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Macromolecular Chemistry and Physics

The next 100 years of polymer science

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Abstract

The year 2020 marks the 100th anniversary of the first article on polymerization, published by Hermann Staudinger. It was Staudinger who realized that polymers consist of long chains of covalently linked building blocks. Polymers have had a tremendous impact on the society ever since this initial publication. People live in a world that is almost impossible to imagine without synthetic polymers. But what does the future hold for polymer science? In this article, the editors and advisory board of *Macromolecular Chemistry and Physics* reflect on this question.

Introduction

The year 2020 marks an important milestone for polymer science: 100 years since Hermann Staudinger published the first article on polymerization.[1] It was Staudinger who realized that polymers consist of long chains of covalently linked building blocks. His initial manifesto was met with skepticism and criticism and catalyzed a lively scientific discourse across many fields of science. It was Staudinger´s persistence and willingness to engage in scientific reasoning that turned this discourse into the beginning of the diverse field of macromolecular and supramolecular science that has since flourished and contributed life-changing innovations still impacting society today.

Right from the early days, Staudinger recognized the importance of having dedicated publishing media to stimulate scientific exchange within the growing macromolecular research community. As the editor of the *Journal für Praktische Chemie* (literally translated to "Journal of Practical Chemistry"), he formally extended the scope of the journal in 1940 to include articles on macromolecular chemistry and added the subheading ‘‘Unter Berücksichtigung der Makromolekularen Chemie’’ (“Considering Macromolecular Chemistry”) to the journal title.[2] Six years later, Staudinger founded the journal *Die Makromolekulare Chemie*, now known as *Macromolecular Chemistry and Physics*, dedicated exclusively to the publication of new insights in the field of polymer science.

It is, therefore, with the greatest pleasure and honor that the Editors and the Members of the Advisory Board of *Macromolecular Chemistry and Physics* celebrate the 100th anniversary of Staudinger’s first paper on polymerization.

Macromolecular Chemistry and Physics has always maintained a friendly and lively home for the polymer scientific community, remaining open to new ideas, even those attracting public skepticism and especially an open discourse. We are convinced that only such an informed dialogue will result in new directions for the field of polymer science as well as for our society, especially in a time where the widespread use of polymers is increasingly questioned and a rethinking of established applications, with the associated necessary technological changes, will be needed. To celebrate the 100th anniversary, the Editors and Advisory Board Members of *Macromolecular Chemistry and Physics* have, therefore, decided to share their views of the future of polymer science. This paper is a summary of our lively exchange.

We initiated the discussion by asking ourselves about the most important topics of the field in the future, from both the viewpoints of scientific merits and societal benefits. Based on the responses received, three top areas were identified: new properties and applications, new synthetic methods, and sustainability. Almost half of the Advisory Board indicated that the development and discovery of polymers with new properties and applications will be the one of the most important topics of the future. Polymers for a sustainable and circular economy ranked second as a topic to be addressed, consistent with the current public concern on the impact of plastics on the environment and climate change. Discovery of new synthetic methods was deemed as very important by several Board Members. As explained by Patrick Théato, "while this [result] may come as a surprise to the reader, it represents a recent trend in polymer science: to drift away from being only a fundamental discipline in itself and reach out into other disciplines, i.e. being a truly interdisciplinary science, ranging from applications to societal demands". "Nevertheless," Sebastian Seiffert adds, "the polymer science community should be aware of not becoming a mere auxiliary science of other disciplines during its current interdisciplinary merger, but instead retain its own basis. In other words, as expressed already by Chi Wu in 2013, 'it should be […] alarming if most polymer researchers are driven into other fields by factors such as funding, fashion, impact factors, and publications'."

In the following sections, the three critical areas identified by the Advisory Board of *Macromolecular Chemistry and Physics* are elaborated in more detail.

