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Bioinspired Green Science and Technology Symposium in NYC

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In observance of Earth Day 2022 and the looming, urgent need to fight climate change and biodiversity loss, scientists gathered in New York City and online to share the latest technological and design breakthroughs that hold promise for the environment and human health. The two-day symposium brought together environmental scientists, materials scientists, chemists, biologists, polymer chemists, chemical engineers, and biotechnologists from academia, government labs, and industry to discuss aspects relevant to the translation of laboratory research concepts to the real world by addressing scalability, circularity, and economic viability. The discussions also included consideration of potential unintended consequences of these promising technical innovations. Such a holistic, systems-level consideration of bioinspired technologies was considered critical to successful implementation of the exciting new developments in green-tech that were shared during our Bioinspired Green (BIG) Science and Technology Symposium co-organized by the City University of New York (CUNY), New York University, and Columbia University (Figure 1).

During the two days, we focused on four technical thematic areas that are at the forefront of sustainable technology development, namely (1) bioinspired advanced materials and systems; (2) bio-derived and biodegradable materials; (3) bio-manufacture, biodesign, and biocatalysis; and (4) bioremediation upcycling and energy harvesting. Each session was chaired by faculty working in BIG science with three or four scientists presenting their recent scientific and technological advances, followed by a "BIG picture" perspective by faculty of the Environmental Science Initiative at the CUNY Advanced Science Research Center (ASRC). The sessions concluded with a reflective panel discussion with all of the speakers in the session. Overall, the BIG symposium reflected on the benefits and promises of new bioinspired technology, as well as further steps in considering the unintended negative consequences of this technology in the living world as a collective, holistic ecosystem. The following narrative provides a brief account, highlights, and insights from each session.

Bioinspired advanced materials and systems, chaired by Rein Ulijn

Nature's materials are often far more sophisticated than human-made materials, and therefore they serve as inspiration for next-generation green materials and systems. This session focused on the re-purposing and redesign of natural materials that can be produced by plants or microbes.

Ruth Stark from the City College of New York discussed how staple crops such as potato tubers and tomato fruits can serve as inspiration for barrier materials and packaging materials. These crops have versatile protective skins that mitigate environmental stresses from water loss, bruising, UV radiation, and

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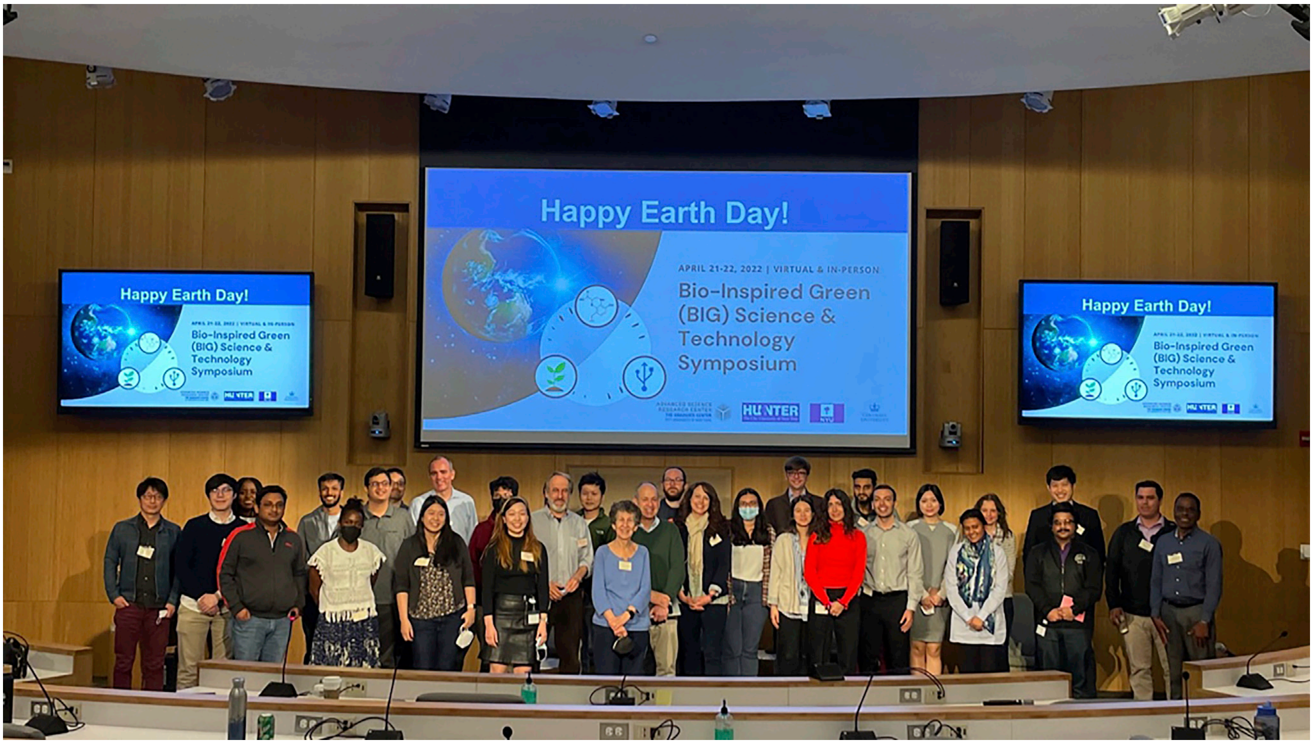

