COMMENT OPEN

Check for updates

# Addressing the climate crisis through engineering biology

Emily R. Aurand[1✉], Tae Seok Moon[2], Nicole R. Buan[3], Kevin V. Solomon[4], Michael Köpke[5] and EBRC Technical Roadmapping Working Group

As the climate crisis deepens and the impacts are felt more often and more acutely worldwide, scientific, engineering, and policy communities need more tools and opportunities to make a difference in tackling climate challenges. The Engineering Biology Research Consortium (EBRC) has recently published a technical research roadmap, *Engineering Biology for Climate & Sustainability*, that describes and details short-, medium-, and long-term milestones for engineering biology tool and technology advancements that can be applied to mitigate, prevent, and adapt to climate change. These ambitious technical achievements can only be realized in the context of complementary research, policy, and investment and in combination with efforts from many other disciplines and approaches. Herein we illustrate the opportunities, as described by the roadmap, in engineering biology research and development to impact climate change and long-term environmental sustainability, and why and how engineering biology and subsequent biotechnologies should be among the most prominent of approaches to overcoming the climate crisis.

*npj Climate Action* (2024)3:9 ; https://doi.org/10.1038/s44168-023-00089-8

Climate change poses a clear and dire threat to the health and well-being of Earth and its inhabitants. Notably, more extreme, frequent, and interconnected climate events are causing widespread vulnerabilities, damage, and loss to humans and nature. Between late June and early August of 2023, extreme heat in North Africa, China, and Europe caused numerous deaths and led to concerns for food supplies and energy grids[1]; the last eight years (2015–2023) have been the hottest on record, illustrating disturbing and accelerating trends[2]. In the U.S. in 2023, smoke from Canadian wildfires has contributed to dangerous air quality, impacting broad swaths of the American East Coast and Midwest, while flooding rains in India have shut schools and businesses and caused deadly landslides[3,4]. These adverse impacts are compounding, often causing irreversible effects and burdening the most vulnerable. Solutions to the looming climate crisis must be dramatic at a global scale to reverse 150 years of unbridled pollution. Few options are immediately compatible with current standards of living in industrialized nations. A simplistic answer would be to halt the use of fossil fuels entirely. Another would be to plant many more trees to capture $CO_2$ and offset emissions. However, relying on nature alone to capture greenhouse gases (GHGs) is impractical. On their own, neither of these—worldwide abandonment of fossil fuels or massive reforestation—are imminently viable solutions for developed countries dependent on petrochemicals or for developing countries with growing populations, where economic advancement and increasing prosperity and quality of life are a priority[5]. We envision that with engineering biology, we can mitigate climate change by cutting GHG emissions by supplanting the need for fossil fuels, creating alternatives for petro-chemically derived materials and carbon-intensive fertilizers, removing carbon-loaded pollutants from the environment, and promoting biodiversity and ecosystem conservation[6]. While biotechnologies are only part of what must be a multipronged approach to tackling the climate crisis, solutions enabled by engineering biology have collectively mitigated several megatons of GHG emissions, based on industry reports[7].

In this article, we promulgate an engineering biology research roadmap that identifies novel approaches and goals for future climate-related research and engineering projects. The roadmap also describes opportunities for engineering biology-enabled, sustainable replacements and alternatives in the sectors that contribute to the greatest use of fossil fuels and release of GHG emissions: food and agriculture, transportation and energy, and materials production and industrial processes[8]. To achieve these solutions, further technical advancements will be needed in the biological engineering of metabolic circuits and pathways, engineering of proteins, plants, and microbial consortia, and novel (methods and processes for developing) bio-based or -enabled materials.

*Engineering Biology for Climate & Sustainability* is the fifth technical roadmap developed by the Engineering Biology Research Consortium (EBRC) and represents the first dedicated to innovations and opportunities towards overcoming a significant global challenge. The roadmap targets and challenges are aligned and were drawn from existing climate and sustainability literature, particularly those focused on long-term impacts and opportunities, including reports from the United Nations' Intergovernmental Panel on Climate Change (http://ipcc.org) and the U.S. Environmental Protection Agency. However, the technical nature and focus on engineering biology solutions give it a unique focus when compared with the many other publications aimed at addressing climate and sustainability issues. In particular, we focused on areas where few or no solutions currently exist or where engineering biology could provide unique advantages. The roadmap content was guided by multiple virtual workshops and collaborative writing sessions through an iterative process of brainstorming, discussion, drafting, review, and revision by contributors and stakeholders. The roadmap was written collaboratively by more than 90 contributors across 56 academic institutions, biotechnology companies, government laboratories, and other organizations. While the roadmap focuses on technical research, conversations during its production were wide-ranging,