New synthetic methods

Polymers are omnipresent in nature: proteins, polysaccharides and DNA are macromolecules. Their use as materials -- what the layperson would refer to as plastics -- has been known practically from the beginning of technology, as glues and resins to sealing applications, but also, for example, in the form of Galalith, an artificial horn-like material made from milk proteins. Yet, the rational development of polymers, as we know and use them today, was made possible only through Staudinger's seminal work of understanding the very nature of macromolecules and their synthesis 100 years ago. Starting from small molecules, so-called monomers, and growing them into large macromolecular chains has since become the hallmark of synthetic polymer chemistry. For a very long time, research in the field of polymer science was guided by the thought that the impact of polymers on our daily lives could be grown through the development of new types of polymers made from new monomers and by new polymerization methods. On the contrary, it turned out that the vast majority of the materials we use today are dominated by a small group of chemically rather simple "commodity" polymers such as polyolefins, polyesters, polyamides, vinyl polymers, styrenics, and acrylics – polymers that are almost as old as Staudinger's pioneering work. That being said, the current commodities are in fact new

polymers, only the monomers are “old”. Superior performance have been attained through better control over molecular weight, chain topology, sequence, and polymer architecture, or “simply” with improved tacticity (stereochemistry), all relating the molecular design to the control of thermal, mechanical, and other vital properties.

Of course, polymer synthesis is also tightly connected to the other two critical topics identified, i.e., the development of new pathways to produce polymers with eco-friendlier and more sustainable processes and to create polymers with new desired properties for advanced applications. But is it really that simple?

Nicola Tirelli states: “Finding new polymers with the real-life potential of the likes of polyethylene, polyamides or polylactide is *per se* an enormously challenging task. It becomes nearly impossible when factoring the constraints that modern societies use to manage innovation: increasingly accurate documentation, privacy and identity protection, ever stricter health and safety regulations, forecast and minimization of environmental impact, reduction both in energy consumption (carbon footprint) and in the cost of individual products. Yet, rather than focusing on the constraints themselves, it may be more feasible to address their underpinning concepts, such as the integration of a high amount of information in a product.”

Thus, from a synthetic point of view, polymer chemistry now seeks to enable polymerization of old momomers towards polymers with “new” properties addressing all the challenges of the 21st century. Essential parts of the solution to this problem are the tools that polymer chemistry offers: the actual reactions and an understanding of their mechanisms. While “one is tempted to consider modern synthetic polymer chemistry a mature field with the majority of all relevant reactions been developed in the last century […], a short glance on recent developments in synthetic polymer chemistry reveals that this is simply not true” states Michael R. Buchmeiser. A good example is the field of controlled polymerizations, polymerization reactions that behave “ideally” and allow us to synthesize highly defined but also structurally much more complex macromolecular architectures. The early efforts in living anionic polymerization created a new understanding on how we can control polymerization reactions and, thus, the polymers we obtain or what we call molecular engineering today. Timothy E. Long points to the field´s further development: “This then sparked initial efforts in nitroxide mediated polymerization, advancing to discoveries in atom transfer radical polymerization and reversible addition-fragmentation chain transfer (RAFT) polymerization methods, where an expanded library of monomers is now amenable to tailored polymer sequence and architecture. Also, the design of metallocene catalysts changed the culture of polymer synthesis in the early 1990s when scientists naively thought that we had all the polymers that were needed. Discovery of the metallocene catalyst quickly convinced the community, especially the commodity polymer community, that there are many more macromolecular architectures to be discovered.”

Michael R. Buchmeiser continues with another example: “So, when risking a forecast on the most important new synthetic methods in polymer science, metal ion- (Lewis acid) assisted dual or, even better, metal-free regio- and maybe stereoselective organocatalysis using (protected) *N*-heterocyclic carbenes (NHCs) and *N*-heterocyclic olefins (NHOs), respectively, will most probably gain further importance. This way, e.g., so far inaccessible high-molecular-weight polyethers ($M_n > 10^6$ g/mol) have already become accessible.”

