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Chairwoman Stevens, Ranking Member Baird, and members of the Subcommittee, thank you for this exciting opportunity to discuss the critical need for emphasis on plastics reclamation, recycling, and upcycling and how new technology investments have the potential to protect our nation's environment and strengthen our industrial competitiveness.

Introduction

My name is Gregg T. Beckham, and I am currently a Senior Research Fellow in the National Bioenergy Center at the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory, or NREL, in Golden, Colorado. In 2007, I obtained my Ph.D. at the Massachusetts Institute of Technology and started my research career at NREL almost immediately. I began leading a research group in 2011 focused on using biology, chemistry, and chemical engineering to solve some of the most pressing energy and environmental problems facing our nation. In particular, my group has been focused on developing renewable energy technologies to advance biofuels, biochemicals, and biomaterials sourced from lignocellulosic biomass—the plant matter that is abundant in the United States. This work is done in collaboration with academic institutions throughout the United States and all over the world, other DOE national laboratories, and with industrial partners from startups to large multinational companies.

Broadly speaking, the science and engineering research conducted at NREL, and at many U.S. research institutions and universities, on biomass conversion can readily be applied to overcoming the waste plastics problem. More recently, I have been co-leading a growing international collaborative team focused on employing biomass conversion science and engineering to overcome the global environmental problem of plastics waste. Our goal is to create a more circular materials economy, both nationally and globally, that minimizes waste by keeping materials in continuous use. Many of the scientific concepts developed for biomass conversion are also used for plastics conversion. For example, lignocellulosic biomass, which is derived from agricultural residues and timber waste, is a diffuse, solid, and diverse feedstock that is highly resistant to breakdown and is of relatively low value. Plastics are conceptually quite similar, as I will describe in more detail below.

Overall, these projects and collaborations have provided me with an understanding of how biology, chemistry, and chemical engineering principles can potentially be applied—with increased emphasis and federal investment—to help the United States lead the way in developing robust, industrially relevant solutions to stem this growing environmental crisis of plastics waste and to ultimately enable a more circular materials economy.

I was invited here today to discuss with you the broader needs, opportunities, and challenges for research, development, and deployment in chemical recycling technologies and to highlight how universities, government research laboratories, industry, and local governments can spur innovation in this space and “close the loop” on plastics recycling. Although I will highlight specific examples relevant to my group’s work at NREL, the broader lessons and capabilities will be applicable to many of the nation’s biologists, chemists, chemical engineers, and experts in related fields. Briefly, we must address two questions: How do we handle the stream of plastics we generate today and how do we design the plastics of tomorrow for recyclability-by-design?

Plastics are creating a global environmental catastrophe

Plastics are everywhere, and they are essential to modern life. Some of the initial plastics were actually developed to avoid the use of ivory and, thus, were motivated by an environmental and conservation perspective. Today, more than 300 million metric tons of plastics are produced each year. Almost all of these are derived from fossil-based resources and ultimately based on byproducts from petroleum refining, ethylene, propylene, and benzene. Humankind uses these versatile, robust materials for myriad things—for example, to keep water clean, prevent infection in hospitals, protect and prolong the life of food, lightweight vehicles and airplanes, and also as fibers in clothing and carpeting, bio-compatible materials for human health, major components in renewable energy and electricity generation and for other applications. Indeed, an amusing experiment that anyone can do is to note every single piece of plastic you touch just as you get ready for work; you will soon get tired of taking notes (probably with a plastic pen). The amount of plastics in our daily lives is simply daunting and something that many of us take for granted. It is undoubtedly the case that plastic materials will continue to be used in various forms for the entirety of the next century. In the developing world, where the middle class is on the rise, the use of plastics will grow.

Given their low cost, extraordinary durability, and utility in so many applications, plastics are also accumulating at alarming rates in the world’s landfills. The statistics are truly staggering. Experts have estimated that 8.3 billion metric tons of plastics have been made and approximately 5 billion metric tons have already been discarded, with an abysmal recycling rate of only 600 million metric tons. This is despite the fact that recycling alone can save 40 to 90 percent of the inherent energy in plastics relative to the production of virgin plastics—energy savings, which if harnessed, could result in massive-scale economic advantages. Moreover, many plastics are produced for single-use packaging. Up to 40 percent of all plastics are used for minutes to hours to days in single-use packaging applications, while the estimated time for many plastics to degrade in a landfill is centuries to millennia.