[1]Engineering Biology Research Consortium, Emeryville, CA, USA. [2]Department of Energy, Environmental and Chemical Engineering, Washington University in St. Louis, St. Louis, MO, USA. [3]Department of Biochemistry, University of Nebraska-Lincoln, Lincoln, NE, USA. [4]Department of Chemical & Biomolecular Engineering, University of Delaware, Newark, DE, USA. [5]LanzaTech Inc., Skokie, IL, USA. A list of members and their affiliations appears in the Supplementary Information. ✉email: eaurand@ebrc.org

**Fig. 1 Major themes in *Engineering Biology for Climate & Sustainability*.** The roadmap considers six areas for technical advancements in engineering biology applications for climate and sustainability, represented by the graphics in each piece of the wheel. These themes are (from top, clockwise): Biosequestration of Greenhouse Gases (gray), Mitigation of Environmental Pollution (blue), Conservation of Ecosystems and Biodiversity (yellow), Food & Agriculture (green), Transportation & Energy (red), and Materials Production & Industrial Processes (purple). Together, these themes encompass milestones toward the achievement of tools and technologies for climate and sustainability across myriad contexts and application spaces. (Figure reproduced, and used by permission, from *Engineering Biology for Climate & Sustainability: A Research Roadmap for a Cleaner Future*, Engineering Biology Research Consortium (2022). Available at https://roadmap.ebrc.org/engineering-biology-for-climate-sustainability/).

as expected with the nature of the challenge, and inclusive of social, economic, and larger environmental considerations. We include Social and Nontechnical Dimension Case Studies for engineering biology practitioners and policymakers with the roadmap to guide discussions of the larger context in which research and technology development must take place[9].

The roadmap consists of six themes in technologies and applications of engineering biology for climate change and environmental sustainability (Fig. 1). Three themes—Biosequestration of Greenhouse Gases, Mitigation of Environmental Pollution, and Conservation of Ecosystems and Biodiversity—focus on technical capacity and novel capabilities in engineering biology to limit further harmful anthropogenic impacts and enable adaptation to climate change, while the other three themes—Food & Agriculture, Transportation & Energy, and Materials Production & Industrial Processes—focus on the development of products and production methods that capitalize on engineering biology to reduce carbon intensity and create sustainable alternatives.

To illustrate one focus area of the roadmap, the technical theme Mitigation of Environmental Pollution "highlights opportunities for engineering biology to prevent and tackle pollution through bioremediation, biosequestration, and biodegradation of contaminants in the environment and from point sources"[6]. As a part of this theme, for example, we consider the development of biosensing technologies to monitor and detect pollutants. Milestones include the development of biosensors compatible with digital infrastructure, which will help to enable rapid signaling and response (short-term milestone), biosensors with dynamic range for field applications that are intrinsic to the environment (medium-term milestone), and autonomous biosensors that cannot only detect but also respond to and mitigate a pollutant (long-term milestone). Each of these milestones is accompanied in the roadmap by any current or presumed technical bottlenecks or challenges to their realization and one or more potential solutions to those bottlenecks. Examples of challenges include: designing biosensor platforms that are wholly contained to simplify preparation and actuation and require little prior knowledge or training to use; developing environmental biosensors that are specific to harmful contaminants, with environmentally relevant ranges of detection; and engineering environmentally deployable organic biosensors (such as engineered microbial consortia) that are defined and contained, stable, and pose no harm to the environment. These challenges will require technical solutions developed through collaboration, fundamental science and engineering, and commercial realization.

Engineering biology is not the only solution for sustainable growth and clean technology, but unique among the myriad approaches we must enable to tackle the climate crisis and should be developed and applied in parallel and in coordination with other methods and technologies. Securely and responsibly engineered biological solutions can be more tenable for incorporation into natural environments and more enduring. As we highlight in our roadmap, researchers can develop engineering biology technologies that capture or recycle industrial off-gases, including carbon monoxide and syngas, or GHGs, such as $CO_2$ or methane, to mitigate global warming. Microbes and plants can be engineered to upcycle plastic waste to reduce plastic pollution in an economically viable way or to enable bacterial nitrogen fixation to reduce the use of synthetic fertilizers and help increase crop yields. Further research and engineering of organisms like methanoarchaea will help us to adapt our current resource landscape to increase feedstock supplies for renewable fuel production, enabling us to reduce GHG emissions from the energy and transportation sectors[10]. Finally, we can take advantage of existing natural environments to support sustainable biomanufacturing[11], replacing petroleum-based chemicals and materials with carbon-neutral or carbon-negative alternatives and opening up new climate-friendly avenues both for creating familiar products that we use every day and for producing new materials heretofore unimagined. To make the most of these solutions, they need to be considered in local and regional contexts, with public input to ensure lower barriers to adoption and ensure they will be effective. The research community will need to foster partnerships to find solutions to sustainability bottlenecks, test prototypes, consult on scale-up, and create and sustain workforce development and education. Not all of these technical opportunities will be realized, and many will require a significant investment of time, money, and responsive policy to achieve; however, the potential for these technologies to contribute, in combination with other approaches, to climate and sustainability solutions is incredibly promising and important (Fig. 2).