Thus, finding new polymerization methods remains an essential challenge for synthetic polymer chemists. Patrick Théato names a few of them: “Identified areas within new synthetic methods are

precision synthesis, orthogonal chemistry, new polymerization methodologies, kinetics, and digital material design. Precision macromolecular synthesis has recently witnessed an impressive development and achieved synthetic control of chemical functionality and stereoselectivity. The use of multicomponent reactions has led to an easy increase in molecular complexity in polymer synthesis. The number of polymerization methodologies is also steadily increasing, while careful kinetic investigations enable broad academic and industrial application." He also points out that today, synthesis goes beyond a flask and person in a lab coat: "In an information-driven age, digitalization of synthesis is becoming more important and puts automated polymer synthesis to the next level, especially when combined with machine learning algorithms. Together this can open the avenue of new synthetic method developments."

Besides the use of digital methods to drive polymer synthesis, polymers that enable digital data storage within the macromolecular chain itself are also emerging. This critical feature is becoming accessible through continuously improving precision polymer synthesis methods, which are developed to ultimately reach perfect sequence-defined incorporation of monomers in macromolecular chains, inspired by Nature's precision of DNA or peptides. Jean-François Lutz states: "Indeed, it is now possible to synthesize a wide variety of sequence-defined oligomers. However, such syntheses require multi-step protocols and, in most cases, remain tedious, time-consuming and limited to small scales. Although such precision macromolecules may find application in domains in which high production costs can be tolerated (*e.g.* anti-counterfeiting technologies, drug delivery) and in which small amounts of matter are usually needed, progress still needs to be made." Michael A. R. Meier adds: "If such sequence-defined macromolecules are to contribute to improving our fundamental understanding of polymers, for instance by developing quantitative structure property/activity relationships, the highest possible molecular precision is to be realized". This still-young field of polymer synthesis also shows the ever-so-important tension in research between developing fundamentally new methods without knowing what useful materials they might give access to and creating new materials with specific functions by applying the available toolbox. Laura Hartmann continues the discussion: "Having the opportunity to install high levels of structural control and complexity will help us to bridge the gap between synthetic and biopolymers further and teach us where precision is truly required, and its lack might indeed have been a limitation so far." New opportunities also arise from the structural order made possible through macromolecular precision: "Beyond primary structure control, the self-organization of precision polymers (*i.e.* formation of precise single-chain folds or multi-chain assemblies) is an emerging subject that may lead to the creation of a new generation of materials" says Giancarlo Galli. "The continually developing and expanding field of polymer single-chain nano-assemblies is inspired by the concept of mimicking naturally folded biomacromolecules that can accomplish complex functions related to their three-dimensional orderly organization. It is expected that the selective self-folding, assembly, and sorting of designed and controlled (co)polymers will shortly become major tools to build up globular soft nanoobjects with specialized activities within their functional compartments. […] Applications of such artificial single-chain nanostructures are at present less obvious; nevertheless, the benefits would be uncountable for exploitation in the next-generation nanotechnologies, e.g. for nanoreactors with unique atom economy in green chemistry, for tagged molecular systems with enhanced efficiency in sensing and probing, for highly specialized bioconjugates and selective vectors of contrast agents in biology and medicine." Ulrich S. Schubert adds: "Personalized nanomedicine, with targeted delivery of multiple drugs to the infected tissues and organs, can profit tremendously from molecularly highly defined smart and robust nanocarriers."

Indeed, polymer synthesis is tightly intertwined with polymer characterization and engineering, highlighting that polymer science, in contrast to the traditional separation of research domains, has been, since its inception, an intrinsically interdisciplinary field. Nowadays, and certainly even more so in the future, this interdisciplinary aspect of polymer science reaches even further, for example with the design of polymers that interact with biological systems in a controlled way, such as polymers that serve as matrices for cells and tissues. Wolfgang H. Binder points out that "not only is a detailed knowledge of nanoscopic domains, individual polymer-chain dynamics, phase structures, and reorganization abilities required but also the necessity to control attachment sites in the 3D environment. Controlled / living polymerization, combined with physical methodologies and novel nanoscopic 3D-printing methods, will have to be developed to use polymers as a triggered, dynamic and adaptive scaffold for cell attachments. A specific focus in polymer science will, therefore, be directed toward the control of dynamic, supramolecular bonds, able to adapt, relax, and react upon changes in the surrounding cell-matrices during differentiation, thus providing the proper environment for cell growth."

