VITRICYCLE: A Potential Breakthrough in Mattress Foam Recycling

Vahid Serajian[1], Sahand Serajian[1]

[1] Edge Global Innovation, Inc., Clearwater, FL

Executive Summary

Under the sponsorship of the Mattress Recycling Council (MRC) and with private industry investment by Edge Global Innovation (EGI) and its subsidiary Vitricycle LLC., a pilot scale process to convert post-consumer mattress foams into reformable polymers with excellent physical properties was developed. The new process does not require the addition of catalysts or solvents thereby having favorable environmental impacts. Products generated via this process were evaluated for potential use in several large-volume applications that traditionally use virgin elastomers including shoe soles, rubber gaskets, floor mats and cell phone covers. Other applications are under consideration.

Vitricycle LLC views this new development as a breakthrough technology that could have a major impact on polyurethane foam recyclability and they are seeking collaboration opportunities to fully commercialize this technology.

Introduction

Annually, 15 - 20 million mattresses are discarded in the U.S., but only 10% are recycled. This trend is mirrored globally. By their nature, discarded mattresses are bulky and degrade slowly in landfills. Post-consumer and post-industrial polyurethane scrap are typically recycled into rebonded carpet foam underlayment (rebond). There are limited markets for rebonds and an urgent need for more sustainable recycling solutions.[3]

The primary material in mattress foams, thermoset polyurethane (PU), presents a significant recycling challenge due to its durable chemical structure. Until recently, thermoset PUs could not

[1] vserajian@egigroups.com , Vitricycle.com

be reprocessed by common, affordable, and environmentally safe methods. Traditional recycling methods are inadequate for the amount of flexible foam generated globally with only a small fraction of waste foams being downcycled into products like rebond. Chemical recycling of foam involves the use of reagents and/or solvents and may require added catalyst, increasing process complexity, cost, and environmental impact, and poses potential health and safety risks. Thermal recycling methods, such as pyrolysis, require high capital investment and can generate harmful emissions, making them controversial and challenging to permit.

In terms of logistical challenges, transporting bulky foams is expensive and uneconomical if the distance from point of collection to end use exceeds approximately 100 miles. Foam storage also presents a challenge, as bulky foams occupy substantial space, leading to high storage costs for recycling facilities. These logistical issues coupled with currently low market price of post-consumer and post-industrial foams, make foam recycling a significant economic burden.

Study Background

Professors Ica Manas-Zloczower at Case Western Reserve University (for example, see [4,5]) and Will Dichtel at Northwestern University (for example, see [6]) have made notable contributions to the field of foam vitrimerization and the recycling of thermoset materials, particularly through their research on Covalent Adaptable Networks (CANs). Their work is primarily focused on laboratory-scale processes that aim to convert crosslinked thermoset networks into recyclable materials. While their research has laid the groundwork for understanding the potential of recycling traditionally non-recyclable thermoset plastics, it faces several significant limitations.

Firstly, their research is largely confined to the lab scale, concentrating on the fundamental chemistry and early-stage processes necessary for vitrimerization and the recycling of thermosets. The methods they have developed often require the use of expensive and specialized catalysts and solvents to facilitate the vitrimerization process. These catalysts and solvents are essential for breaking down crosslinked networks and enabling recycling, but they introduce a substantial cost factor.

Moreover, while these catalysts and solvents may be effective, many are not necessarily environmentally safe, raising concerns about the sustainability of these methods on a larger scale.

As a result, the methods developed by Professors Manas-Zloczower, Dichtel and others are not yet suited for large-scale industrial implementation. Their work, while pioneering, remains constrained by these factors, making it less viable for widespread commercial use at this stage.

Vitricycle's Innovative Solutions

Vitricycle LLC. has developed a patent-pending technology and suite of customized and proprietary hardware and processes that transform bulky thermoset PU mattress foams into dense, processable thermoplastic vitrimerized sheets. This process reduces foam volume by over 90%, making it more manageable and cost-effective. The sheets are then ground and mixed with additives and other materials to create masterbatch pellets. Using commercially available additives/materials, these masterbatches can be tailored based on customer needs. It is important to note, our proprietary process does NOT require added catalysts or solvents.

