Engineering Biology for Climate & Sustainability: A Research Roadmap for a Cleaner Future

EXECUTIVE SUMMARY

Climate change poses dire threats to the health and well-being of Earth and its inhabitants. "Engineering Biology for Climate & Sustainability: A Research Roadmap for a Cleaner Future," released by the Engineering Biology Research Consortium (EBRC) in September 2022, is a technical assessment of opportunities for engineering biology to help tackle the climate crisis, enable sustainable products and solutions, and grow the circular bioeconomy. Engineering biology is the design and construction of new biological entities such as DNA, genetic circuits, enzymes, and cells. These components can be used to develop new sensing and monitoring technologies, such as for smart agriculture or tracking water quality; produce chemicals and materials from microorganisms more sustainably than from current manufacturing operations; and adapt plants and animals to confer new abilities and modify performance, such as increasing resilience to drought or heat. Engineering biology-based tools and technologies are contributing to some of the most impactful biotechnologies being realized today. For example, cell-free detection approaches, such as *in vitro* gene expression systems and nucleic acid-based sensors can be deployed to monitor and detect pollutants in fields and marine environments. Spider silk textiles can be made more sustainably by producing silk proteins from chassis organisms such as *Escherichia coli* and yeast, rather than harvesting the fibers from spiders. Plastic degradation can be enabled by engineering PETase enzymatic activity and stability to depolymerize polyethylene, polypropylene, and polystyrene. Engineering methane-consuming methanotrophs to colonize the microbiome of cattle and other ruminant livestock could reduce methane emissions from meat production.

While the tools and technologies described in this roadmap exist as a part of the myriad solutions needed to effectively address climate change, they can make significant contributions towards climate solutions. Moreover, engineering biology is often scaleable, making it suitable to address challenges in both local and global contexts, and it is customizable to fit regional ecosystems and economies. The companies, governments, and countries that seize the opportunities for the technological advancements and product- and process-developments outlined in this roadmap can become global leaders in combating the climate crisis, as well as accelerate bioeconomy development, which is becoming a top priority for many countries around the world. Additional sustainability can be achieved by including circularity in the design of the bioeconomy from its outset.

About the Roadmap

This roadmap is intended to be a resource for scientists, engineers, educators, and policymakers to guide their efforts in combating climate change and promoting sustainability through engineering biology technologies. For the most effective implementation, the opportunities identified in this roadmap should be considered and developed along with other solutions, thrusts of research contributed by other disciplines, appropriate policy and regulation, and with input from local, national, and international communities. Clean air and water, healthy ecosystems, food security, and strong biodiversity are all part of the cleaner future that engineering biology can foster for Earth's inhabitants. Realizing the technologies presented in this roadmap would also generate new avenues for employment, in research, scale-up, and industrial settings, would improve the robustness of the bioeconomy, and would demonstrate global leadership in biotechnology.

The roadmap comprises six themes, organized into two parts. Part 1 focuses on novel capabilities in the themes: Biosequestration of Greenhouse Gases, Mitigation of Environmental Pollution, and Conservation of Ecosystems and Biodiversity. Part 2 focuses on solutions for application sectors outlined by the themes: Food & Agriculture, Transportation & Energy, and Materials Production & Industrial Processes. Each theme is broken down into elements that become increasingly more technical: at the highest level, societal-level concerns are described in Goals and Breakthrough Capabilities, followed by a Current State-of-the-Art summary of recent advances, and finally, Short-, Medium-, and Long-Term Milestones describe the tools and technologies that must be developed to reach the Goals and Breakthrough Technologies. At the more-technical, detailed level, a non-comprehensive list of Bottlenecks and Potential Solutions are included for each milestone.

In addition to the technical roadmap, four Social and Nontechnical Dimensions Case Studies are provided to illustrate a holistic approach to research and technology development. A Glossary of terms and concepts in the context of the roadmap is also included, to provide "common language" and facilitate connection and collaboration.

