DESIGN OF A DISSOLUTION AND FILTRATION SYSTEM FOR FAST DISSOLUTION IN A SOLVENT-BASED PLASTIC RECYCLING SYSTEM

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Abstract:
The Solvent Targeted Recovery and Precipitation (STRAP) process is an innovative solvent-based recycling technology designed for the selective recovery of polymers from mixed plastic waste. STRAP operates by dissolving a specific polymer in a solvent system where the targeted polymer is soluble while other polymers remain undissolved. The dissolved polymer is then separated from the undissolved materials through mechanical filtration and recovered via precipitation by altering the system temperature. We have developed a 25 kg/hr STRAP Pilot-Scale Unit (PSU) to demonstrate the scalability and efficiency of this process. The PSU comprises several critical components: (i) solid material conveying and dosing systems; (ii) a dissolution vessel; (iii) centrifugal and candle filters; (iv) a precipitator; (v) an outgassing extruder; (vi) a solid material dryer; (vii) a solvent recovery system; (viii) oil heating and water-cooling systems; and (ix) a nitrogen generator. The core functionalities of the PSU are centered around the dissolution vessel and centrifugal filter. Our unique dissolution process implements high-shear mixing using propellers rotating at 1700 rpm, coupled with wall baffles in the vessel to induce high intensity turbulent flow, for enhanced dissolution. The non-dissolved solid is separated from the hot resin solution by a centrifugal sifter, which employs a screw conveyor to transfer the solid-liquid mixture into a steel screen and axial brushes section, rotating at 800–1700 rpm, ensuring efficient filtration and low solvent content in the solid material. The dissolved polymer solution is centrifugally expelled through the screen, while undissolved residues are conveyed axially by paddles to the outlet. Extensive testing and iterative design improvements have optimized the system's performance, achieving dissolution times of <30 seconds and complete separation of solution and undissolved solids in <3 minutes. These advancements enable high operational efficiency, making the STRAP PSU a critical step toward scaling the technology for industrial applications. The data generated provides essential insights for future upscaling efforts, positioning STRAP as a viable solution for enhancing polymer recycling and supporting a circular economy.

1. Introduction and Motivation

The global plastic waste crisis has reached alarming levels, with more than 35.6 million tons of plastic wastes were generated, within which, only 8.7% was recycled, while about 75% was disposed of in landfills.[1] Traditional mechanical recycling methods are often inadequate for dealing with complex, multicomponent plastics, which are prevalent in packaging and other applications. These materials, such as multilayer plastic films, combine various polymers to achieve specific properties, making them difficult to recycle using conventional methods. We have been developing a technology named STRAP (Solvent-Targeted Recovery and Precipitation) to mitigate the above challenges. The principle of STRAP is the selective dissolution of a single polymer in a solvent system in which the targeted polymer is soluble, but other polymers are not.[2-4] The dissolved resin is separated from the undissolved polymers by mechanical filtration and then precipitated by changing the temperature. The solvent is recycled and re-used in this process, and the targeted polymer is recovered as dry, pure solid pellets. This process can be sequentially repeated for each of the polymers in Mixed Plastic Waste (MPW), resulting in several segregated streams of high-quality resin products. To aid in solvent selection, we developed a first-principles molecular modeling approach to rapidly predict temperature-dependent polymer solubilities in thousands of solvents.[5] This approach has facilitated the creation of an extensive, experimentally validated database encompassing thousands of solvent/polymer combinations. This state-of-the-art tool enables us to select the solvent that can pinpoint any of the known polymers, providing the composition information of the blend.

However, dissolving the polymer in a laboratory setting can be a time-consuming process, often taking several hours. Various factors influence the dissolution of polymers, such as temperature, turbulence, and the properties of the solvent.[6] In this paper, we present the design of a dissolution and filtration system that employs high-speed mixing and turbulence to significantly increase the dissolution rate of plastics. This system is intended for industrial applications of the STRAP technology, aiming to enhance the efficiency and scalability of solvent-based plastic recycling.