The research and development for the vitrimerization project were conducted in two phases beginning in 2021. Phase I focused on proving the concept at the lab scale, establishing the feasibility of vitrimerizing thermoset foams. Based on these findings, Phase II involved designing and developing the necessary hardware, procedures, and expertise to scale up production. This phase culminated in the successful production of several physical samples and large quantities of masterbatch pellets, demonstrating the process's scalability and commercial viability.

During Phases I and II of the study, an extensive array of tests, including but not limited to microscopic analysis, tensile testing, Differential Scanning Calorimetry (DSC), Dynamic Mechanical Analysis (DMA), Melt Flow Index (MFI), and Mass Spectrometry-Gas Chromatography, were conducted to determine the microstructure and physical properties of the vitrimerized products. While we cannot delve into technical specifics at this stage, we present select test results to substantiate our key technical points.

For example, Figure 1 demonstrates microscopic images of the plastic dog bone samples we produced from pellets made of 75% recycled MDI[2] (memory foam) and 75% recycled TDI[3] (regular foam). Given that these samples are made of 75% post-consumer recycled mattress foam and 25% virgin material, the images at 20X and 200X magnification show impressive homogeneity.

[2]Methylene diphenyl diisocyanate
[3]Toluene diisocyanate

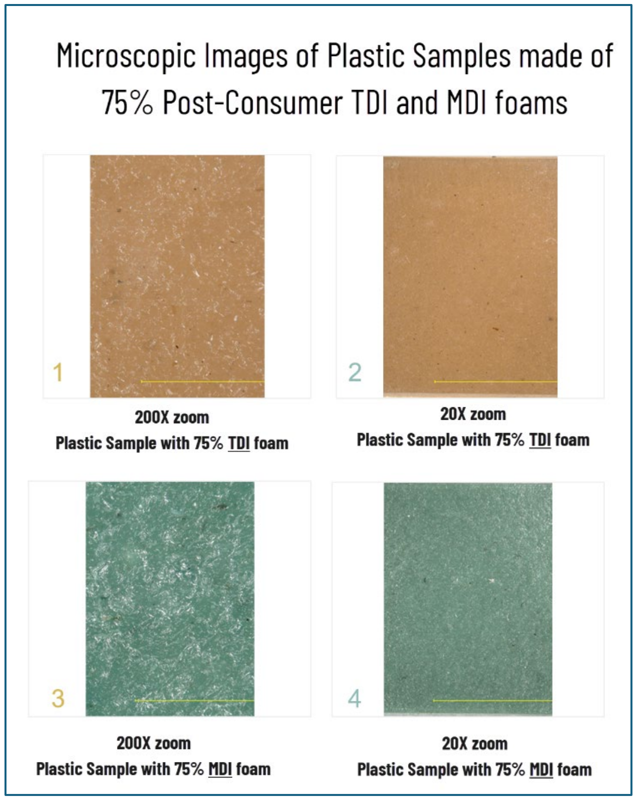

Figure 1. Microscopic images of plastic dog bone samples made of 75% TDI and MDI foams under 20 and 200-X magnifications.

During Phase I of the study, both TDI and MDI foam samples were evaluated for their upcycling potential, resulting in the successful production of dog bone samples with 50% and 75% recycled content, varying foam types, and different hardness levels, as shown in Figure 2.

Figure 2 is horizontally divided into samples with 75% versus 50% recycled content (RC) and vertically into MDI or TDI foam types. Within each section, samples are organized from top to bottom by very soft, soft, and medium hardness levels.

The main objective of demonstrating Figure 2 is to illustrate the variety of plastic samples that can be produced with different foam types, hardness levels, and recycled contents. This flexibility allows us to adjust the desired parameters to achieve the specific hardness and tactile qualities required for the plastic samples.