Yet, to master the challenges of the future, the polymer community encourages the coming generations of scientists to engage in solving the known and foreseen problems. As an interdisciplinary science, bright minds of all disciplines are invited on this journey of polymer synthesis. As João B.P. Soares, who "disliked polymers" before he started his doctoral studies, told this story: "It was the realization that what happens in the polymerization reactor becomes imprinted in the polymer microstructure, which in turn determines polymer properties, in addition to the fact that all of these steps could be described with elegant mathematical equations, that made me passionate about this field." Let this passion drive the future, because "you can't fake passion" as Barbara A. Corcoran said, which nowadays is truer than ever.

Advanced Properties and Functions

The field of polymer science quickly expanded from developing a fundamental understanding and knowledge in (controlled) synthesis and structure analysis to creating materials that offer increasingly advanced properties and functions. A large body of science and knowledge acquired by our community is driven by curiosity, creativity, and the interest to create materials with tailored properties. Indeed, the discovery of so-far unknown or inaccessible features and functions as well as the new chemical structure of polymers, is an eternal topic for polymer researchers. Furthermore, the uniqueness of polymer properties necessitates the discovery of novel analytical tools, ones that are able to reveal the most complex viscoelastic properties commonly found in polymers.

We already live in a world that is impossible to imagine without synthetic polymers or, more precisely, without their functions being expressed in our daily lives. Indeed, as Andreas Lendlein states: "The broad success of polymers in consumer products (e.g. textiles, cosmetics, healthcare products), in agriculture, as packaging materials, as membranes or in construction / building materials is substantially based on their versatility in providing the specifically required functions." Brigitte Voit puts it in one sentence: "If we think of polymers in everyday life, we think about their function." More generally, society does not pay for a glass transition temperature, but they pay for performance where the glass transition temperature dictates applications, from adhesion and surface properties to gas barrier properties to tear resistance. Of course, this is valid for all application-related properties.

Thus, it is not surprising that, when asked during an initial exchange preparing this paper, most of the Board Members considered advanced properties and functions as key aspects of ongoing and future polymer research. Three significant opportunities were highlighted: First, enhancing the properties and functions of state-of-the-art polymers to a higher level (i.e. better performance); second, applying the currently known properties and functions of polymers to explore their applications in new fields, especially high-tech areas as well as potential life in space, outside our planet; third, identifying and creating properties and functions that are classically not covered by "conventional polymers", *i.e.* extreme or unknown properties and functions, like the discovery of intrinsically conducting polymers. Indeed, this paradigm-changing work of Alan J. Heeger, Alan G. MacDiarmid, and Hideki Shirakawa, who were awarded the Nobel Prize in Chemistry in 2000, represents a notable example of new properties and functionalities of polymers that opened up an entirely new field and led to polymer research and technological applications in energy and electronics.

Generally, "none of the high-tech devices we use every day would be possible without specialty polymer concepts and materials (e.g., photoresists for microchip technology). This trend will continue: Highly specialized polymers with specific functionality will be the "enabling components" for many key technologies" states Holger Frey. Brigitte Voit points out that "[the] increasing digitalization of our daily life (automatization, transport, smart house, smart city, industrial processes (Industry 4.0), product safety, augmented medicine and so on) needs a huge amount of low-cost tagging and (wireless) communication, which are only possible with printable electronics and smart systems involving polymers as key functional components as well as for packaging and bulk materials. Similarly, functional polymer architectures and systems will have a significant impact on personalized medicine, including diagnostics, therapy and medical technology." As a further step, digitalization will affect the way we develop polymers, as Klaus Müllen envisions: "Beyond the classical issues of how to make polymers and how to get rid of them, artificial intelligence and machine learning will deeply influence the whole protocols by which we do research, also in polymer science. Non-conventional issues like organic lasing, spintronics, sensing, computing, but also theranostics and gene transfection, will need the adequate polymers. The decline of the image of polymer science will not continue; there will be a definite revival."