Besides choking landfills, plastics are also entering the environment at increasingly alarming rates, perhaps most strikingly in the world’s oceans. It is estimated that over 7 million metric tons of plastics enter the ocean every year, a significant portion of which is in the developing world in coastal regions and through major freshwater entry points into the oceans. From there, plastics enter natural food chains, poisoning sea life from pole to pole through the ingestion of plastics by sea life. To put this into context, 7 million metric tons of plastics per year entering the oceans is the equivalent of a dump truck of plastics entering the ocean per minute, all year round. Based on this statistic, the projected population growth, and the projected upward economic mobility of the global middle class, a survey led by researchers at the University of Georgia estimated that by 2050 there will be more plastic in the ocean than fish by mass. Given the reliance of the planet on the health of the world’s oceans, this staggering prediction should give us all pause.

Plastics in the environment are by no means limited to polluting the world's oceans. Microplastics are found far and wide in the soil and in the entirety of the global food chain, polluting what we once considered pristine freshwater bodies, and, as highlighted in a study released just this month, they are carried in the air we breathe. Given the amount of plastics in the food chain, plastics are commonly now found in the human body, with potential toxicological effects that are not yet fully understood. Indeed, it is nearly impossible to read or listen to the news and not hear about this problem. Although plastics currently in the biosphere will likely subsist for centuries and millennia, urgent action on a global scale will be required to stem the tide of plastics that enter our controlled landfills, the natural world, and even our own bodies.

Current recycling infrastructure is failing

Since plastics have come into circulation, various forms of a recycling industry have developed around the world, catalyzed by social pressures, governmental regulations, and in some cases economic motivations. However, nearly all recycling today is mechanical in nature. For example, a water bottle—a common, single-use plastic mostly comprising polyethylene terephthalate (PET, recycling code #1)—when recycled, will typically be sorted from other plastics, have the label and cap removed, be washed, and then chopped into flakes. Depending on the color (clear or green), the reclaimed PET plastic will then be heated up and extruded into a new PET plastic that will typically exhibit compromised material properties relative to virgin, bottle-grade PET. This means that reclaimed, recycled PET will typically go into applications such as polyester carpet or clothing. While this represents a second life for the plastic, the value of the reclaimed PET is significantly lower than that of virgin, bottle-grade PET, and in many cases, the plastic will still ultimately end up in a landfill. Thus, most recycling of this nature can be thought of as "downcycling."

Beyond this, China's passage of their "National Sword" policy banned the imports of most waste plastics from North America and the European Union into that nation. Many of the "recycled" plastics in the United States were considered and counted as "recycled" before 2018 if they were sent to China. The passage of the National Sword policy is causing overflows and massive stress on the existing, domestic supply chains. While a major upset in the flow of reclaimed plastics, this policy also presents a significant opportunity for the United States (and more broadly, many countries in the developed world) to rethink and reinvent the recycling value and supply chain toward a more circular materials economy.

Recycling and upcycling technologies provide potential solutions

As noted above, plastics recycling today is mostly mechanical. Alternative strategies for recovering and reclaiming value from plastics should be examined as soon as possible to address the problem of dealing with today's waste plastics. For example, some countries, such as Sweden and Austria, already reclaim and burn a significant amount of the waste plastics generated. Energy recovery from waste plastics, in many cases, is able to circumvent the need for sorting heterogeneous materials from one another and is a cost-effective strategy. Yet in an era of cheap natural gas and renewable electrons coming onto the grid, energy recovery from plastics represents a baseline and likely a non-sustainable means to recover value from plastics. In many regions of the United States, this will be little better than current mechanical recycling or simply landfilling plastics. Moreover, emissions from plastics combustion, beyond carbon dioxide, often contain toxic metals resulting from specific polymerization catalysts, causing yet another potential environmental cleanup problem while simultaneously adding to the amount of carbon dioxide in the atmosphere.

Instead, the use of chemical recycling—using catalysts to break plastics down to their building blocks and build them back into new, virgin-like materials—offers a more sustainable, innovative, and profitable approach around which we can completely rebuild the American recycling industry. Let’s address several aspects of what this could look like.

First, why is chemical recycling not already used today? As mentioned earlier, the breakdown of plastics is similar to the breakdown of lignocellulosic biomass. Especially in consumer applications like packaging, plastics are diffusely distributed and often are costly to recover. They are similar to agricultural residues produced on American farmland. Plastics are also incredibly durable and hard to break back down to their building blocks, just like cellulose is in plants. The genesis and continued development of plastic materials almost universally focuses only on “during lifetime” properties, with end-of-life considerations being an afterthought. Thus, plastics are inherently hard to break down and existing approaches to do so are, for the most part, not yet commercial. Drawing on the parallels to biomass conversion, the advent of a lignocellulosic-based economy has required sustained and continued investment in the scientific and engineering enterprises, and over the last 40 years, massive gains in efficiency, process designs, and economic viability of biomass conversion now has the United States and the world on the cusp of utilizing biomass as a foundation for renewable fuels, chemicals, and materials. The stubborn problem of today’s plastics, like lignocellulosic biomass, will require sustained commitment to develop viable processes, but the urgency of this problem is clear.