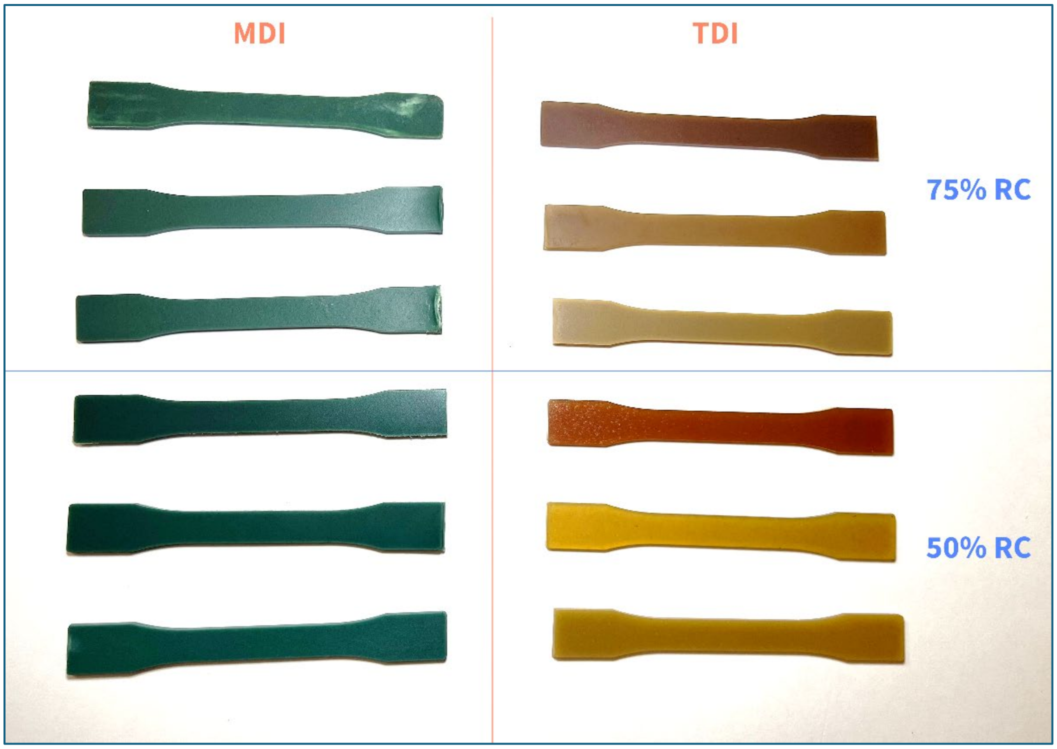

Figure 2. Dog bone samples made of different percentages of Recycled Content (RC), different foam type (MDI, TDI) and different hardnesses (top to the bottom, very soft, soft and medium hardness).

During Phase II of the study, the mixing of TDI and MDI foams was investigated. The primary motivation behind this research was the common challenge encountered in mattress recycling facilities, where bales of mattress foam typically contain *both* TDI (regular) foam and MDI (memory or topper) foam which prompted an exploration into whether both TDI and MDI foams could be upcycled together. However, the results revealed that when comparing the strength of samples made from a mixture of TDI, MDI, and the additive with those made by combining the additive with either foam type individually, the quality of the samples significantly deteriorated when TDI and MDI foams were mixed together. Consequently, it is technically advisable to avoid mixing TDI and MDI foams and instead combine the additive package separately with either TDI or MDI to ensure the preservation of desired material properties.

Both TDI and MDI foam samples passed the proof-of-concept stage and several plastic samples were produced (as shown in Figure 2). After detailed analysis of the tests, TDI foams were selected as a priority for further study. This decision was based on the superior tensile strength, elongation percentages at break, better DMA results of the TDI foam samples and more importantly abundance at foam recycling centers. As a result, TDI foams were chosen to proceed for pilot-scale testing.

It is worth emphasizing that the additives incorporated into the recycled content of Vitricycle resins play a crucial role in adjusting its mechanical performance. These additives enable the tailoring of material properties to suit various applications, ensuring that despite the inherent variability in recycled foams, the final product can be customized to meet specific performance requirements for diverse industrial and consumer applications.

