended up either in a landfill or in the natural environment. Because waste disposal in the healthcare industry is carefully managed, medical plastic waste represents a minimal amount of the plastic pollution leaked into the environment. Rather, leakage is predominantly made up of improperly disposed consumer products such as cigarette butts, food packaging, beverage containers, and plastic bags — with heavier concentration in areas where waste management systems are underdeveloped. Driven by its core commitment to improve human health, the healthcare industry shares the broader concern for preventing plastic pollution and is constantly seeking paths to reducing its own environmental impact. The work presented in this report helps bridge knowledge gaps in the healthcare plastics recycling system to realize that vision.

To minimize its negative environmental impacts, the global plastics industry must transition to a circular economy that is optimized for reuse and recycling. HPRC views the healthcare industry as a prime enabler of the circular economy. Unlike household and municipal recycling streams, which are composed of a wide variety of recyclable materials such as paper, metal, and plastics found throughout communities, healthcare plastics waste is concentrated in specific collection points — hospitals and healthcare facilities — and, as reported in this paper, are composed of a predictable set of materials that are generally less contaminated than residential waste streams. Based on our Healthcare Plastics Industry Packaging Survey, the healthcare plastics packaging waste stream appears to be comprised primarily of olefin-based materials. These factors make healthcare plastics an ideal feedstock to support the circular economy.

Broader strategies to address the issue of single use plastic waste in the U.S. include:

- setting a national standard requiring that plastic packaging contain at least 30 percent recycled plastic by 2030;
- developing an appropriate regulatory system that enables rapid scaling of advanced recycling; and
- establishing a producer-responsibility system for packaging that raises critical funding dedicated to improving recycling access, collection, and education for all materials (Toto 2021).

V. Conclusions

The Advanced Recycling Pilot Project demonstrated that more than 90 percent of the healthcare plastics evaluated in this study can be processed using one or more advanced recycling technologies and that a mixed healthcare packaging waste stream appears to be a well-suited feedstock for advanced recycling. Bioprocessing containers are composed of similar materials and would be a compatible feedstock when combined with healthcare plastic packaging materials.

Based on specific capabilities of each advanced recycling technology and possible biohazardous contamination of healthcare plastics, some sorting of materials may be required either at the point of generation or downstream prior to the advanced recycling process. Non-plastic materials such as paper, aluminum and glass are still best managed within their own recycling streams.

In the plastic waste stream, separating olefins from polyesters is a good step toward optimizing yields across various recycling technologies. Multi-layer materials can be processed via pyrolysis or gasification when their concentration is diluted in a mixed stream where olefins total 90 percent or more. In cases where precise segregation is impractical, gasification provides additional flexibility to ensure these materials can be reincorporated into useful products rather than going to waste.

The products described in the HPRC Healthcare Plastics: Guidance for Recyclers document — including sterilization wrap, tubs, basins, pitchers, and bottles — are also good candidates for advanced recycling based on their composition.

A. Key Takeaways by Stakeholder

Hospitals

- Plastics provide unique benefits and are essential for delivering cost-effective, successful outcomes in healthcare settings, but a robust recycling strategy is critical to helping reduce the environmental impacts of healthcare plastics.
- Possible barriers to advanced recycling in healthcare settings are expected to be similar to those found with mechanical recycling and include space limitations for collection, competing staff priorities, and education required to enable effective collection of materials.
- Because 90 percent of healthcare plastics can be processed using two or more advanced recycling technologies, the need for sorting may be minimal.
- In real-world hospital settings, plastics may be considered biohazardous in some cases and may need to be sterilized prior to being sent to an advanced recycling facility.

Medical Product Manufacturers

- The priority in healthcare packaging should always be to deliver a safe, sterile, and effective product to the customer. Regulatory requirements may also reflect this priority over considerations such as shipping weight, conservation of resources, or recyclability.
- "Designing for recyclability" will improve the healthcare industry's ability to provide recyclable plastic feedstock, which will in turn supply growing market demand and help control cost increases. Recyclability of products and packaging should be considered from the standpoint of both mechanical and advanced recycling processes.
- Consideration should be given to the impact of each product on the mixed waste stream as a whole, with an effort to reduce the use of materials that reduce recycling yield; focus should be on maximizing overall recycling stream desirability within the constraints of functional needs.
- Paper is universally found to reduce advanced recycling output yields. Laminated paper lids, some multilaminate plastic films, and paper labels reduce yield and are not considered desirable for advanced recycling waste streams. While the transition away from paper labels presents logistical challenges for manufacturers, efforts to transition to plastic labels or directly printing onto packages (as seen in the food and beverage industry) should receive proper consideration.
- There is medical-industry consensus that functionality of PVC is uniquely beneficial but is only compatible with advanced recycling systems when limited to very small proportion of overall mixed waste streams. Based on the Healthcare Industry Plastics Packaging Survey, the hypothetical mixed plastic sample stream contained less than 0.5 percent PVC.
- Across the value network, industry groups can help educate and develop strategies and design practices that enhance waste recycling compatibility.