Especially when talking about the properties of polymers in this continued revival, we need to think about polymer characterization. Parallel to the development of advanced properties and functions of polymers, the development of advanced analytical instruments and characterization methods to identify and monitor these properties and functions should be fostered. "The determination of polymer properties will more closely align with emerging applications in the future, wherein polymer characterization tools will be tailored to be more predictive of performance" states Timothy E. Long. He continues, "recent advances in additive manufacturing (3D printing) have catalyzed a resurgence in rheological and molar mass analysis, as these advanced manufacturing platforms challenge polymer scientists to design for future processing tools." While emerging 3D printing techniques certainly require polymer characterization, this also brings us back to the synthesis of new polymers. As Christopher Barner-Kowollik points out, "the design of advanced inks for 3D printing from the macro to the nanoscale is of critical importance. Estimates say that, by 2030, 10% of all consumer products will be 3D printed. In particular, functional photoresists that allow subdiffraction printing via 3D laser lithography can be envisaged, ultimately enabling printing of only nanometer wide arrays of polymers with enormous implications for electronic device fabrication."

Such precision is not only envisioned for 3D printing, but "also the measurement of polymers at [the] micro, nano, and molecular level should be further improved. For example, measurements of porosity at the nanometer and micrometer scale[s] will accelerate discoveries in energy generation and storage, where porosity and transport coupled with morphological analysis have created unprecedented performance" writes Timothy E. Long. "The development of in-situ measurement tools where emerging manufacturing platforms require a real-time assessment of the molecular structure, physical properties, and morphological development will continue to be critical for the future of polymer design. Testing materials performance during operation will be critical as we ask polymers to behave more dynamically in the future. Technologies continue to spring from polymeric materials, and this will accelerate as geometric designs at the micrometer dimension continue to demonstrate improved performance."

This leads to the daring question, what new technologies do we envision to be enabled by polymers of the future? Or, asked the other way around, what polymers do we think are needed to inspire new technologies? Several new fields where the functions of a polymer are expected to be decisive have been discussed in the polymer community. Functions, such as on-demand (rapid) biodegradation, programmability, re-shapeability, adaptivity, and self-healing, have been in focus to open new application fields recently. "Polymers are needed that respond to all kinds of stimuli, not only light, and also [to] develop a memory of the treatment and interact with the stimulus itself", says Klaus Müllen, and "while most stimuli-responsive polymers investigated so far were intended to respond to one stimulus with one specific property change, it is also possible to create multi-responsive polymers that respond to different stimuli with more than one response. Similar to living organisms, which can respond to different environmental cues as needed, multi-responsive polymers promise access to complex response behaviors, including functions that are based on emergent behavior", points out Christoph Weder. However, "despite the rapid progress in the development of new stimuli-responsive polymers, there are still many challenges to be overcome to apply them in real-world situations" comments Ben Zhong Tang, echoed by Christoph Weder: "As possibilities to tailor polymers with adaptive properties are endless, and the technological impact that these materials may have is immense, it is probably safe to assume that the development of multi-responsive polymer systems and their translation into advanced technologies will be important aspects of the field for decades to come."

