Testimony for the Record Submitted to
The House Committee on Science, Space, and Technology
Subcommittee on Research and Technology

For the Hearing:

"*Plastic Waste Reduction and Recycling Research:
Moving from Staggering Statistics to Sustainable Systems*"

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Chairwoman Stevens, ranking member Waltz, and distinguished members of the Subcommittee thank you for the invitation to provide testimony in today's hearing. I am honored to have this opportunity. I am currently a McKnight Presidential Endowed Chair in the Department of Chemistry at the University of Minnesota and the Director of the National Science Foundation Center for Sustainable Polymers.

I have worked in the field of polymer science since I was an undergraduate researcher at the University of Florida where I was introduced to the thrill of scientific discovery and incredible properties of polymers, the molecules of plastic. I continued polymer science research as a graduate student at the California Institute of Technology. Since beginning as a Professor of Chemistry at the University of Minnesota, I have worked in the areas of sustainable polymers and much of my research today has connections to sustainability. My research group is currently exploring numerous projects that include next generation polymeric membranes for applications in water purification and remediation, new compostable barrier materials for food packaging, and the valorization of biomass for new high-performance polymers that can be chemically recycled. As the director the Center for Sustainable Polymers since its inception 2009, I have led numerous research efforts and managed a broad research portfolio focused on sustainable polymers. I have personal and professional passion for advancing sustainable polymers that enable a circular economy for future generations.

I am here today to provide (i) an overview of research efforts carried out in the National Science Foundation Center for Sustainable Polymers; (ii) my views on the broader research needs, opportunities and challenges for federal research in bio-based, compostable, and alternative plastics and in chemical or advanced recycling; and (iii) my input on the *"Plastic Waste Reduction and Recycling Research: Moving from Staggering Statistics to Sustainable Systems"* proposed research activities at the National Science Foundation, Department of Energy, and any other research and standards development activities directed under the bill.

As a society that depends on plastics every day and in nearly all established, new and emerging technologies, we are faced with a crisis. Just like our thirst for energy leads to the generation of the greenhouse gases, our need and desire to enjoy the comforts, conveniences, and efficiencies that come with modern materials also comes at a cost: ever increasing, broadly distributed, and persistent plastic pollution.[1] Moreover, nearly all the hundreds of million metric tons of new plastic that is produced globally every year is derived from non-renewable fossil resources (i.e., petroleum and natural gas) thus contributing to the depletion of finite feedstocks harbored by Earth. While we all know about plastics recycling and the chasing arrow indicators on plastic materials, the fact is that a very small percentage of plastics are effectively recycled.[2] To make matters worse, most plastics are used for a short period of time (e.g., packaging) and then disposed, often indiscriminately. The value of that plastic material is lost, waste is generated, very little is recycled, and a staggering level of these discarded materials end up in our environment.[3] It is clear that plastic articles (e.g., beverage bottles), microplastics (i.e., small bits of plastics liberated from plastic waste), and nanoplastics (i.e., even smaller plastic pollution from, for example, textiles) are negatively impacting our environment, ecosystems and Human health.[4] Using oil and gas to make plastics that typically have very short use lifetimes, a good fraction of which ends up in the environment, and cause damage to our ecosystems is simply unsustainable.

So, why not just stop using plastics? The answer is to this is also clear. These remarkable materials are so important and often contribute positively to sustainability, it is difficult to image modern society without them. Lightweight transportation, food preservation, modern water purification, defense applications, renewable energy, efficient agricultural, biomedicine, additive manufacturing, microelectronics, and communications are all examples in an incredibly long list of areas where polymers play an integral role. Although there are people with good intentions that try to eliminate plastic from their daily lives, this is basically impossible to do without experiencing major inconveniences but also without having more environmental impact in certain scenarios (for example, paper vs. plastic). Nonetheless, we don’t need all plastic. There are so many examples of unnecessary plastic “stuff” that permeate society, and dematerialization will unquestionably play an important role in a sustainable polymer future; there are some places where we simply use too much plastic. The other main contributing factor for our love of plastic is that these materials are extremely low cost. The materials performance to price ratio of plastics is about as high as it gets.

