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New Technologies are Needed to Improve the Recycling and Upcycling of Waste Plastics

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In their Editorial to the Special Issue on The Chemistry of Waste Plastics Upcycling, the Guest Editors Adam Guss, George Huber, Carol Lin, Xianzhi Meng, Hugh O'Neill, Arthur Ragauskas, Jia Wang, Yanqin Wang, and Frederik Wurm highlight some of the increasingly urgent efforts being made by chemists to address challenges related to the fate of plastics at the end of, their useful lives and the valorization of plastic waste.

Modern society has become critically dependent on high-performance/low-cost plastics that support our lifestyles. These plastics are ubiquitous in everyday items, such as bags, plates, food packaging, and state-of-the-art electronics and fields such as transportation and construction. In recent decades, increasing scientific data has emerged on challenges related to the fate of plastic components at the end of their useful lives.[1–4] Along with the leakage of plastic components into ecosystems, the presence of microplastic particles in ocean and terrestrial food systems has heightened public concern. The widespread nature of plastic particulate waste was originally documented in the western Sargasso Sea in 1972.[5] News items and documentaries, such as *Plastic Paradise: The Great Pacific Garbage Patch* and "Researcher discovers microplastics in Bay of Fundy clams" on *CBC News*, have driven public demand for solutions to these problems.[6] It has been estimated that if current global plastic disposal practices continue, by 2050 there will be more plastics than fish (by weight) in the ocean.[7] Moreover, *The New Plastics Economy: Catalysing Action*, published by the Ellen Macarthur Foundation in 2017, states that plastic packaging represents 26% of all plastics generated but that, despite 40 years of concerted recycling efforts, only 14% of this material is currently recycled.[1] In the USA, only approximately 8% of plastics are currently recycled.[8] In China, 80.9 million tons of all plastics are currently consumed, only 30% of which are recycled.[9] In 2016, 27.1 Mt of post-consumer plastics waste was collected in Europe, 27.3% of which ended up in landfill, with 41.6% in energy recovery and 31.1% being recycled (63% inside the EU and 37% outside the EU).[10]

There are several reasons for low plastic recycling rates; a primary reason is the lack of technologies that can efficiently

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recycle plastic materials of diverse compositions. This diversity of composition is due to plastics' diverse chemical structures, which necessitate different strategies for recycling processes for each type of plastic. Polyethylene terephthalate (PET; denoted with recycling code #1) is the most commonly recycled plastic (e.g., 20% and 58% of PET is recycled in the US and EU, respectively), and this is typically done by mechanical means: PET is ground into flakes, cleaned, and re-extruded to make recycled PET (r-PET) flakes or pellets for resale. As the molecular weight of r-PET is decreased by this grinding and re-extrusion process, r-PET must often be blended with virgin PET to afford a product that has suitable properties for a desired end use. Moreover, although the mechanical recycling of PET works well for bottles made of PET, it does not work well for PET used in

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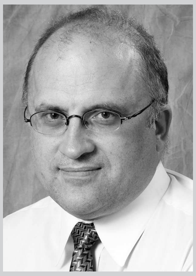
George Willis Huber is the Richard Antoine Professor of Chemical Engineering at University of Wisconsin-Madison. His research focus is the design of disruptive technologies for the conversion of biomass, waste plastics, and waste resources into fuels and chemicals. He is cofounder of Anellotech and Pyran. He is the director of the Center on Chemical Upcycling of Waste Plastics (CUWP). George did a postdoctoral stay with Avelino Corma at the Technical Chemical Institute at the Polytechnical University of Valencia, Spain (UPV-CSIC). He obtained his Ph.D. in Chemical Engineering from University of Wisconsin-Madison (2005). He obtained his B.S. (1999) and M.S.(2000) degrees from Brigham Young University.

Carol Sze Ki Lin is an Associate Professor at the School of Energy and Environment in City University of Hong Kong. Her academic background covers waste management, with special focus on development of integrated biorefineries utilizing renewable resources including food and beverage wastes and by-product streams (e.g., waste streams from bakeries, mixed food waste from restaurants, textile wastes) for sustainable production of biochemicals, biomaterials, bioplastics, and biofuels. Dr. Lin also has experience in biochemical engineering, industrial biotechnology, bioprocess design and technoeconomic evaluation. Together with graduate students and colleagues, Dr. Lin has published over 140 research papers and 16 book chapters.

Xianzhi Meng is a research associate at University of Tennessee-Knoxville. He obtained his Bachelor of Science degree in Chemistry at the Bloomsburg University of Pennsylvania in 2010 and got his Ph.D. degree in chemistry at the Georgia Institute of Technology in 2016. His research interests are improving the utilization of lignocellulosic biomass by understanding its characteristics and creating sustainable chemical solutions essential for converting lignocellulosic biomass resources into bioplastics, biofuels, and biochemicals. He has published more than 80 peer-reviewed articles.

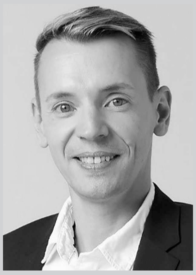
Hugh O'Neill serves as the director of the Center for Structural Molecular Biology (CSMB) and group leader of the Biological Labeling and Scattering group at Oak Ridge National Laboratory. Dr. O'Neill was awarded his B.Sc. degree in Biochemistry and Chemistry from National University of Ireland in 1992 and a Ph.D. degree in Biochemistry in 1997. He has authored and co-authored greater than 100 publications, patents, and reports in structural biology and biomaterials related research. His current research interests are focused on various aspects of biofuels-related work including applying neutron scattering techniques to develop efficient biomass pretreatment strategies and the structural properties of enzymes involved in cellulose synthesis in plants.