Thus, one future feature of the stimuli-responsive function of polymers is certainly the mentioned multi-stimuli-responsiveness. Assembling multi-responsiveness in a relevant, meaningful way will further develop their functions, or as Nicola Tirelli states, "[a relevant topic for the future is] the possibility to inter-relate multiple stimuli in an unified, complex response; they can be linked in succession as in a cascade mechanism (the effect of a first stimulus, i.e. the first response, is modified by a second stimulus, and so on), or with a contemporaneous entrance as in a logic gate system (a response is obtained only by appropriately combining different stimuli). The result is the possibility to obtain a selective, "clean" response also for "soft", low-intensity stimuli that may well be below thermal noise. Thereby enabling extremely precise interventions and advancing the emergence of a "peripheral and autonomous intelligence" from this complex behavior is an avenue not to be underplayed. The areas of application would not only be diagnostics, pharma and biomaterials, but also optoelectronics, etc." When thinking about combining different functions, we can even imagine "autonomous systems, e.g. soft robots […] which could be realized by integrating multiple functions including energy generation and harvesting (e.g. catalysis, motion, photovoltaic, osmosis), energy

storage (batteries, mechanical storage, thermal energy), sensory functions, and the capability of motion", as Andreas Lendlein points out.

Finally, we think about new functions by generating entirely new polymers and materials: "New advanced polymer materials will show properties that are classically only found in the materials spaces of, e.g., metals or ceramics, and this will be achieved by combining control over order/disorder (locally and globally) in sophisticated polymer combinations that are nano-/micostructured", states Miriam M. Unterlass. Polymers of extreme properties and functions or polymers serving in extreme environments are expected to carry properties and display functions that are not often or never seen in traditional polymers. Jiayin Yuan envisions: "New properties and functions that can break the traditional restriction and image of polymeric materials, such as ionic polymers with ultra-low glass transition temperature (approaching -100 °C) that resemble liquids at room temperature, ultrahigh-temperature stable polymers (400-500 °C), ultrahigh ion-conductive polymers, and ultratough/ultrasoft polymers. Innovative polymer structure designs at molecular and nanoscopic scales will be the key to break the property and application limit of polymers."

We can even think beyond our planet, as Jiayin Juan suggests: "The new wave of marching to Mars has started, and this time human beings will face a completely new event, living collectively on another planet and in space. Life self-sustaining systems are required, and polymers should join this challenge. While most polymers that we will use in space colonies are fulfilling their functions similar to the earth environment, there are also needs [for] polymers that can hold their properties and functions at ultrahigh vacuum (space vacuum) and ultralow temperature (space temperature)."

Functions of polymers will continue to evolve to reflect and match the urgent need of each technological era. Automation, digitalization, new mobility concepts, advance in biomedicine, as well as space exploration are only some examples [that] illustrate the rapidly evolving times we live in. Because of its versatility, polymer research can substantially contribute and, in selective cases, actively lead these developments by generating and enabling functions that overcome existing limitations or pave the way to entirely new solutions. Indeed, the third identified topic of significant concern and future impact, sustainability, now picks up aspects of synthesis and functions of polymers to address questions of polymer research - past, present, and future.

Sustainability

The macromolecular science and engineering community has demonstrated the ability to deliver sustainable technologies to society, from polylactides for biodegradation and drug delivery to, most recently, bisphenol-A-free polymers for food packaging. This dedication to sustainability will continue as society continues to demand more sustainable solutions. For instance, new sustainable technologies to improve agriculture, energy generation, and consumption as well as access to pure water are in high demand. Thus, polymeric membranes with nanoscale morphology to optimize selective transport of ions and water, packaging materials with a stimuli-responsive feature to allow triggered depolymerization, and more environmentally friendly polymers for the delivery of fertilizers in agriculture exemplify potential future directions for research. As the global population approaches 10 billion, macromolecular science and engineering has to deliver sustainable solutions to meet rapidly emerging grand global challenges.