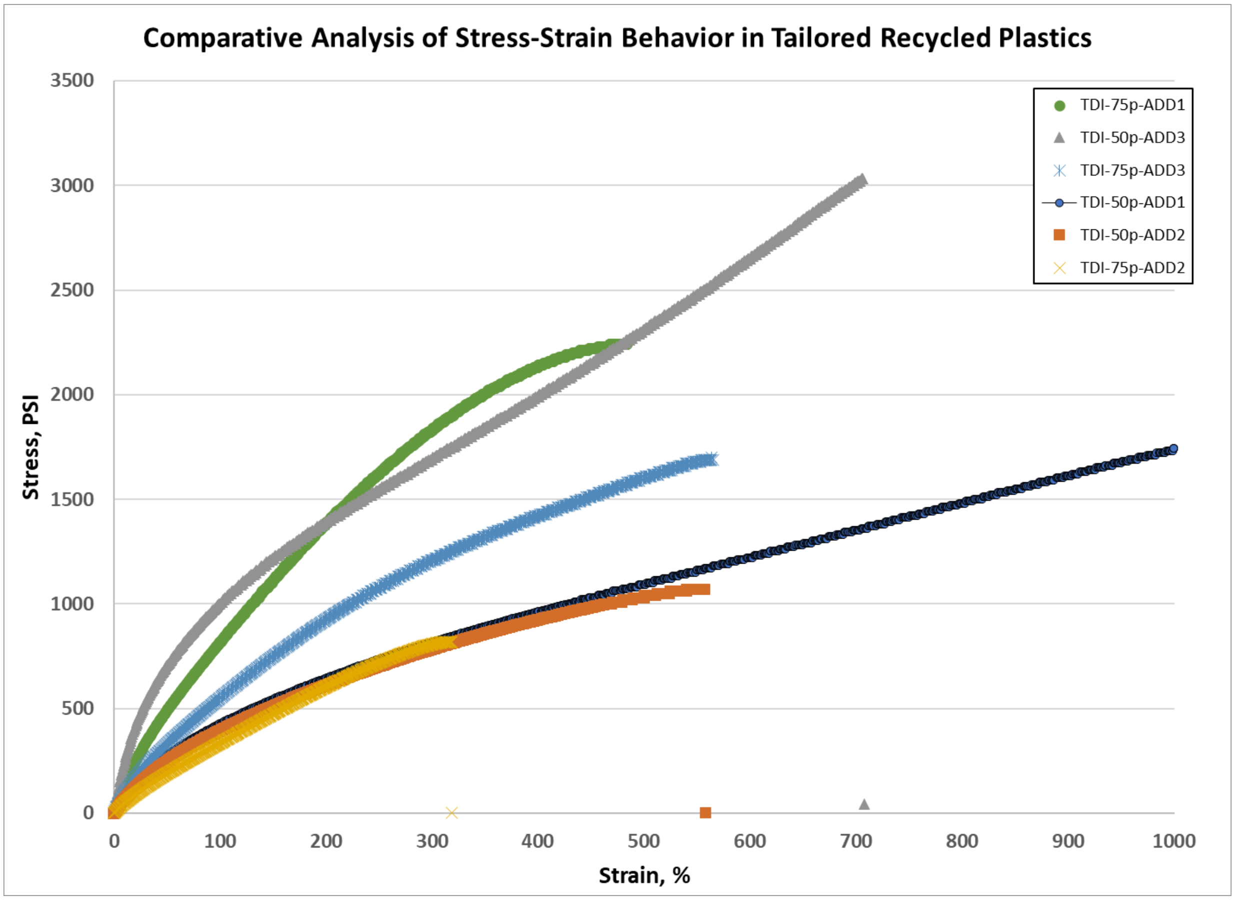

Figure 3. Stress-strain curves for dog bone samples made of recycled TDI foams, with 50% (50p) or 75% (75p) recycled content and containing different types of additives (ADDitive 1,2 or 3)

The distinct variations observed in the stress-strain curves in Figure 3 with different levels of recycled content of 50% and 75% and various additives, underscore the ability to engineer and tailor the material properties, performance, and strength of the recycled plastic, thereby enabling the creation of a product with precisely desired performance characteristics.