2. Review of Related Work

Plastic recycling using solvent-based dissolution and precipitation[7-11] has several advantages over traditional mechanical recycling and other chemical recycling methods. Specifically, the selective dissolution effectively separates polymers from contaminates, additives and other plastics types, resulting in a higher-purity recycled plastic product. In addition, it maintains the polymer integrity and reduce degradation compared to pyrolysis or depolymerization techniques. Several companies have made significant progress in commercializing solvent-based plastic recycling technologies. These companies are at various stages of development, ranging from pilot-scale operations to full commercial deployment. For example, PureCycle Technologies uses a solvent-based purification process licensed from Procter & Gamble to recycle polypropylene (PP).[12] APK Newcycling focuses on recovering LDPE and polyamides (PA) from industrial plastic wastes.[13] The Fraunhofer Institute has developed a solvent-based recycling process named Creasolv®, which has been licensed to several companies.[14] Despite these efforts in building solvent-based commercial plants, the current processes used in the industry can only work with certain types of plastic feedstocks with required purity, and the overall recovery efficiency reduces when using lower-quality feedstocks. Additionally, various companies are encountering challenges in producing pure resins due to the presence of diverse types of additives in the raw materials. Several of the solvent plants have struggled to operate at their designed capacity. Moreover, PureCycle uses supercritical butane at >40 bars and >150℃ to extract PP, which requires high capital and operational costs. Creasolv uses solvents with flash points >200℃ at high energy costs. Little information is available about APK in the public domain. The main advantage of STRAP is using relatively inexpensive solvents (heptane, xylene, etc.) at low temperatures (90-110℃) and ambient pressure (<1 bar). From comprehensive lab-scale experiments and TEA, we have demonstrated that STRAP can extract multiple resins from a single feedstock in an economical manner.[2,4,15] We believe that the STRAP process can solve several of the existing problems in plastic recycling by offering a more efficient and scalable solution. Our proposed dissolution and filtration system builds on these advancements by incorporating high-speed mixing and turbulence to enhance the dissolution rate of plastics, thereby contributing to the development of more efficient and sustainable recycling solutions.

3. Technology Approach

We have designed and built a 25 kg/hr STRAP Pilot-Scale Unit (PSU) at Michigan Technological University.[16-18] Main components include the following: (i) solid material conveying and dosing, including a single-screw conveyor, a live bottom hopper and a bucket elevator, at the required rate of 4 kg/min, which was tested for various MPW feedstocks, for thousands of hours. No bridging was observed; (ii) 40 L dissolution vessel, with a shaft rotates at 1700 rpm. The solvent-to-plastic ratio is 6:1 to 10:1. Turbulent flow created by the wall baffles enabled complete dissolution within minutes; (iii) centrifugal filter, which separates solution from undissolved solids. A screw conveys the mix into the centrifugal section with a still screen and axial paddles (with or without brushes depending on the feedstock) rotating at 800-1000 rpm. The solution is centrifugally "pushed" outward through the screen, whereas the non-dissolved residue is conveyed axially by four paddles to the outlet. The filter is heated to avoid early precipitation; (iv) solution filtration. A candle filter with sizes from 0.45 μm to 100 μm is used to filter fine solid particles remaining in the solution; (v) precipitator, a patent pending design,[19] precipitates the dissolved resin and removes the colorants using a combination of mechanical filtration and activated carbon; (vi) outgassing extruder, to produce pure resin pellets; (vii) solid material dryer. The undissolved solids from the centrifugal filter may have 10-30% solvent which will be recovered. The dryer can achieve <0.5% solvent content with a residence time of 10-30 minutes. (viii) solvent recovery system, with a powerful vacuum and condensation system to recover 99.9% of the solvent; (ix) oil heating and water cooling; (x) nitrogen generator, to ensure an oxygen free environment throughout the system.