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[1] Lavender Law, K.; Starr, N.; Siegler, T. R.; Jambeck, J. R.; Mallos, N. J. “The United States’ contribution of plastic waste to land and ocean” *Sci. Adv.* **2020**, *6*, eabd0288.

[2] https://www.epa.gov/sites/production/files/2021-01/documents/2018_ff_fact_sheet_dec_2020_fnl_508.pdf (accessed 20 June 2021)

[3] Geyer, R.; Jambeck, J. R.; Lavendar Law, K. “Production, Use, and Fate of All Plastics Ever Made.” *Sci. Adv.* **2017**, *3*, e1700782.

[4] Lavendar Law, K.; Thompson, R. C. “Microplastics in the seas” *Science* **2014**, *345*, 144-145.

We need a major change in the way we produce, use, discard, and recycle plastics. The goal of zero plastic pollution is a lofty but necessary aim for a sustainable plastics future.[5] To realize this vision there are many interwoven factors and needs. These include policy initiatives, improved recycling and other end-of-life infrastructure, and industry adoption of sustainable alternatives for their current plastic products, packaging, and processes. However, there is no question that basic and fundamental research in sustainable polymers is and will continue to be essential to build a strong foundation from which new sustainable technologies can be built. This is where government, industry, and private foundation support all play critically important roles. Basic research in sustainable polymers that aims to uncover the underlying principles associated with, for example, efficient conversion of renewable feedstocks to valuable chemical intermediates, green processes to incorporate those chemicals in to advanced polymeric structures, and how to design materials for viable and sustainable end-of-life scenarios post use will all positively contribute to a sustainable polymer future. This important research aimed at understanding fundamentals and revealing what is possible with sustainable polymers is decades behind analogous work in non-renewable, fossil-derived, non-degradable, practically non-recyclable materials that dominate today's landscape. Effort, support, and new initiatives are imperative to for future generations to enjoy the benefits of plastics while minimizing or eliminating their negative consequences.

The Center for Sustainable Polymers headquartered at the University of Minnesota has been focused on this important basic research since 2009 and has been supported by the National Science Foundation since 2011 through the Centers for Chemical Innovation program.[6] The Centers for Chemical Innovation are comprised of "research centers focused on major, long-term fundamental chemical research challenges. Centers for Chemical Innovation work to address these challenges to produce transformative research that leads to innovation and attracts broad scientific and public interest." The work in the NSF Center for Sustainable Polymers is squarely in line with this directive. Our mission is to transform how plastics are made, unmade, and remade through innovative research, engaging education, and diverse partnerships that together foster environmental stewardship. Center participants aim to design, prepare, and implement polymers derived from renewable resources for a wide range of advanced applications, and to promote future economic development, energy efficiency, and environmental sustainability in the emergent area of bio-based products.[7] Our work is currently grouped into three interwoven Grand Challenge Project Areas focused on (i) Efficient and sustainable conversion of biomass to polymer ingredients; (ii) High-performance sustainable plastics and elastomers; and (iii) Sustainable polymer degradation, chemical recycling, and compatibilization.

At the Center, we embrace all important facets of modern sustainable polymer research. To better help formulate our work, we recently established a "Sustainable Polymer Framework". This framework allows researchers in the Center to better contextualize and communicate the areas that contribute to sustainability in their polymer research efforts. More details on this

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[5] Lau, W. W. Y. et al. "Evaluating scenarios toward zero plastic pollution" **2020**, *369*, 1455–1461.

[6] https://www.nsfcci.org/currentcenters (accessed 17 June 2021)

[7] https://csp.umn.edu/about/ (accessed 17 June 2021)

framework and the associated background are available.[8] In short, we are concerned with research efforts that emphasize (i) renewable, waste, and recycled feedstocks; (ii) green, low-energy, non-toxic processes to generate new polymeric materials; (iii) advanced, low-cost, and high-performing new polymers that are competitive with incumbent materials; and (iv) the design, development, and deployment of new polymers that can be efficiently recycled, degraded, or reused. All these features are important for a sustainable plastics future and some projects in the Center address all facets simultaneously. We have also integrated life cycle analysis into our studies to help us better quantify the expected environmental impacts of new discoveries as they make their way from the laboratory through translation to the marketplace. With these important pillars of sustainability, researchers in the Center work in a synergistic fashion toward these combined goals. Several research highlights that emphasize this synergy have been captured,[9] and three examples of some of our most impactful recent research accomplishments that emphasize plastics recycling and degradation from our published work are summarized below.