Vitricycle LLC has produced “Vitricycle-75” masterbatch granules with up to 75% recycled TDI foam and 25% virgin additives, as well as “Vitricycle-50” with 50% recycled TDI foam content and up to 20 MPa strength, suitable for general injection molding purposes. Figure 4 shows the general look of the pellets. Pellets’ light brown or tan color allows for the addition of various coloring pigments for aesthetic purposes.

Figure 4. Sample of "Vitricycle-75", a masterbatch pellet made of 75% recycled TDI foam, for plastic manufacturing.

Economic and Environmental Advantages

Vitricycle's proprietary method is significantly cheaper and faster than traditional recycling methods, requiring much less capital expenditure (CAPEX) and operational expenditure (OPEX) compared to other foam recycling methods. Vitricycle plans to work directly with mattress recyclers to carry out key parts of the operation at recycling facilities. This includes compacting foam sheets at recycler facilities using specially designed machines and operational instructions provided by Vitricycle, drastically reducing transportation costs and CO_2 emissions associated with foam transportation.

Another major economic-environmental advantage is that the process is solvent-free and does not require expensive catalysts, making it both inexpensive and environmentally friendly. This process could also be adopted at existing mattress manufacturing facilities that generate significant quantities of post-industrial scrap foam.

The emissions testing results on TDI foam indicated the presence of various chemicals, but their concentrations were extremely low. The only noticeable concentration was that of butyl-diphenylamine as an antioxidant, measured at approximately 7.8 nanograms per gram. In other words, burning or thermally degrading 1 ton of TDI foam could emit 7.8 milligrams of butyl-diphenylamine. Given that butyl-diphenylamine is not specifically regulated by the EPA under environmental laws such as the Clean Air Act and is typically not classified as a highly hazardous substance, Vitricycle LLC considers this emission level acceptable and within normal expectations for emissions.

Although the upcycling process is not carbon-negative due to electricity use and the incorporation of some virgin materials, this recycling method has a very low carbon footprint, contributing positively to environmental sustainability. A detailed Life Cycle Analysis (LCA) has not been conducted as it was beyond the scope of this project.

Applications Across Industries

Performance data indicates that Vitricycle pellets are versatile and can be used in many applications where soft TPUs are traditionally employed. We find that pellets sourced from *post-consumer* foams are inherently more variable than pellets sourced from post-industrial foams. However, we believe that post-consumer sourced feedstock is still suitable for less demanding applications, or in higher performance applications with lower post-consumer recycled content. We find that material produced from *post-industrial* foams are far more consistent and can be effectively used in high-performance applications with high recycled content.

Figure 5 showcases nine diverse applications of Vitricycle that have been explored, highlighting its versatility in manufacturing various plastic parts. Among these, sample gaskets and shoe soles were specifically manufactured by Vitricycle, demonstrating its adaptability and performance. Other products, such as car floor mats, mud flaps, handles/grips, wiring covers, electronics covers, soft plastics, and sporting goods, are under development. This broad range of potential applications emphasizes Vitricycle's potential to create circular solutions for the thermoset elastomer market.

Figure 5. Versatile Applications of Vitricycle: Sustainable Solutions for Diverse Industries.

Market Entry and Integration: Vitricycle's Role in the Supply Chain

The flowchart in Figure 6 illustrates planned market entry points within the vitrimer supply channel, showcasing the flow of materials from the initial stages of virgin resin manufacturing to the final recycling stage and entry point for Vitricycle.