Roadmapping Process

This publication was written collaboratively with more than 90 contributors across 56 academic institutions, biotechnology companies, government laboratories, and other organizations. Though the contents of this roadmap reflect only a fraction of the great potential for engineering biology to address climate and sustainability, it reflects the depth and breadth of the expertise of its contributors. In scoping the roadmap, the focus was on common themes from existing climate-related literature, especially from the United Nations, making the opportunities and impacts global in scale. That said, due to funding support from U.S. federal agencies, the roadmap largely specifies U.S.-based applications. Construction of the roadmap followed an iterative process of brainstorming, discussion, drafting, review, and revision by contributors and stakeholders, that took place over numerous virtual workshops and collaborative writing sessions, before final edits and preparation for publication.

About EBRC

The Engineering Biology Research Consortium (EBRC) is a non-profit, public-private partnership dedicated to bringing together an inclusive community committed to advancing engineering biology to address national and global needs. EBRC has over 175 academic members, more than 20 member biotechnology companies, and representation and affiliates from government, non-profits, and philanthropic institutions. We also support a 200+ member Student & Postdoc Association. More about EBRC can be found at https://ebrc.org. To contact EBRC about this roadmap, please email roadmapping@ebrc.org.

Part 1: Developing Novel Capabilities for Climate Change Mitigation and Ecosystem Resilience

Biosequestration of Greenhouse Gases

Engineering biology can be leveraged to restore, or even increase, the biosphere's ability to uptake and sequester carbon and remove greenhouse gases (GHGs) from the atmosphere. Engineered biological systems, including organisms, enzymes, and cell-free systems, can be programmed to capture, store, and utilize carbon by uptaking it for growth or converting captured carbon into value-added chemicals. The innate ability of natural systems, like soil, biocrusts, ice environments, and oceans, to combat climate change can be enhanced through engineering biology technologies. Through the advancements outlined in this roadmap theme, engineered plants, soil, enzymes, microbes, algae, and oceans could all be part of the approach to keep global warming under 1.5°C and achieve U.S. and global emissions reduction targets, in conjunction with other approaches to deep decarbonization.

Mitigation of Environmental Pollution

Historically, much of the human activity that sustains and expands greater quality of life, such as urbanization and advanced technological capabilities, results in environmental contamination and pollution. In envisioning a future with clean air, water, and land, in which technological advances do not come at the expense of the natural world that life relies on and there is mitigation for the damage that has already been done, engineering biology can be used to protect biology and the biosphere. Pollutants in the environment can be detected, continuously monitored, sequestered, and degraded with various engineering biology technologies. This roadmap theme focuses on select impactful pollutants (plastic waste, per- and polyfluoroalkyl substances, and heavy metals, including electronics waste) and circumstances of anthropogenic contamination (municipal wastewater, agriculture and aquaculture, and industrial effluent, which often contains harsh chemical waste) that could be captured and remediated with engineering biology.

Conservation of Ecosystems and Biodiversity

Climate change threatens the ecosystems and global biodiversity that humans rely on for food, medicine, shelter, and protection from diseases. This threat requires global-scale coordination to ensure that local regions of each Nation stay habitable. Approaches to preserving and restoring biodiversity should scale from individual organisms or species to entire ecosystems, since their health is interconnected. This roadmap theme identifies opportunities for engineering biology to make forests and marine ecosystems more resilient to climate stressors, and reduce biodiversity loss through monitoring ecosystem health and protecting threatened species. A key consideration in employing any and all engineering biology technologies, including all that is envisioned by this roadmap, is to ensure their biocontainment to prevent negative impacts on biodiversity or ecosystem health.