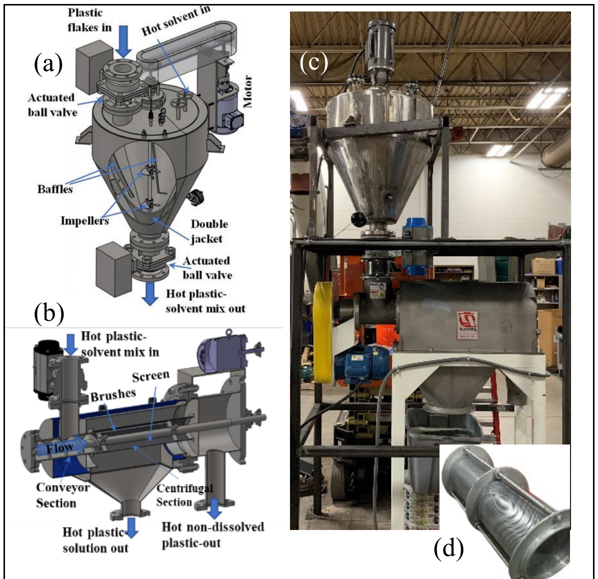

Figure 1. 3D schematics of (a) Dissolution Vessel, (b) Centrifugal Sifter, (c) the latest model of the combined system, (d) the cylindrical filter.

The heart of the system is the dissolution vessel and centrifugal filter. The 3D schematics are shown in Figure 1 (a) and (b), and the latest models are shown in Figure 1 (c). The dissolution vessel used a one HP motor (Marathon, Model No. 056T17G15599), which could drive a shaft (¾" diameter, 24" long) up to 1700 rpm. Four 5" propellers were mounted on the shaft for high-speed mixing. Four 2" wide baffles were mounted along the inner wall of the vessel to introduce turbulence.

After the dissolution, it is critical to separate the solution from the undissolved solids. The solution and undissolved solids are released from the dissolution vessel by opening a pneumatic butterfly valve, and flowing into the conveyor junction of the centrifugal sifter. Inside the junction, the auger sends the slurry to centrifugal section of the sifter. In the centrifugal section the auger spirals are replaced by four stainless steel paddles that fit inside a cylindrical filter housing, as shown in Figure 1 (d). The paddles have a slight curve and are placed on an angle such that the solid material is guided towards the end of the filter screen.

This filter housing consists of two layers: a stainless-steel mesh and a stainless-steel perforation sheet. The mesh is the innermost layer and has a screen size of 300 microns and a thickness of 0.009 inches. This inner surface is the interface between the slurry and the filter housing. Due to the small screen size and thickness of the mesh a protective structure is needed to prevent rupturing of the screen from the weight of the material. A 0.05" thick perforated sheet with 1/16" diameter holes is wrapped on the outside of the mesh as a reinforcement.

The separation occurs in this system of centrifugal force. As the paddles rotate, both the solid and liquid are thrown against the inner surface of the mesh screen. The mesh is small enough to prevent solid escaping. Once the liquid passes through the filter screen it is funneled into the liquid recovery chute and discharged from the liquid outlet. The paddles then sweep the solid material through the remaining length of the filter screen and is deposited into the solid outlet.

4. Discussion

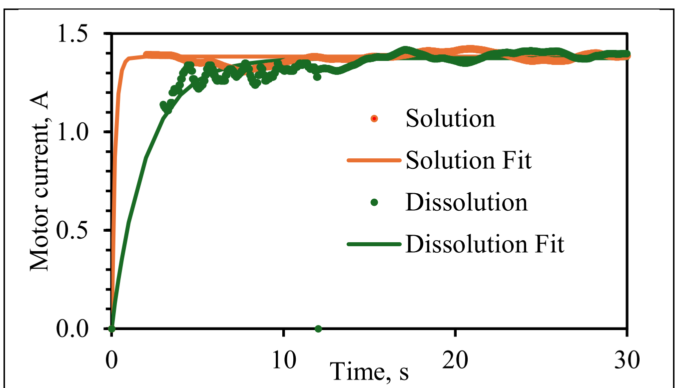

Figure 2. Measuring the dissolution transient behavior using 20 L water and 30 kg sugar.

The dissolution vessel was tested with 30 kg sugar and 20 L water. The VFD was ramped up to 1700 rpm (60 Hz) in 0 seconds. We measured the transient dissolution process by comparing (i) add 20 L water in the vessel, then add 30 kg sugar and immediately turn on the motor; (ii) add 20 L – 30 kg sugar water solution. The results are shown in Figure 2. A first order model was used to fit the measured data:

$$A = 1.4\left(1 - e^{-\frac{t}{\tau}}\right) \quad eq(1)$$

Where the 1.4 A was determined from the average of the steady-state and the only fitting parameter is the characteristic time τ.