Chemical recycling can be envisioned in many variations, and the type of process design ultimately employed will depend on many factors, including the type of plastic being chemically processed. For example, PET (recycling code #1) exhibits a very different chemical structure from polyethylene (recycling codes #2 and #4, depending on the form) and polypropylene (recycling code #5), and, thus, will require significantly different types of processes to be developed. The types of catalysts and processing conditions used in chemical recycling will likely vary significantly also based on the type of plastic being targeted. Ideally, chemical recycling processes will be able to handle mixed waste plastic streams, and the ability of a process to selectively extract one building block from mixed plastics streams will help avoid upstream sorting costs in a process—a key driver for process viability and robustness. Given the ability to develop new processes from a completely fresh perspective, adherence to the principles of green chemistry and green engineering should be followed and designed into theoretical process concepts.

New developments in catalysis to break down plastics will certainly be required. Thus, the development of robust, scalable, economically viable processes will require advances in chemical catalysis and related fields. Engagement with industry and formation of key partnerships will be essential to ensure the viability of catalytic approaches. Chemical recycling may also include biological elements as well, and indeed, the United States is a world leader in the development of advanced industrial biotechnology. This may include elements such as engineered or evolved enzymes to break down plastics, or the use of engineered microbes to break down plastics and turn the deconstruction products into new building blocks. As an example, NREL and an international team recently engineered a natural enzyme for improved PET biodegradation, and we are working now with a large group of collaborators in the United States and Europe to find even better enzymes that can operate at much higher temperatures as would be needed for industrial utility. We have also engineered a microbe to be able to produce enzymes that break down plastics and then convert the deconstruction products into higher-value materials, such as composite materials for snowboards.

Regardless of the approach for chemical plastics upcycling, scale-up will be a critical component of the research and development in this space. A potential advantage for plastics, relative to biomass, is that many places in the United States already have reclamation facilities with infrastructure in place to collect and process plastics in centralized facilities. How chemical recycling links to the current recycling infrastructure will be a key consideration.

Another major question in chemical recycling is: What do we do with the breakdown products? Among several, one obvious and oft-cited option is to use chemical recycling to break down a plastic and turn it back into the same exact plastic with virgin-like materials properties. This would then ideally result in a closed-loop circular materials flow. For example, IBM has developed an innovative chemical recycling process where they can break PET down to building blocks that can be reprocessed into PET bottles with properties akin to virgin PET bottles for carbonated beverages or water. For processes like this, economics will be a key driver in terms of whether the cost for chemical recycling makes sense relative to buying virgin plastics that have never been used in an application before.

Conversely, instead of having a closed-loop cycle for a single plastic, another option in chemical recycling is the concept of upcycling. Upcycling is the creation of a more valuable product from a waste material. In the same example, perhaps the breakdown products from a PET bottle depolymerization process could go into a higher-value, longer-lifetime material, instead of being put back into the PET supply chain. If the upcycled product has more value than the reclaimed and recycled plastic, this may be an early and easier way to produce market pull for reclaiming and breaking down plastics using chemical recycling. Several key elements must be considered here, including: Does the upcycled material have any inherent advantage over making the same material from virgin sources? For example, if an upcycled material can more easily and more cheaply be made from virgin building blocks derived from petroleum, it will be challenging to create an economic incentive for upcycling.

Another key consideration in plastics upcycling is: What is the market size for the upcycled material? For example, if PET is being converted into a composite that could be used as a car part, how does the demand in scale align with that of PET bottles that can be reclaimed? If the market size is considerably smaller, then multiple upcycling solutions will likely need to be developed to justify the reclamation of waste plastics. In my group at NREL, for instance, we have developed a robust process to convert PET plastic found in single-use water bottles into high-strength composite materials that could be used in high-performance applications like in a wind turbine blade or vehicle parts. The selling price of reclaimed PET is between $0.31 and $0.51 per pound, whereas composite materials like we made sell for around $2.50 per pound, representing a considerable upcycling potential. Examples like this will need to be developed and scaled in collaboration with industry to make these ideas into a reality that helps stem the flow of plastics into the environment and also incentivizes the economics of reclamation.