Part 2: Enabling Sustainable, Climate-friendly Production in Application Sectors

Food & Agriculture

Improved food security is urgently needed as extreme weather events have decimated agricultural output around the world and the global population grows. Many current agricultural practices contribute to climate change and ecological disruption as significant sources of GHG emissions and nutrient run-off into surrounding environments. Through the technological advancements described in this roadmap theme, engineering biology can minimize the impact of, and sustain output from, agricultural practices by reducing GHG emissions from fertilizers, pesticides, herbicides, agricultural crops, and livestock, by sustainability producing meat and meat-alternatives, by repurposing and reducing waste, and by bolstering crop and soil resilience. These advancements will be needed to continue feeding the people of the world and sustaining the livelihood of farmers and workers in the agricultural sector.

Transportation & Energy

Transportation and energy account for the vast majority of GHG production. The engineering biology technologies outlined in this roadmap theme can play a role in establishing carbon-free transportation by decarbonizing modes of transport with biofuels made from biomass or other renewable feedstocks, and improving efficiencies during the transition to carbon-negative sources of energy. Bio-batteries and biobased fuel cells for electricity storage and generation can also improve sustainability in the energy sector. Moving towards sustainable fuels and energy are imperative to powering the development of communities, societies, and technologies across the world without the externality of worsening climate change.

Materials Production & Industrial Processes

Engineering biology technologies play an important part in moving towards a circular bioeconomy, in which materials and waste can be recycled into value-added products. Manufacturing of materials and products, including plastics, chemicals, textiles, cement, building materials, and electronics, consumes large amounts of energy and generates substantial GHG emissions. This roadmap theme focuses on how to replace some of today's most energy-, resource-, and emissions-intensive materials and products with less environmentally-damaging, biobased alternatives, thereby aiding the transition towards a circular bioeconomy with more sustainable and environmentally-friendly manufacturing.

Social and Nontechnical Dimensions Case Studies

The technical solutions presented in this roadmap must be developed appropriately in a larger societal context for them to be accepted, implemented, and successful. Aspects that must be considered include relevant ethical, social, economic, political, and legal frameworks, as well as local, national, and international landscapes. For example, the consideration of a broad solutions landscape and the feasibility of use at scale are necessary to ensure biotechnologies developed to mitigate climate change are effective. An understanding of regulatory and governance frameworks will also aid in implementation. Additionally, the benefits and consequences of engineering biology research, and the micro- and macro-level impacts of engineered organisms or products should be considered. Finally, the competing values and priorities of various stakeholders will likely lead to differing perspectives on what and how biotechnologies should be implemented; this must be considered to make progress towards addressing complex climate challenges.

In many instances, consultation and collaboration with colleagues in the social sciences will be needed to adequately address these dimensions. We encourage the development, funding, and implementation of partnerships, collaborations, and pathways to strengthen professional networks between technical and social science researchers, which are currently sparse. Though there is often a lack of incentives, or even opportunities, to think about the holistic impacts of the development and use of biotechnology, we encourage technical researchers to commit to doing so.

The case studies presented with this roadmap consist of hypothetical technologies drawn from this roadmap and were developed primarily for technical researchers to consider nontechnical elements of their research, since many concerns can be alleviated with design choices made during the research process. The case studies provided are:

1. Release of engineered algae with increased carbon capture capability in U.S. coastal waters off California.
2. Application of biofertilizers based on engineered rhizobia to corn fields in the American Midwest.
3. High efficiency lithium biomining in Nevada with engineered microbes.
4. Engineering cattle gut microbiomes to reduce methane emissions in American agriculture.

Conclusion

There is an urgent need to address climate and sustainability challenges to preserve and promote life on Earth. Engineering biology technologies can provide a suite of solutions to mitigate climate change and enhance ecosystem resilience while enabling sustainable production of the goods and products that maintain everyday life. While the innovations highlighted in this roadmap can make substantial contributions towards mitigating climate change, they must be developed with the broader societal context in mind and in collaboration with stakeholders from diverse personal, professional, and geographical backgrounds. These efforts, in concert with other solutions, can ensure planetary and economic health for a sustainable future.