Arthur J. Ragauskas held the first Fulbright Chair in Alternative Energy and is a Fellow of the American Association for the Advancement of Science, the International Academy of Wood Science and TAPPI. In 2014, he assumed a Governor's Chair for Biorefining based in University of Tennessee's Department of Chemical and Biomolecular Engineering, with a complementary appointment in the UT Institute of Agriculture's Department of Forestry, Wildlife, and Fisheries and serves in the US Energy and Environmental Sciences Directorate, Biosciences Division, at ORNL. His research program is directed at understanding and exploiting innovative sustainable bioresources to develop new and improved routes to biofuels, biopower, and bio-based materials and chemicals. His research program has been sponsored by the NSF, USDA, DOE, GA Traditional Industry Program, a consortium of industry partners, and several fellowship programs.

Jia Wang is an associate professor at Nanjing Forestry University (NJFU). He obtained his B.Sc. and M.Sc. degrees from Huazhong University of Science and Technology (HUST) and North China Electric Power University (NCEPU) in 2011 and 2014, respectively, and Ph.D. degree in Thermal Engineering at Southeast University (SEU) in 2019. Sponsored by the CSC, he conducted his research on plastics liquefaction in Dr. Ragauskas's group from 2017 to 2018, and now he is following postdoctoral training with Prof. Jianchun Jiang at the NJFU and the Institute of Chemical Industry of Forest Products, Chinese Academy of Forestry (ICIFP). His current research interests are mainly focused on biomass conversion and plastics upcycling. He has published more than 40 peer-reviewed articles.

Yanqin Wang was appointed as a full professor at East China University of Science and Technoly in 2004. She obtained her B.Sc. and M.Sc. degrees from Shandong University in 1987 and 1990, respectively, and her Ph.D. degree from Peking University in 1999. Thereafter, she undertook postdoctoral work at Bar-Ilan University (Israel, 1999–2000), Max-Planck Institute of Colloid and Interface Science (Germany, 2000–2001), and Max-Planck Institute of Coal Research (Germany, 2002–2044). Her research focuses on nanoporous materials and catalysis for biomass and waste plastic conversion. In recent years, her group has developed a series of highly efficient Nb-based catalysts for the valorization of biomass and aromatic plastics. She has published over 250 papers and owns 30 patents.



Frederik Wurm leads the Sustainable Polymer Chemistry group at the Universiteit Twente (UT, Enschede, The Netherlands), which designs materials with molecularly defined functions for degradable polymers, nanocarriers for agricultural or biomedical applications, and phosphorus-based polymers. A major recent focus has also been the polymer waste problem and polymer degradation in general. Frederik received his Ph.D. in 2009 at Johannes Gutenberg University of Mainz in Germany. After a two-year stay at EPFL in Switzerlab as a Humboldt fellow, he joined the Max Planck Institute for Polymer Research in Mainz and finished his habilitation in Macromolecular Chemistry in 2016. In August 2020, he was appointed as a full professor at UT. He has published more than 200 peer-reviewed articles and his research has received several awards, such as the Reimund Stadler Award of the German Chemical Society (2016), the Dozentenpreis des Fonds der Deutschen Chemischen Industrie (2017), and the Polymer Chemistry Lectureship (2019).

clam-shell packaging or in clothing fiber. High-density polyethylene (HDPE; denoted with recycling code #2) is the second most commonly recycled plastic (e.g., 10% and 10–15% of HDPE is recycled in the US and EU, respectively). The mechanical recycling of HDPE is similar to that of PET but it requires more rigorous devolatilization of food odors and other contaminants. However, only a small quantity of food-grade r-HDPE is currently marketed.

Alternatively, several companies burn waste plastics to generate heat and electricity, which recovers energy but does not constitute recycling. Other companies downcycle mixed plastic streams into construction materials or asphalt and claim that this is "recycling." However, true plastic recycling enables an end user to use a recycled plastic in the same application as the virgin plastics. Currently, there is no technology capable of recycling or upcycling plastic films into virgin plastic pellets. Furthermore, low-density polyethylene (LDPE; recycling code #4), polyvinyl chloride (PVC; recycling code #3), polypropylene (PP; recycling code #5), polystyrene (PS; recycling code #6), and multilayer plastic materials (recycling code #7) are not recycled, because the technology to recycle them does not exist or is too expensive. Other commonly available plastics found in waste streams include nylon, polycarbonate, and polylactic acid.

Another critical challenge to the recycling or upcycling of plastics is the removal of contaminants and additives acquired during plastic processing (e.g., colorants, antioxidants, plasticizers, foils, and paper) or from plastic packaging contents, such as those introduced by consumers (e.g., sugars and other foods). Dealing with plastic waste is a dirty business! In addition, plastics have a very low density and thus are difficult to collect and sort. Although efforts are underway to re-engineer packaging materials to mitigate some of these problems, even the most optimistic estimates predict that at least 50% of plastic waste streams will not be economically viable for recycling.

The problems described above show that society must develop economic approaches for the recycling or upcycling of multiple plastic materials to address the proliferation of plastic wastes. This Special Issue highlights recent advances in the field of waste plastics upcycling and explores the evolution of this field from a niche research area to a burgeoning mainstream research topic within the concept of the Circular Economy. The processing of waste plastic resources calls for a multidisciplinary approach involving innovative depolymerization chemistry, advances in catalyst science, novel biotechnology and analytical characterization capabilities, new approaches to separation science and waste management, and full economic analyses and lifecycle assessments. All of these topics will be featured in this Special Issue.

In closing, the guest editors would like to acknowledge all the authors, reviewers, and the editorial team of *ChemSusChem*, whose timely efforts have made it possible to produce this Special Issue. We hope these advances will seed further developments toward the upcycling and valorization of plastic waste.

Keywords: circular economy · heterogeneous catalysis · plastics · recycling · waste valorization

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