Biodegradable polymers have been used in many applications including packaging, disposable service ware, and biomedical devices. Such materials will play a role in a sustainable plastics future. However, there has been an often-mistaken interpretation that degradable materials are necessarily biodegradable and/or compostable over reasonable time frames. Undoubtably, more basic research is needed to help better understand the fundamental degradation process and associated time scales.[10] Given that some compostable materials cannot degrade under the action of natural microorganism metabolism under ambient conditions, it is important to both understand and define the specific meaning of terms such as “degradable”, “biodegradable”, and “compostable”. Moreover, it is imperative to understand any potential adverse toxicity resulting from the release of degradation products into the environment when ascribing these properties and labels to a material. To this end, researchers in the NSF Center for Sustainable Polymers developed two novel, and high-performing polyester materials that were successfully degraded in natural and engineered environments (i.e., under industrial composting conditions). Moreover, the hydrolysis products were shown to have low cytotoxicity, not unlike the commercially available polymers used for biomedical applications. This research paves the way for the continued development and assessment of new polyester materials and their associated degradation profiles.[11]

Cross-linked polyurethane foam is used in many commercial applications including mattresses, insulation, and construction materials. Due to the permanent nature of the chemical crosslinks in these materials, conventional polyurethane foam does not flow upon heating, and this severely thwarts its ability to be effectively reprocessed. Instead, polyurethane foam, if recycled at all, is

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[8] https://conservancy.umn.edu/handle/11299/211643 (accessed 17 June 2021)

[9] https://csp.umn.edu/synergy/ (accessed 17 June 2021)

[10] Zumstein, M.T.; Narayan, R.; Kohler, H-P. E.; McNeill, K.; Sander, M. “Dos and Do Nots When Assessing the Biodegradation of Plastics” *Environ. Sci. Technol.* **2019**, *53*, 9967–9969.

[11] Reisman, L.; Siehr, A.; Horn, J.; Batiste, D. C.; Kim, H. J.; De Hoe, G. X.; Ellison, C. J. Shen, W.; White, E. M.; Hillmyer, M. A. “Respirometry and cell viability studies for sustainable polyesters and their hydrolysis products” *ACS Sustainable Chem. Eng.* **2021**, *9*, 2736–2744.

typically downcycled into less useful materials. Given that polyurethanes represent nearly a third of the thermoset materials market and foam is less dense than other materials, this results in a sizeable waste stream that takes up large amounts of space when landfilled. In groundbreaking work from the Center, polyurethane foam waste was successfully reprocessed via a dissociative carbamate exchange mechanism activated at elevated temperature facilitated by a catalyst and effective mixing via twin screw extrusion. To address sustainability goals of reprocessing end-of-use materials, Center researchers discovered that waste polyurethane could be melt reprocessed by introducing a catalyst via solvent swelling. However, such methods that led to successfully reprocessed polyurethane films were not efficient. To address the challenge the team developed a new method of reprocessing post-consumer polyurethane foam waste using twin screw extrusion. This new method involves efficient mixing of catalyst-containing polyurethane foam waste in order to ensure air is removed from foam during reprocessing. This work demonstrates that with innovative chemical approaches, new methods for recycling traditionally recalcitrant materials is possible and holds promise for technological advances in polyurethane recycling.[12]

Polyethylene and isotactic polypropylene are the two most abundant plastics worldwide and account for about two-thirds of all plastic production. Despite their similar hydrocarbon nature these polymers phase separate, which erodes the mechanical properties of melt blends and creates challenges for effectively recycling the materials. Given the abundance, utility, and environmental impact of these ubiquitous polyolefins, there is a compelling need to improve the recyclability and associated mechanical properties of these repurposed materials. An NSF Center for Sustainable Polymer research team of synthetic chemists, and chemical and materials engineers discovered that as little as 1% by weight of a newly created multiblock copolymer could combine commercial polyethylene and isotactic polypropylene into remarkably tough composite blends. The team used their experience in olefin polymerization to synthesize well-defined multiblock copolymers, studied combinations of various types of multiblock polymers as additives, and discovered a new mechanism of polyolefin blend compatibilization, resulting in unprecedented mechanical integrity in otherwise brittle blends of these top two plastics. This work has led the way for new approaches to recycling the world's top two plastics.[13]