The solution reached a steady state in < 1 second, corresponding to a characteristic time of 0.2 seconds. Meanwhile, complete dissolution of 30 kg sugar was done in <10 seconds, corresponding to a characteristic time of ~2 seconds. The results demonstrated that the combination of high shear mixing and turbulence can significantly facilitate the dissolution process.

To optimize the operation parameters, we monitored the steady-state motor power consumptions of air (no water and sugar), 20 L water, 40 L water, and 40 L water and 60 kg sugar, from 0 Hz to 60 Hz VFD frequencies with 5 Hz increment, as shown in Figure 3 (a). The power consumption increased linearly with the VFD frequency except for the water sugar mixture. This implies the non-linear fluidic behavior of the viscous solution has a significant impact on the motor power. The difference in power consumptions at 40 L water with or without 60 kg sugar is shown in Figure 3 (b). The results clearly indicate if the motor runs at 20 Hz VFD frequency, the motor power is almost the same even with the extra 60 kg dissolved sugar. This methodology can be applied to solvent and plastic mixture in the future to obtain the optimized operational parameters for the dissolution vessel.

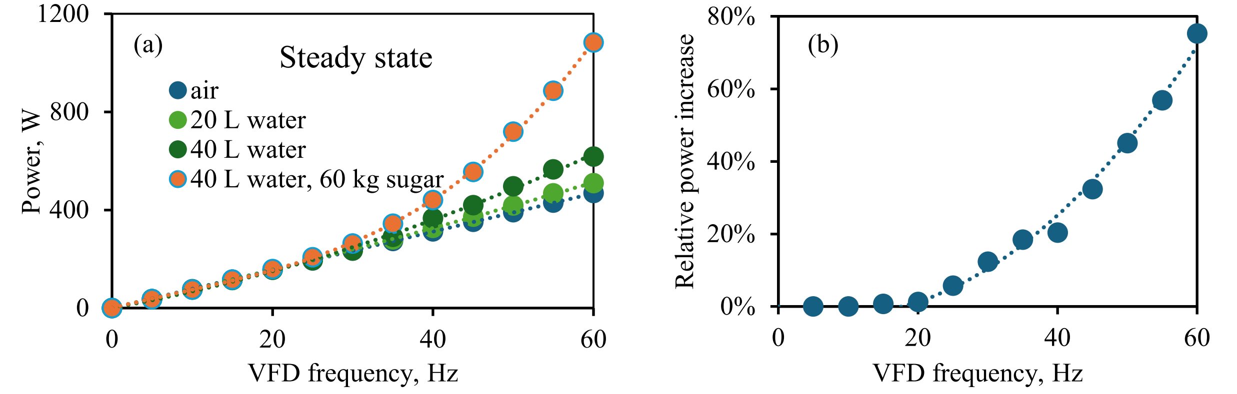

Figure 3. (a) Steady-state motor power consumption of air, 20 L water, 40 L water, and 40 L water and 60 kg sugar, from 0 Hz to 60 Hz VFD frequencies with 5 Hz increment. (b) Relative power increase of 40 L water with and without 60 kg sugar.

To test the performance of the centrifugal sifter, we used 20 L of water and 2 kg of plastic flakes, which was sourced from Amcor Post-Industrial Recyclable (PIR) films and shredded to 2-4 mm size. The solid and liquid mixture was added to the dissolution vessel, and was mixed at 1700 rpm for 60 seconds. Then the butterfly valve was opened and the solid liquid mixture was released into the centrifugal sifter. The weights of the separated solid and liquid from the sifter outlets were monitored in real time. Figure 4 (a) shows the solid and liquid mass measured from the centrifugal sifter outlets of eight consecutive experiments. The time for the liquid to separate from the solid is significantly faster than the time needed for the sifter to clear out the solid material. Figure 4 (b) shows the mass flow rates of both solid and liquid. The complete separation of liquid takes about 25 seconds whereas the solid takes about 150 seconds. Overall, the entire time needed to separate the solid liquid mixture is less than 150 seconds, which is critical for industrial applications. Another key highlight of these experiments is the repeatability. Throughout the eight tests, the time to reach steady-state for both solid and liquid is nearly identical, demonstrating that the system behaves in a consistent and predictable manner.