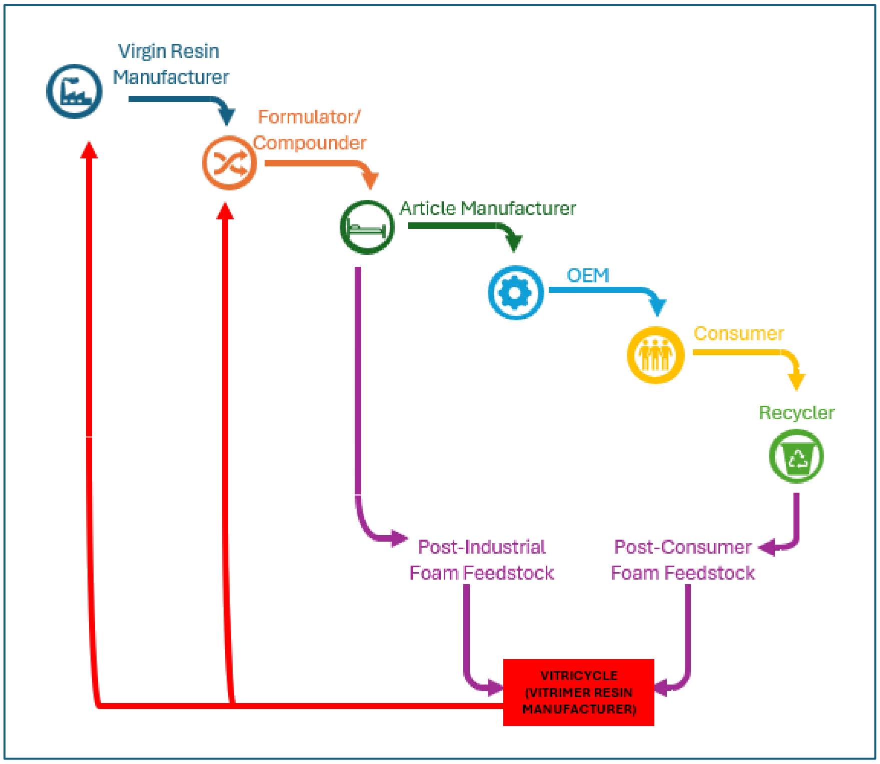

Figure 6. Vitrimer Supply Chain Overview: Market Entry Points and Vitricycle's Position

The process begins with the **Virgin Resin Manufacturers**, who supply foam manufacturing materials to **Formulators/Compounders**. These compounders may add additives as needed. The formulated foam materials are then passed on to **Article Manufacturers**, who manufacture items such as mattress foams. **Article Manufacturers** produce post-industrial foam feedstocks which can be processed by **Vitrimer Resin Manufacturer (Vitricycle)**. These manufactured foams are subsequently sent to **Original Equipment Manufacturers (OEMs)**, and finally sold to **Consumers**.

Once the products reach the end of their lifecycle, they become **Post Consumer Foam Feedstock**, which is then processed by **Recyclers** and sold to **Vitrimer Resin Manufacturer (Vitricycle)**.

The **Vitrimer Resin Manufacturer**, highlighted in red, represents the critical role of Vitricycle in this supply chain. Vitricycle operates at the intersection of post-industrial and post-consumer foam scrap, transforming these materials into vitrimer resins that are reintroduced into the manufacturing cycle, ensuring a sustainable and efficient recycling process.