These research examples are among numerous advances the NSF Center for Sustainable Polymers has made since its inception. In addition to adding to the basic research foundation, researchers in the Center have also protected many inventive ideas through patent filings. Intellectual property from the Center has been licensed by industry or has been the basis for the formation of start-up companies thus directly contributing to the innovation mission of the Centers for Chemical Innovation. Basic research and scientific discovery are of course not mutually exclusive and in our search for the fundamental knowledge that is so critical for future technologies we have also uncovered what is possible. In that way, we have contributed directly

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[12] Sheppard, D. T.; Jin, K.; Hamachi, L. S.; Dean, W.; Fortman, D. J.; Ellison, C. J.; Dichtel, W. R. Reprocessing Postconsumer Polyurethane Foam Using Carbamate Exchange Catalysis and Twin-Screw Extrusion. *ACS Cent. Sci*. **2020**, *6*, 921–927.

[13] Eagan, J. M; Xu, J.; Di Girolamo, R.; Thurber, C. M.; Macosko, C. W.; LaPointe, A. M.; Bates, F. S.; Coates, G.W. "Combining polyethylene and polypropylene: Enhanced performance with PE/*i*PP multiblock polymers." *Science*, **2017**, *355*, 814–816.

to new horizons and new vistas in the field. In addition to our important scientific work, the Center has also strongly supported the younger researchers through professional development programing and has made great strides in engaging, fostering, and promoting researchers from historically excluded and under-represented folks in the sciences thus making inroads to broadening participation in science, technology, engineering, and mathematics.

Sustainable practices must be the future. The NSF Center for Sustainable Polymers has and continues to contribute to the important basic research aspects of this work through synergistic research effort that is cross-disciplinary within the broadly defined chemical sciences. Through the efforts of many researchers over many years, we have certainly strengthened the scientific foundation, made numerous discoveries, and have promoted the field of sustainable polymers in many ways. We are excited about future possibilities and will continue to carry out this necessary work for a sustainable future.

With respect to broader research needs, opportunities, and challenges for federal research in bio-based, compostable, and alternative plastics and in chemical or advanced recycling there are several important avenues to pursue, and I highlight a few key areas below.

Starting with bio-based products there is need for more investment in the efficient conversion of biomass into polymeric ingredients.[14] The use of non-nutritive biomass that is typically quite difficult to process through standard fermentation strategies is important to support. The idea of low material and energy input perennial crops that do not take from the food supply being used for industrial chemical products is quite attractive. However, this will require continued support and investment in the conversion of crops that are more amenable to fermentation processes such as corn and sugar beets. This will allow the chemical industry to see what is possible with respect to so-called drop-in replacements for fossil resource derived chemical intermediates. If the science is supported in this arena, the fermentation technologies will continue to be improved and the bio-based products will continue to become more cost competitive with the analogous petrochemicals. Moreover, lower cost and lower input crops will become more viable. Steady progress in this arena will ultimately lead to bio-based resources becoming preferred over fossil resources not only from an environmental perspective, but also from an economic perspective. In addition to supporting fermentative processes, there are research needs in thermochemical and catalytic conversion of biomass to useful products such as lignin, seed oils, and cellulose. Here again, efficiency, high yields, and low-cost processes will be imperative for a sustainable bio-based economy.

In the area of compostable polymers, an important research need is in the basic understanding of degradative processes under more mild and less engineered composting conditions (such as home composting). In this way, households may be able to have composting outlets for food contaminated packaging that is difficult to recycle if there is no access to commercial composting infrastructure, as an example. Developing polymers that are robust and effective in use and that can be rapidly composted upon disposable is tall order. Understanding chemical triggering that

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[14] Hillmyer, M. A. "The promise of plastics from plants" *Science* **2017**, *358*, 868-870.

is induced by light, temperature, humidity, or other stimulus is an important research area.[15] Polymeric materials that are multifunctional in this way are attractive research targets. Of course, proper management of waste streams will be important here, and thus concomitant research in effective waste separation will also be important to pursue.