To better simulate the plastic dissolution in solvent, we tested the dissolution vessel and the centrifugal sifter with water soluble Polyethylene Glycol (PEG-20000, Twin Specialties Corp.). The reason for selecting PEG water solution is that it has

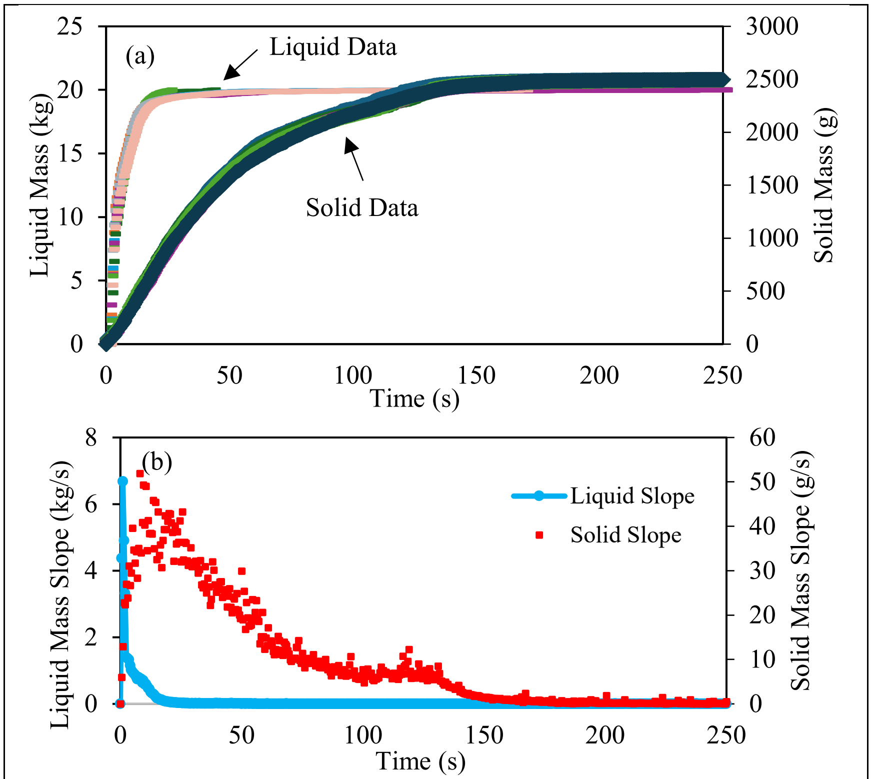

Figure 4. (a) Centrifugal sifter mass outputs of the solid and liquid from eight consecutive tests of 20 L water and 2 kg plastic flakes. (b) Average centrifugal sifter mass flow rates of the solid and liquid outputs.

similar range of viscosity as the polymer solutions,[20-21] therefore, can simulate the fluidic behavior of the polymer solution.

This test was accomplished by first adding 20 L of water into the dissolution vessel, followed by 2 kg of PEG. The motor was immediately powered on and ran at various rpm for a predetermined amount of mixing time, varying from 0 to 60 seconds. Once the mixing time was met, the motor was powered off and the butterfly valve between the dissolution vessel and the centrifugal sifter was open to release materials into the sifter, allowing the separation of undissolved solids from the solution. The masses of the solid and solution were measured separately to evaluate the dissolution efficiency.

Figure 5 shows the dissolution efficiency of 900 rpm and 1700 rpm of various mixing times. We used equation (1) to fit the data. At 900 rpm the complete dissolution of 2 kg PEG was done in ~40 seconds, while that of the 1700 rpm is ~20 seconds. The characteristic dissolution time is inversely proportional to the motor speed. The results provide critical information for future optimization of the system parameters.