Figure 1. Delegates of the BIG Science and Technology Symposium on Earth Day 2022 at CUNY Advanced Science Research Center

microbial pathogens. Stark discussed how her team was able to fabricate mechanically robust polymeric films that resist water uptake and transmission.[1] Together, these plant-inspired composite materials lay the groundwork for sustainable food packaging that can avoid the deleterious environmental impacts of petroleum-based plastics.

Norma Alcantar from the University of South Florida shared her work on the use of plant materials as sustainable functional materials.[2] In particular, cutin, the waxy protective coating on plants based on polymerized fatty acids, and mucilage, a mix of polysaccharides extracted from prickly pear cactus plants, were investigated. It was shown that cutin can be engineered for specialty food packaging offering UV protection and anti-microbial properties. Cactus-derived mucilage proved a promising and scalable solution for the removal of impurities from water. In particular, the materials have been explored in clean-up of oil spills (including work at the Deepwater Horizon disaster) and in providing locally accessible means for water contamination, exemplified by Alcantar's work after the 2010 earthquake in Haiti, where mucilage-derived materials were used to purify water.

Neel Joshi from Northeastern University discussed his lab's work on microbial production of so-called living materials, inspired by the mechanisms that biological systems use to build structure—cell-directed bottom-up processes that involve self-reproduction as well as biopolymer synthesis and orientation into hierarchical structural morphologies with tailored material properties. They specifically base their materials on a biosynthetic pathway found in bacteria that enables the production of a network of extracellular protein fibers.[3] Joshi showed that bacterial production of his living materials can, in principle, be scaled by leveraging existing types of infrastructure for recombinant protein production in order to fabricate materials (bioplastics, fibers, etc.) in a streamlined manner—directly from microbial biomass with little need for purification.

Reflection: Switch in paradigm—working with biology, not against it

Plant-based materials such as those studied by Alcantar and Stark use feedstocks that are, in principle, fully renewable. It is estimated that plant-derived bioplastics could replace as much as 90% of their persistent and hazardous petroleum-based homologs. Nonetheless, environmental scientists are cognizant of how their scale-up could involve intensified farming, potentially competing with food production and requiring fertilizers that augment the production of greenhouse gases. In addition, scaling up farming of particular crops could also threaten biodiversity and lead to slower biodegradation unless excess water and oxygen are present. With enough foresight, these potential environmental concerns could be addressed by broadening the choice of crops developed for bioplastic applications and adjusting landfill management to promote timely degradation of these materials. Therefore, as summarized by Andrew Reinmann from the Environmental Science Initiative at CUNY ASRC, we must learn from (be bio-informed by) nature and focus on the nuances of achieving scaling on the material production by applying nature's teachings to technological innovation.

Bioderived and biodegradable materials, chaired by Mandë Holford

Session two focused on bioderived and biodegradable materials and systems, with a particular focus on engineering insights gained from millions of years of aquatic evolution that can serve as inspiration to advance the development of new drugs, eco-friendly cosmetics, to purify water. This session showcased the power of interdisciplinary skills and expertise for tackling complex systems, mining them for pathways that produce valuable molecules, and elucidating mechanisms of action.

Leila Deravi from Northeastern University started the session by describing how design solutions inspired by aquatic life forms can serve as a platform for creating sustainable alternatives to consumer product goods in need of new materials. She specifically highlighted her group's work on cephalopods (cuttlefish, octopus, and squid) as one model system that has inspired the creation of a new class of adaptive materials. Current and ongoing work from her team include the use of chemically synthesized pigments that were initially found in squid skin in paints, cosmetics, and displays/sensors.[4] While she noted that the materials generated in the lab still have a long way to go before becoming fully sustainable, she discussed how recent advancements in biosynthetic manufacturing and controls are enabling fast progress toward this long-term vision.