The public awareness of climate change and, more generally, sustainability issues with their ever more visible consequences, as drastically visualized by the Earth Overshoot Day (the calculated illustrative calendar date, on which humanity's resource consumption for the year exceeds Earth's capacity to regenerate such resources the same year),[3] illustrates the significance of considering sustainability in all aspects of daily life and of course also in materials science and engineering. Timely actions to prevent further damage over the complete life cycle of products are necessary and require reconsidering current methods of polymer production, assessing its consumption as well as the fate of the materials at the end of their use. Humankind has to re-learn how to foster "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", the definition of sustainable development according to the Brundtland Report *"Our common future"*.[4] This might be regarded as an arduous task, as drastic measures are inevitable if we want to keep our planet inhabitable for humankind, but also offer enormous opportunities for new academic discoveries as well as economic success. A recent industrially successful example is the introduction of "bio" polyethylene derived from sugarcane. However, it is not sure if this is a more sustainable solution since the global warming potential (GWP) highly depends on the not fully established contribution of a possible land use change. Depending on different scenarios, GWP might decrease or increase compared to fossil resource-derived low-density polyethylene. Changing the raw material from sugarcane to second generation bioethanol, derived from cellulosic waste materials, might be the key to a sustainable solution.

As polymers are undoubtedly a vast output of the chemical industry and polymers have raised significant and increased environmental concerns, it is very worthwhile to consider the development of "sustainable polymer chemistry" as a task of our scientific community. In other words, as alluded to by Chuanbing Tang: "It was never the intention of the pioneers [of polymer science], that polymers could bring much more complicated consequence for the evolution of society, particularly at the cost of environment and climate change. The development of greener and sustainable polymers is a consciousness that is widely accepted. Projecting the next century of polymer science is a tough task. One ought to place sustainable polymers among the top priority. We should also trace back to the initial excitements as to why polymers. From there, we hope to address new challenges."

Indeed, polymer science is expected to provide sustainable solutions addressing grand challenges related to climate change, energy, health, quality of life, food, and clean water. These ambitious aims can be achieved by pursuing a highly interdisciplinary approach along with development and production chains. As pointed out by Richard Hoogenboom as well as by several other Board Members, technological innovations are required on polymer design and efficient synthesis, including green synthetic routes and processing methods (low energy consumption, fewer organic solvents, and less impact on the environment). Krzysztof Matyjaszewski, for instance, states that "more environmental friendly conditions and catalytic systems more tolerant to air and moisture" for polymer synthesis are certainly necessary. Significant contributions to sustainability are anticipated from the systematic implementation of a product-oriented life-cycle management by reduction of the carbon footprint associated with polymer-based products and by conserving natural resources.

"The mitigation of environmental costs and damage associated with the synthesis, usage and post-life-cycle deposition of polymers requires critical innovations in the realm of sustainable polymer lifetime cycles. Relevant research topics become apparent when following the fate of polymer products. These comprise, inter alia, disassembly technologies, recycling methods, and plastic waste management, including chemical identification, storage, polymer separation, and degradation by combustion or

composting. Traceable product stewardship is especially required for commodity polymers to overcome the "locked-in" status quo" stated Christopher Barner-Kowollik. This exciting approach can be realized by sequence-defined macromolecules and is one of the many examples of how sustainable development can foster innovations in polymer science. More obvious are end-of-life considerations with options ranging from land-fill via (chemical or physical) recycling or incineration to (bio)degradation. Miriam M. Unterlass adds, "we need to be able to recycle advanced polymer materials when the device they are part of fails irreversibly", but this will not always be possible in a sustainable and economically feasible fashion. Consumer education and the change of current user practices can substantially contribute to reducing the amount of plastics released to the environment. Finally, properly functioning waste disposal systems are required (including incineration with energy recovery as a sustainable option). "Biodegradable polymers have never been considered so seriously as they are nowadays, driven strongly by the microplastic problems in the soil and ocean," said Jiayin Yuan. However, whereas biodegradation might be able to reduce microplastics in the environment, the degradation products need to be carefully evaluated in terms of their environmental impact. Equally important, biodegradation versus recycling (even as energy source) needs to be delicately balanced.