With respect to "new to the world" alternatives to our current suite of commodity plastics, many are being developed in research laboratories every day. This research effort continues to show us what is possible by demonstrating new and exciting phenomena. Going forward there is a critical need to work on not only what is possible but also what is practical. Moving from the establishment of a new research discovery using more esoteric or sophisticated molecular structures to those that can exhibit the same basic utility but that are simpler, that can be derived from abundant bio-based materials, and that can be easily recycled or degraded is a significant challenge. Here understanding the key fundamental principles associated with important structure/property relationships in new sustainable polymers will be crucial to establish. Support for this kind of basic research will be very important going forward to help move discoveries from the laboratories to the important translational work that can lead to new technologies. The fascinating array of new molecular structures available to polymer scientists is boundless and research aimed at the design and development of new bio-based material that can be recycled or degraded in a facile manner should be strongly supported.

With respect to recycling, there really is need for more research on how to deal with a heterogenous waste stream of recycled plastics more effectively.[16] We have a quite abundant resource with waste plastics and research aimed at valorizing this resource is necessary. In the realm of mechanical recycling, new ways to separate and/or compatibilize mixed waste streams are needed as mixtures of recycled plastics are generally inferior to homogeneous materials. The emerging area of chemical recycling is exciting and of great importance. Here plastics are reverted or depolymerized back to their monomeric constituents so they can be repolymerized again to the same pristine material. For example, polyethylene is made by polymerizing ethylene. Imagine depolymerizing polyethylene back to ethylene and then using that recovered ethylene to make new polyethylene. Understanding the fundamental thermodynamic, kinetic, and catalytic processes in detail will help scientists and engineers devise new processes and new materials that are capable of being recycled repeatedly without compromising properties. There are efforts along these lines currently being developed.[17] Utilizing the products of chemically recycled plastics to build new plastic of the same value in a circular manner could have many benefits. Research aimed at extracting value from an ample waste resource is needed, and chemical recycling has attractive aspects that could lead to new overarching strategies to managing plastic waste.

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[15] Albertsson, A. C.; Hakkarainen, M. "Designed to degrade" *Science* **2017**, *358*, 872–873.

[16] Garcia, J. M.; Robertson, M. L. "The future of plastics recycling" *Science* **2017**, *358*, 870–872.

[17] Ellis, L. D.; Orski, S. V.; Kenlaw, G. A.; Norman, A. G.; Beers, K. L.; Román-Leshkov, Y.; Beckham, G. T. "Tandem Heterogeneous Catalysis for Polyethylene Depolymerization via an Olefin-Intermediate Process" *ACS Sustainable Chem. Eng.* **2021**, *9*, 623–628.

I am fully supportive of the *"Plastic Waste Reduction and Recycling Research Act"* proposed research activities. I resonate with the proposed support for United States leadership in development of Nation and International standards for sustainable plastics design and plastic recycling infrastructure, technologies, processes. There is also no doubt that public-private partnerships will play a key role in future to help accelerated research and technology development. The emphasis on moving developments from the research laboratory to commercial applications is well founded and an important aspect of the proposed program. Also, the support of multi-disciplinary research on advanced plastics designed for recyclability or biodegradation is very important for a sustainable plastics future. The integration of research efforts across fields and disciplines will be important to emphasize given that polymer research spans several scientific endeavors that range from: metabolic engineering, to organic chemistry, to catalysis, to materials science and processing to environmental degradation. Research focused on new materials that include end of life considerations in their design will define new polymeric materials for future generations. In addition, research on how to deal with our current suite of polymeric materials that allows the enormous amount of plastic waste to be effectively recycled at much higher levels will also be important to support. In the world of sustainable polymers, there will be multiple solutions to our current practices that are unsustainable. A portfolio of renewable resources will need to be utilized to make a range of polymeric products that are high performance in their applications, and that have sensible end of life solutions that include mechanical recycling, chemical recycling, or biodegradation (e.g., via industrial composting).

Thank you again for this opportunity to testify today. I am honored to be able to share my thoughts and visions for a sustainable polymer future. I look forward to answering any questions you may have.