Bradley Moore's lab at UC San Diego is focused on the discovery of how marine organisms, from microbes to animals, construct their specialized molecules that empower their diverse lifestyles. Moore described how his group broadly applies this basic knowledge that links genomics and small-molecule chemistry to produce promising bioactive compounds, develop biocatalysts, and empower a deeper understanding of life's diverse chemistry.[5] Specifically, by reading and writing the genetic code of marine life, his team has identified novel enzymes that can be introduced in bacteria to enable the synthesis of biomolecules and developed several compounds that can be used to treat human diseases and disorders.

Julia Ortony from Massachusetts Institute of Technology investigates materials that undergo molecular self-assembly in water to create nanostructures with tuned dynamic and mechanical behavior for applications related to environmental sustainability and human health. In her talk, she described Kevlar-inspired aramid nanoribbons that are composed of small molecules and self-assemble in the presence of water to form remarkably stable structures with tensile strengths greater than those of steel. These materials are versatile and have been functionalized with lead-capturing moieties for use in water purification.[6]

Reflection: Riding the wave from beach to bench—inspirations from the sea

Dianne Greenfield, a biological oceanographer from the Environmental Science Initiative at CUNY ASRC, outlined some of the challenges and opportunities of taking inspiration from aquatic environments when considering future bio-derived technologies. Specifically, she discussed biomimicry through the lens of how the challenges of oceanic life (limiting light and nutrients, pressure, viscosity, predation, etc.) have influenced the evolutionary trajectory of aquatic organisms. By understanding these complex and often delicate adaptations, we can reproduce these strategies to help solve modern-day problems. She highlighted examples where humans have drawn ocean-inspired innovation from marine organisms such as the Arctic icefish, oysters, corals, mantis shrimp, cephalopods, and phytoplankton to develop technologies that enhance food storage, construction materials, materials science, and others. As we better understand nature's diverse solutions to environmental challenges, we envision a future in which biocatalysis and genome evolution will efficiently support the scalable production of biomolecules to support future challenges. In this way, we may not only address supply chain issues but also create new opportunities that take advantage of an expanded understanding of how to program the chemistry of life. The year 2030 is looming with increasing biodiversity loss during the Anthropocene. How this will affect our ability to learn from nature is of great concern. This session illustrated one method for mitigating this risk by pushing through barriers using transdisciplinary approaches.

Bio-manufacture, biodesign, and biocatalysis, chaired by George John

Session three was a concerted effort to bring experts from different fields to discuss the future directions in bio-manufacture, biodesign, and biocatalysis to accelerate future discoveries in a sustainable pathway, evoking the need of a circular bioeconomy design concept.[7]

Jon Dordick from Rensselaer Polytechnic Institute elegantly introduced how to adapt cues from nature to design biological molecules and endow them with unique structural and functional properties that enable new process technologies. By exploiting modular design, Dordick's research group has successfully developed a range of hybrid biomolecular species that consist of integrated biologic and abiotic components.

Corey Wilson from Georgia Tech made a seamless transition from modular technologies to developing synthetic biology tools that can systematically manage the dynamic activation, de-activation, and distribution of biosynthetic pathways—i.e., in a way that facilitates the facile optimization of titer, productivity, yield, and metabolic burden to enable biomanufacturing strategies and technologies.[8] The Wilson Lab at Georgia Tech aims to develop new synthetic biology tools that manage and regulate the activation and de-activation of discrete steps in a given metabolic route via engineered biological signal processing filters and related transcriptional programming (decision-making) technologies.

Nick Kotov from University of Michigan discussed the design of the next generation of high-complexity nanoscale materials, such as spiky colloids dubbed "hedgehog particles." Such spiky, functional biological structures include viruses, marine algae, dendritic cells, and pollen particles. They can be observed at multiple scales from nanoscale to macroscale, indicating the functional significance of such topology in the structural design of these biological materials and systems manifesting as enhanced dispersability in unfriendly media. The complexity of the different hedgehog particles can be enumerated using their graph theoretical description. The technological significance of bioinspired hedgehog particles made from metal oxides was demonstrated for synthesis of a large family of particles with chiral spikes for photonic coatings, and in particular, the application of the bioinspired particles enables order-of-magnitude reduction of the energy expenditures for cyclohexane oxidation.[9]

Reflection: Circular bio-economy—a not-so-distant future

Bioinspired composites and self-assembled nanoscale systems have greatly contributed to energy and sustainable technologies. The current venues for their rapid expansion are (1) incorporation of biomolecular engineering and (2) transition to scalable biomanufacturing. The resulting biomolecular assemblies can be environmentally benign compared to their alternatives. Future biomanufacturing will rely on systematic management of the rate of production, titer of biochemicals, and the overall energetic and mass efficiency of substrate to product conversion at large scale. Peter Groffman, an environmental scientist from CUNY ASRC, addressed problems such as the high cost of nanoscale components and environmentally unfriendly methods of synthesis of nanoparticles requiring expensive and toxic media, which necessitates further development of their synthesis in aqueous media with minimal toxicity and low cost.