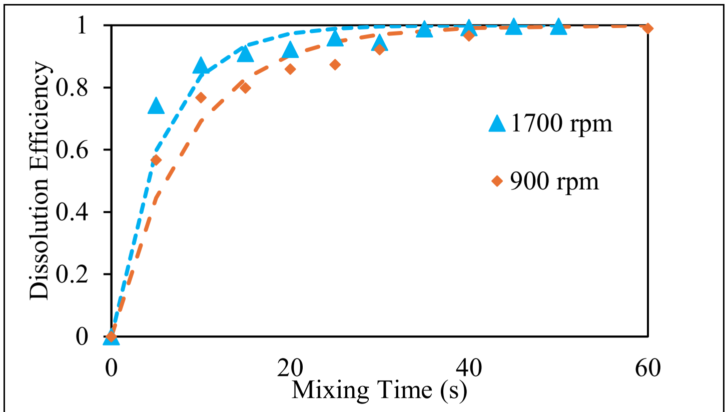

Figure 5. Dissolution efficiency of 2 kg PEG in 20 L of water at mixing speeds of 900 and 1700 rpm at various mixing time.

5. Safety Considerations

We selected PEG to simulate the real polymer solution due to their similar viscosity, and can be done at room temperature. The next step is to test the system with solvent and plastic for fast dissolution and filtration at elevated temperatures below the boiling point. Considering the organic solvents used to dissolve polymer waste may be very volatile (e.g., heptane, dodecane and xylene), and thus have low flashing and boiling points, all the vessels in the STRAP pilot system were fabricated by certified manufacturer with ASME pressure vessel stamps. In addition, all motors were explosion-proof Class I Division I/II rated.

6. Conclusions & Recommendations

The STRAP process can recover high-quality plastic resins from feedstocks that pose challenges to the existing recycling infrastructure. This paper summarizes the recent progress of the STRAP PSU on the development of the Dissolution and Filtration system for industrial applications. Combining high-speed mixing and turbulence, we have demonstrated the characteristic dissolution time of sugar and PEG in water in <10 seconds and complete the separation of solution and undissolved solids in <150 seconds. The current results of the PEG dissolution do not consider the liquid that escapes along with the solid, causing the measured solid mass to be larger. This means that the results of the testing are more conservative and would show greater dissolution performance if the liquid weight is removed. Future testing will involve a drying process so that the true dissolution percentage can be obtained. Moreover, the system will be tested with organic solvents and real plastic waste, such as multilayer films, and comprehensive techno-economical assessment and lifecycle assessment will be conducted.

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8. References

1. Advancing Sustainable Materials Management: 2018 Tables and Figures, USEPA, https://www.epa.gov/, 2018.
2. Theodore W. Walker, Nathan Frelka, Zhizhang Shen, Alex K. Chew, Jesse Banick, Steven Grey, Min Soo Kim, James A. Dumesic, Reid C. Van Lehn, and George W. Huber, Recycling of multilayer plastic packaging materials by solvent-targeted recovery and precipitation. Science Advances 6, eaba7599, 2021.
3. Kevin L. Sánchez-Rivera, Aurora del Carmen Munguía-López, Panzheng Zhou, Victor S. Cecon, Jiuling Yu, Kevin Nelson, Daniel Miller, Steve Grey, Zhuo Xu, Ezra Bar-Ziv, Keith L. Vorst, Greg W. Curtzwiler, Reid C. Van Lehn, Victor M. Zavala, George W. Huber, Recycling of a post-industrial printed multilayer plastic film