Regardless of what kind of processes are developed, judicious techno-economic analysis and life-cycle assessment must be a key part of the research portfolio. Doing these kinds of analyses “early and often” can best inform the research community as to the main research areas to focus on to be most impactful. These kinds of tools are universally applied in the industrial chemical processing fields, and they will be critical for the development of a new recycling and upcycling industry based on chemical recycling. In addition, resource assessments will be another critical component of this endeavor. Identifying and understanding the current supply chains, where plastics are collected, and where they are currently recycled will help industry identify new opportunities and existing reclamation infrastructure for investment into chemical recycling technologies.

Transforming the plastics of tomorrow to be recyclable-by-design

Today, most plastics are made from petroleum-based building blocks with recycling as an afterthought relative to lifetime performance and application. This is undoubtedly an unsustainable approach for the long-term health of the nation and the planet. Beyond developing robust chemical recycling and upcycling strategies that deal with the plastics we make now, we also urgently need a transition to sustainably sourced building blocks for plastics, and we need to simultaneously develop plastics that are recyclable-by-design. This will require a fundamental shift in our materials economy.

In terms of new building blocks, research done in the United States and globally in the last two decades has identified a large portfolio of accessible bio-based building blocks that can be derived from waste agricultural residues, waste wood from the timber industry, or produced from dedicated energy crops. Similar building blocks can be made from algae or waste organic materials (e.g., food waste) for producing similar new building blocks. Work from our group at NREL, for example, has produced completely new building block molecules that can go into high-value performance materials such as improved nylons for automotive applications. As another example, work from the Center for Biorenewable Chemicals, led from Iowa State University, also developed a range of new bio-based chemicals that can be leveraged for new plastics applications.

The sourcing of new building blocks for materials from bio-based resources is timely and critically needed. While thinking about redesigning new materials from bio-based resources, we also should inherently design these materials to be recyclable-by-design, not as an afterthought. For example, separate works from IBM, Lawrence Berkeley National Laboratory, and Colorado State University, among others, have developed materials that can serve in the place of petroleum-sourced plastics today but can also be infinitely recycled. The ability, for example, to recycle a computer case into its building blocks easily and chemically could then enable turning that plastic into something completely different, such as a car panel. Innovation in this space, namely the combination of renewably sourced building blocks and plastics that are recyclable-by-design will solve the problem of what to do about “tomorrow’s” plastics. Further research and innovation are desperately needed in this space, especially in collaboration with industry, academia, and government research institutions.

More research is urgently needed in plastics

In Episode 7 of the BBC series Blue Planet II, Sir David Attenborough remarked:

> “We are at a unique stage in our history. Never before have we had such an awareness of what we are doing to the planet, and never before have we had the power to do something about that. Surely, we have a responsibility to care for our blue planet. The future of humanity and, indeed, all life on Earth, now depends on us.”

This is absolutely the case with the plastics pollution problem. These versatile materials are now choking the world’s oceans, killing aquatic and terrestrial life, and in the air we breathe and the food we eat. While reducing our individual plastic use, especially single-use packaging, must be part of the solution, plastic materials are truly useful and provide benefits to many aspects of modern life. This means plastics will not go away anytime soon.

Dedicated investment that harnesses the innovation of the United States research community needs to be applied to dealing with today’s plastics through both the development of chemical recycling and re-engineering tomorrow’s plastics to be recyclable-by-design. Developing robust processes that can reach economic viability rapidly would enable creation of a completely new industry in the United States and result in millions of jobs. This would also establish the United States as a world leader to solve this global-scale problem.

In a 2017 paper, Roland Geyer wrote that: “without a well-designed and tailor-made management strategy for end-of-life plastics, humans are conducting a singular uncontrolled experiment on a global scale, in which billions of metric tons of material will accumulate across all major terrestrial and aquatic ecosystems on the planet.” Aggressive federally supported R&D programs in this area will maximize the nation’s economic and environmental benefits, for decades to come.

Gregg T. Beckham is a Senior Research Fellow at NREL. He received his PhD in Chemical Engineering at MIT in 2007. He currently leads and works with an interdisciplinary team of biologists, chemists, and engineers at NREL on conversion of biomass to chemicals and materials and in the area of plastics upcycling. He has published 163 peer-reviewed articles since 2007 and was awarded the ACS OpenEye Outstanding Junior Faculty Award, the AIChE Computational Science and Engineering Forum Young Investigator Award, the *ACS Sustainable Chemistry and Engineering* Lectureship, the SIMB Young Investigator Award, an R&D100 Award, and the Beilby Medal and Prize. He is on the Editorial Board of the*Journal of Biological Chemistry* and the Editorial Advisory Board of *Microbial Biotechnology* and *ACS Sustainable Chemistry and Engineering.* He is also the founding chair of the Lignin Gordon Research Conference.