Implementation and Collaboration

- **For Foam Recyclers**: Vitricycle LLC offers licensing, training, and machinery (purchase or lease) for compacting post-consumer scrap foams, significantly reducing storage and transportation costs, making recycling economically viable. This solution is particularly beneficial for large-scale foam recycling facilities facing storage challenges. Upon agreement and purchase of our machinery, Vitricycle will provide the necessary machinery and training and will purchase the compacted sheets from foam recyclers. Foam recyclers will benefit from substantial savings on storage space and the opportunity to sell the compacted sheets to Vitricycle LLC.
- **For Mattress and Foam Manufacturers**: Vitricycle LLC offers intellectual property and machinery (purchase or lease) for in-house compaction and recycling of post-industrial foams. This reduces costs and enhances sustainability by creating value from foam that was historically sold to third party brokers. This process not only frees up storage space but also offers potential cost savings and tax incentives. Additionally, using more recycled content aligns with environmental regulations and enhances the company's green credentials.
- **For Virgin Resin Manufacturers**: Large chemical companies and virgin resin manufacturers can significantly benefit, by licensing Vitricycle's technology to produce high-recycled content resins in-house. This approach reduces costs and environmental impact, providing a competitive edge in sustainable material production. Given that major virgin resin manufacturer companies also supply the chemicals and additives necessary for foam and resin production, it is advantageous for them to leverage this technology. By producing and selling high-recycled content resins, they can cater to the growing demand for sustainable resins. These granules are competitively priced compared to virgin TPU materials, which is unprecedented in the industry.
- The Vitricycle technology has patents pending in the US, EU, and China, and is poised to expand into these markets.

Intellectual Property

We have submitted a patent application titled "POLYURETHANE RECYCLING METHODS AND SYSTEMS" for this project, which is pending approval in the United States, European Union, and China. The US patent application number is 63235194, the international application number is PCT/US2022/040888, the European patent application number is E 22859219.2, and the Chinese application number is 202280008192.3.

Conclusion

In this work, we demonstrated a commercial scale process to convert post-consumer mattress foams into reformable elastomers with excellent physical properties. The new process does not require the addition of catalysts or solvents thereby having favorable environmental impacts. Vitricycle's foam vitrimerization project addresses critical environmental and economic challenges in mattress foam recycling. The innovative technology not only makes recycling economically viable but also opens numerous applications across various industries. With competitive costs, product performance and products with high recycled content, Vitricycle is poised to make a significant impact, promoting a circular solution and reducing landfill waste.

Acknowledgement

We would like to express our deepest gratitude to the Mattress Recycling Council (MRC) for their unwavering technical and financial support, without which this project would not have been possible.

References

1. "Our Impact - Mattress Recycling Council | Recycling Programs in California, Connecticut & Rhode Island." [Online]. Available: https://mattressrecyclingcouncil.org/our-impact/
2. "Mattress recycling: a US success story • Recycling International." [Online]. Available: https://recyclinginternational.com/business/mattress-recycling-a-us-success-story/2516/
3. "The Future of Mattress Disposal: Prioritizing the Planet While Upgrading Bedding — Green Mattress." [Online]. Available: https://www.greenmattressco.com/blog/the-future-of-mattress-disposal
4. "Vitrimerization: converting thermoset polymers into vitrimers." Yue, Liang, Haochen Guo, Alison Kennedy, Ammar Patel, Xuehui Gong, Tianxiong Ju, Thomas Gray, and Ica Manas-Zloczower. ACS Macro Letters 9, no. 6 (2020): 836-842. [Online]. Available: Vitrimerization: Converting Thermoset Polymers into Vitrimers | ACS Macro Letters
5. "Vitrimerization of Rigid Thermoset Polyurethane Foams: A Mechanochemical Method to Recycle and Reprocess Thermosets." Bandegi, A., Montemayor, M., & Manas-Zloczower, I. (2022). Polymers of Advanced Technology, 33 (10). [Online]. Available: Vitrimerization of rigid thermoset polyurethane foams: A mechanochemical method to recycle and reprocess thermosets - Bandegi - 2022 - Polymers for Advanced Technologies - Wiley Online Library
6. "Reprocessing Postconsumer Polyurethane Foam Using Carbamate Exchange Catalysis and Twin-Screw Extrusion" Sheppard, D.T.; Jin, K.; Hamachi, L.S; Dean, W.; Fortman, D.J.; Ellison, C.J.; Dichtel, W.R.; ACS Cent. Sci. 2020, 6, 6, 921-927, DOI: 10.1021/acscentsci.0c00083. [Online]. Available: Reprocessing Postconsumer Polyurethane Foam Using Carbamate Exchange Catalysis and Twin-Screw Extrusion (acs.org)