The use of renewables for the synthesis of polymeric materials has to be further developed and offers the potential, at least in principle, of a carbon-neutral replacement of the currently used and petroleum-derived plastic materials. In terms of sustainability, this provides a significant reduction of CO_2 emissions and pays attention to the depleting fossil resources. This concept for starting materials is straightforward to implement if the necessary investments are made, as our planet produces 10^{11} metric tons of biomass each year, of which only ~3.5% are used by humankind, including all food, feed, and other applications.[5] An additional benefit of using renewables is the global distribution of different kinds of biomass, minimizing resource-related politics. However, increasing the portion of starting materials from renewable resources demands carefully balancing pros and cons. "Renewability is not enough and an environmental burden shifting needs to be strictly avoided," states Michael A. R. Meier. A current example is the discussion about wood as a natural resource offering cellulose, hemicelluloses, lignin, terpenes, and fatty acids as versatile polymer chemistry feedstocks. The restoration of forested land at a global scale is discussed to show great potential in capturing atmospheric carbon and, in this way, mitigate climate change.

As mentioned earlier, the immense success of polymers in consumer products is substantially based on their versatility in providing the specifically required functions. This strength will also determine their future potential concerning sustainability. Brent S. Sumerlin reflects: "In many ways, it is ironic that many of the challenges of sustainability faced by polymer scientists of today arise from the polymer scientists of yesterday doing their job too well. Our predecessors developed innovative routes to materials that are, perhaps, too robust, last too long, and come from resources that are too inexpensive. One of the key responsibilities of the polymer community in the second century is to continue innovating through creative chemistry while not forgetting the lessons of the past."

The success of sustainable polymer chemistry will strongly rely on further scientific advances in the field, but even more so on the willingness of society to change for the better. It is critical for polymer scientists to initiate and lead these discussions.

Conclusions

We asked about the future of polymer science, but we should end our perspective with also looking at where we are today and what challenges we currently face. Polymer science has always been in need of a great variety of competencies, from synthesis to physics, engineering, and theory, from physical to biological and medicinal properties as well as from fundamental to applied topics. While truly representing the enormous bandwidth of polymer science contributions, one recent challenge associated with this increasing interdisciplinarity is that more and more polymer-related topics appear in new scientific journals not directly associated with the polymer field. In particular at times, where science is increasingly judged by bibliometric data and impact factors, this easily leads to a dilution effect and to a decrease in the recognition of contributions of polymer science as a field. As a community, we need to address this challenge and find mechanisms to compensate for this asymmetry.

Besides its interdisciplinarity, the polymer community has long been famous and even been envied by other chemical societies for bridging academia with industry. We are not sure whether the long-term accord between both sides still exists, but we firmly believe that fundamental research can always be a major stimulus for industry, as we have witnessed ever since Staudinger's early days of polymer science. Stephen ZD Cheng envisions: "today it is even more critical to emphasize how important [it is] to build up close relationships between academic findings and industrial productions. This relationship must be further strengthened rather [than] weakenes."

To us, a future world without polymers is unthinkable: They are making the difference in, e.g., heat insulation, fibers and apparel, mobility, construction materials, microelectronics, green energy generation, soil fertility, food packaging and safety, the search for new antibiotics, regenerative medicine, ink-jet based decentral manufacturing, lightweight composite materials for windmills and e-mobility, up to exploration of space, just to name a few from a sheer endless list. This societal "market pool" will keep us busy at least for a foreseeable future, and polymer industry and the related job market will change but continue to be productive and full of opportunities.

It is reassuring to see that the vector carrying polymer science from the early days of Staudinger's hypothesis to its current status of a blooming, industrially highly relevant, enabling field is unbroken. It is, however, our responsibility to continue to be the ones shaping the future of polymer science. While the challenges Herrmann Staudinger faced with the notion of macromolecular structures are legendary, they also provide us with a role model for scientific rigor. We believe such tenacity and enthusiasm will be necessary to address the above-discussed challenges of the present and future, to foster our field and let polymer science continue to flourish over the next century. It is up to us to invest in our field and to continue to communicate, and to take care of our diverse, polyglot, and interdisciplinary field. Reading and writing publications in well-managed journals is one crucial aspect, and we are happy to be a part of it!

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