containing polyurethane inks by solvent-targeted recovery and precipitation. Resour. conserv. recycl., 197, 107086, 2023.
4. Sánchez-Rivera KL, Zhou P, Kim MS, González Chávez LD, Grey S, Nelson K, Wang SC, Hermans I, Zavala VM, Van Lehn RC, Huber GW. Reducing Antisolvent Use in the STRAP Process by Enabling a Temperature-Controlled Polymer Dissolution and Precipitation for the Recycling of Multilayer Plastic Films. ChemSusChem. 14, 4317, 2021.
5. Zhou, P.; Yu, J.; Sánchez-Rivera, K. L.; Huber, G. W.; Van Lehn, R. C., Large-Scale Computational Polymer Solubility Predictions and Applications to Dissolution-Based Plastic Recycling, Green Chemistry, 25, 4402, 2023.
6. Rita Kol, Ruben Denolf, Gwendoline Bernaert, Dave Manhaeghe, Ezra Bar-Ziv, George W. Huber, Norbert Niessner, Michiel Verswyvel, Angeliki Lemonidou, Dimitris S. Achilias, Steven De Meester, ACS Sustainable Chemistry & Engineering, 12, 4619, 2024.
7. C.D. Papaspyrides, J.G. Poulakis, P.C.Varelides, A model recycling process for low density polyethylene, Res. Conserv. Recycl. 12 (1994) 177–184.
8. J.G. Poulakis, C.D. Papaspyrides, Recycling of polypropylene by the dissolution/reprecipitation technique: I. A model study, Res. Conserv. Recycl. 20 (1997) 31–41.
9. J.G. Poulakis, C.D. Papaspyrides, The dissolution/reprecipitation technique applied on high-density polyethylene: I. Model recycling experiments, Adv. Polym. Techn. 14 (3) (1995) 237–242.
10. G. Pappa, C. Boukouvalas, C. Giannaris, N. Ntaras, V. Zografos, K. Magoulas, A. Lygeros, D. Tassios, The selective dissolution/precipitation technique for polymer recycling: a pilot unit application, Res. Conserv. Recycl. 34 (2001) 33.
11. D. S. Achilias, C. Roupakias, P. Megalokonomos, A. A. Lappas, E. V. Antonakou, Chemical recycling of plastic wastes made from polyethylene (LDPE and HDPE) and polypropylene (PP). *J. Hazard. Mater.* 149, 536–542 (2007).
12. Layman, J.; Collias, D.; Schonemann, H.; Williams, K.; Weymouth, S., Method for Separating and Purifying Polymers from Reclaimed Product, US Patent 11008433B2, May 8, 2021.
13. Hanel, H.; Wohnig, K., Method for Plastic Pre-Treatment and Solvent-Based Plastic Recycling, US Patent 20230331952A1, October 19, 2023
14. Maurer, A.; Schlummer, M.; Beck, O., Method for Recycling Plastic Materials and Use Thereof, US Patent 8138232B2, March 20, 2012
15. Aurora del Carmen Munguía-López, Dilara Göreke, Kevin L. Sánchez-Rivera, Horacio A. Aguirre-Villegas, Styliani Avraamidou, George W. Huber and Victor M. Zavala, Quantifying the environmental benefits of a solvent-based separation process for multilayer plastic films, Green Chemistry, 25, 1611, 2023.
16. Ezra Bar-Ziv, George Huber et al, United States Patent P230018US01 Application, 2022.
17. Ezra Bar-Ziv, Shreyas Kolapkar, George W. Huber and Reid C. Van Lehn, Technology Innovation for the Circular Economy: Recycling, Remanufacturing, Design, Systems Analysis and Logistics, Scrivener Publishing LLC, 2024, 477
18. Zhuo Xu, Fei Long, Ezra Bar-Ziv, George Huber et al, "Extraction of Pure Plastic Resins from PCR Plastic Waste By Solvent-Targeted Recovery And Precipitation (STRAP)," Journal of Advanced Manufacturing and Processing, REMADE Summit 2024
19. Ezra Bar-Ziv, Fei Long, George Huber et al, United States Patent P240282US01 Application, 2024.
20. Basheer Al-Shammari, Tariq Al-Fariss, Fares Al-Sewailm, Rabeh Elleithy, The effect of polymer concentration and temperature on the rheological behavior of metallocene linear low density polyethylene (mLLDPE) solutions. J. King Saud Univ. Eng. Sci. 23, 9, 2011.
21. F. Han, J. Zhang, G. Chen and X. Wei, Density, Viscosity, and Excess Properties for Aqueous Poly(ethylene glycol) Solutions from (298.15 to 323.15) K, J. Chem. Eng. Data, 53, 2598, 2008.

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