Advanced Recyclers

- A typical mixed stream of healthcare plastic packaging waste is a readily acceptable and well-suited feedstock for advanced recycling technologies.
- Advanced recyclers can help promote and drive viability of processing real-world mixed plastic waste streams from hospitals by focusing on the impact of various materials on yield, communicating about acceptable levels of difficult-to-recycle materials in a mixed stream, and providing guidance for medical manufacturing and healthcare industries.
- Instead of considering whether to accept or reject certain materials, recyclers should focus on acceptable levels of undesirable materials, the impact of various materials on yield and outputs, and providing guidance to the medical manufacturing and healthcare industries.
- As manufacturers seek to reduce the presence of challenging materials in recycling waste streams, advanced recyclers should also seek to expand recycling technologies to deliver high yields from as many types of plastic materials as possible.

- Advanced recyclers whose outputs are used to create like or better products enable material circularity, thereby reducing landfill waste, carbon emissions, and reliance on fossil fuels.

i. Future Research

Future project work has been proposed to test actual mixed plastic waste streams from two or more hospitals. The goal of this work would be to process a real-world mixed plastic healthcare waste stream with a range of current advanced recycling technologies. Examining real-world waste streams, rather than undiluted single-stream batches of discrete products, will more accurately represent overall compatibility of mixed waste streams with advanced recycling and will provide insights into the way impurities are diluted in order to achieve strong yields.

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Appendix 1: Table Summary of Samples

Primary Composition	Generic Product Description	Additional Materials	# of Samples	# of Samples Determined to be Compatible with Advanced Recycling
POLYPROPYLENE	PP forming film	POLYETHYLENES*	1	1
	PP/Nylon forming film	POLYAMIDE NYLON (OPA)	2	2
	PP sealed pouch with synthetic lidstock	—	1	1
	PP tray with synthetic lidstock	—	1	1
POLYETHYLENES*	Bioprocess container film	TIE RESINS (UNSPECIFIED), POLYESTER, ETHYLENE VINYL ALCOHOL (EVOH)	4	4
	Coated synthetic	POLYETHYLENES*	1	1
	HDPE tray with synthetic lidstock	—	1	1
	HDPE/peelable PE coex to PE coex forming web 3D pouch	—	1	1
	HDPE/peelable PE coex to synthetic 2D pouch	—	1	1
	Nylon/PE forming film	POLYAMIDE NYLON (OPA)	1	1
	Nylon/PE pouch laminate	POLYAMIDE NYLON (OPA)	1	1
	OPET AlOx barrier/PE	POLYETHYLENE TEREPHTHALATE (PET)	1	1
	OPET/PE pouch laminate	POLYETHYLENE TEREPHTHALATE (PET)	1	1
	PE/nylon forming film	POLYAMIDE NYLON	1	1
POLYETHYLENE TEREPHTHALATE (PET)	OPET AlOx barrier/APET	—	1	1
	OPET/APET	—	1	1
	OPET/PET coating	—	1	1
	PETG Insert/Retainer	—	1	1
	PETG Tray	—	1	1
	PETG tray with synthetic lidstock	POLYETHYLENES*	1	1
POLYAMIDE NYLON (OPA)	Nylon film	POLYAMIDE NYLON (OPA)	1	0
PAPER	Coated paper	POLYETHYLENES*	1	0

Primary Composition	Generic Product Description	Additional Materials	# of Samples	# of Samples Determined to be Compatible with Advanced Recycling
IONOMER	EVA/Ionomer forming film	ETHYLENE VINYL ACETATE	1	1
FOIL	OPET/Foil/PE Foil pouch laminate	POLYETHYLENES*, POLYETHYLENE TEREPHTHALATE (PET)	1	1
* Polyethylenes include: polyethylene (PE), high density polyethylene (HDPE), low density polyethylene (LDPE), and linear low-density polyethylene (LLDPE). HDPE comprises ~30% of surveyed materials.				

Appendix 2: Terminology

This white paper includes terminology commonly used in the healthcare and recycling industries. For the purposes of this white paper, the following definitions provide HPRC's core audiences — hospitals, manufacturers, and recyclers — with appropriate clarity and technical detail in the context of this white paper:

Bioprocessing containers: multi-layer, single-use plastic film containers used in critical sterile liquid-handling applications in the biopharmaceutical industry, with vaccine production being an example of how these containers are used.

Healthcare packaging plastics: materials commonly used to protect products used in various healthcare settings such as hospitals and clinics from damage or contamination prior to use on a patient.

Outputs: materials created through recycling, referred to as outputs from advanced recycling technologies in this white paper.

Sterile: designed, manufactured, and handled in such a way to ensure there will be no interaction with foreign substances prior to use in a healthcare setting.

Uncontaminated: can be defined differently for different recyclers; for purposes of this white paper, the term "uncontaminated" means there are no materials that are unwanted by the recycler, which are typically biological or infectious materials and/or other materials (including other plastics) that are not compatible with their recycling process and/or reduce the yield of output.