Bioremediation, upcycling, and energy harvesting, chaired by Jin Kim Montclare

The closing session was focused on concepts of maximizing re-use of natural capital and materials, neutralizing investments of non-renewable feedstocks and energy, and minimizing waste.[7] The overall message was one of new scientific and technological advances to achieve these goals at a scale that provides meaningful benefits to society and the environment. Researchers borrow concepts from biology and apply them to chemistry and materials science to overcome bottlenecks in manufacturing, materials design, and plastic depolymerization efficiency, with the ultimate aim of meeting present and future demands for circularity and sustainability.

Xi Chen from CUNY ASRC discussed opportunities to capture or recover energy from existing large-scale natural and industrial processes like evaporation and water-cooling using so-called water-responsive materials. For example, peptidoglycan-based materials can reversibly and forcefully swell and shrink in response to humidity changes, and they exhibit greater energy and power densities than other materials commonly recognized for their mechanical and energetic properties. Recent proof-of-concept demonstrations show possible strategies for using these materials to perform engineering tasks powered by water evaporation.[10]

Chris DelRe from Harvard University spoke about the ability to increase the degradability of plastics by utilizing bio-inspired designs. For instance, it is now possible to embed enzymes inside of plastics and control the plastics' lifetime and degradation by-products by engineering the enzyme/polymer interactions at the molecular level. The embedded enzymes can be designed to selectively degrade the synthetic polymer from its chain ends, which avoids unwanted degradation during the plastic's lifetime and converts the plastic into useful chemical feedstocks in warm water or compost conditions at its end of life.[11]

Reflection: Forethoughts on organic versus bio-contaminants

Upcycling and harvesting energy from existing materials and biological, chemical, and physical processes offers significant opportunities to close the loop on our energy- and resource-intensive linear economy. The necessary scientific and technological advances to achieve these opportunities at a meaningful scale are challenged by bottlenecks in manufacturing, materials design, and depolymerization efficiency. Yet, as Brian Giebel from Environmental Science Initiative at CUNY ASRC reminds us, somehow nature and life has overcome many of the same limitations at a smaller scale and remains as a design model or blueprint for our success. Creating viable strategies to overcome big societal challenges requires complex collaborations across scientific fields, with cooperating efforts from biologists, chemists, engineers, and environmental scientists alike. While these challenges seem daunting, we must recall that nature has elegantly and repeatedly paved a path toward sustainability that can be followed and emulated to create grand solutions. More broadly, we need to develop approaches and protocols that systematically consider the following: (1) what are we releasing into the environment? (2) Where is it going to end up? (3) How is it going to interact with other contaminants? (4) How is it going to interact with other environmental components, e.g., soils and sediments or food chains?

Conclusions

The symposium topics hint at an ambitious vision of the future in which all human-made things and processes are biomimetic, bioinspired, bioderived, and fully biodegradable, from cosmetics ingredients to drinking straws and from batteries to plastic bags. Collective research excellence in biotechnology, nanoparticle synthesis, materials chemistry, polymer engineering, and environmental science has the power to create new technology for human and environmental health. Re-purposing "chemistry-of-life" building blocks, including inorganic nanostructures, and processes will facilitate the promise of a transition from a petroleum-based to a bio-based economy. However, this is not an easy task, and it requires integration across disciplines with a need to learn how to navigate and enumerate complexity of molecules, supramolecular assemblies, multiscale nanostructures, cells, organisms, and ecosystems. There have been significant developments toward these goals, as we learned in this symposium, including the development of new synthetic biology and bioengineering tools through genome mapping and editing and the introduction of the techniques of directed evolution and protein design to create better biocatalysts. In addition, insights into biomolecular folding and self-assembly of polydispersed inorganic nanoparticles are used to create materials and structures with designed functions that can be expressed by plants or bacterial cells at scale. Springboarding from examples of nature, supramolecular chemists and bioinspired nanotechnologists are increasingly adapting their materials and chemistry approaches by embracing aqueous systems and low-energy processes, and they are using reversible bonds to replace covalent bonds, yielding biodegradable materials. As with any new technology, there can be unintended consequences, especially if the new technology is considered in isolation.

It is clear that collaborative engagement of scientists from all fields, from environmental scientists to technology developers, is critical to help mitigate and foresee potential issues that might be detrimental. It was also recognized that policy makers have a significant role to play in the development of future science that impacts our planet and should be part of the discussion at our next BIG symposium. We hope to make the conference a recurring one around Earth Day as an annual check-in that helps our community take stock of progress and ensure that we hold each other accountable as we design and develop future bioinspired science that impacts our planet and society.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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