To enable the opportunities communicated in our technical roadmap, governments should increase funding for fundamental and applied research, as well as commercialization efforts, of climate-related technologies. Governments at all levels (local to multinational) should consider and implement policy and economic incentives for commercializing sustainable technologies, including emission reduction credits, pollution tax, and—specifically to promote engineering biology solutions—policies and regulations that promote and enable the use and adoption of genetically-modified or engineered biological organisms. Given the interdisciplinary and global nature of research focusing on climate issues, center-scale funding, and multinational support will be important. At the same time, opportunities that emphasize innovation will facilitate the initiation of high-risk and high-return

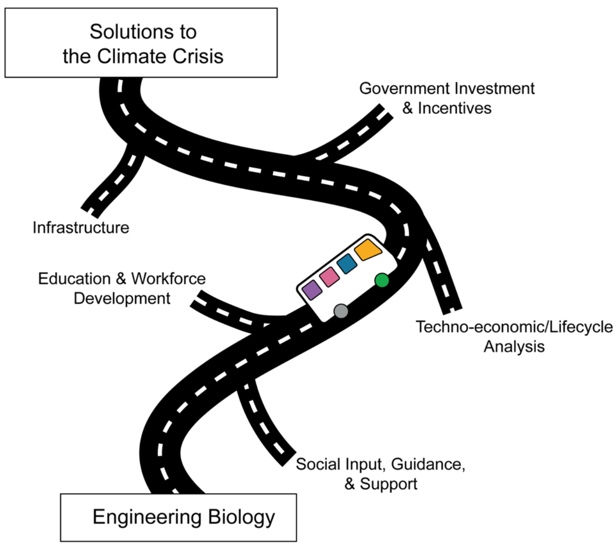


**Fig. 2 Factors that fortify the road to achieving engineering biology solutions to the climate crisis.** Achieving the technical solutions to the climate crisis envisioned by the roadmap will require more than just scientific research and development. Numerous other factors and influences will determine the pace and realization of biotechnologies. Technical solutions must be developed with the input of society, and engineering biology research can be improved through collaborations with social scientists and the public. Realizing biotechnology commercialization and application requires that start-ups and established companies undertake comprehensive techno-economic and lifecycle analyses of their potential products. The next generation of students and the workforce is highly motivated to engage in research toward mitigating climate change and achieving environmental sustainability, but they need to be afforded accessible opportunities, tools, and training to take part. And nearly all of this requires investment, infrastructure, and incentives from government, philanthropy, and private sources. However, with deep and diversified collaboration and collective aims, engineering biology has the potential to be an incredibly powerful solution to the climate crisis.

projects, and funding agencies such as the U.S. ARPA-C[12] will have an important role in nurturing environments that encourage diverse and innovative ideas.

Beyond research, other factors will influence the potential of engineering biology to revolutionize the way we address the climate crisis and ensure lasting sustainability. In the Social and Nontechnical Dimension Case Studies that accompany the technical roadmap, we draw attention to a number of considerations for engineering biology researchers and their potential partners in the social and economic sciences, policymakers and regulators, and others to realize engineering biology technologies beyond the laboratory bench. This includes private and public funding and incentives for biotechnological infrastructure, including engineering biology research centers, incubators for climate technology start-up companies, and scale-up facilities for bioproduction[13]; and see for example[14]. Scale-up of engineering biology solutions remains a major barrier, but many examples exist (in biopharmaceutical production, commercial agriculture, and industrial and municipal waste treatment) for expanding and enhancing existing bioindustry to overcome this barrier. Additionally, technology developers will benefit from close collaboration with experts in techno-economic analysis (TEA), life-cycle analysis (LCA), ecology, and natural resource management.

Along with this comes the education and workforce development necessary to facilitate and drive the burgeoning bioindustry. We have reached an inflection point in which we need to continue generating entrepreneurial leaders to imagine new possibilities and industries for engineered biology and also expanding the workforce with the skills and capacity to realize commercial-scale biomanufacturing and implementation of sustainable environmental biotechnologies. Importantly, to allow for diverse solutions to complex climate issues, academic institutions, industry, and government must consider diversity, equity, and inclusion as the next generations are educated and welcomed to the workforce[15]. The climate crisis is guaranteed to disproportionately affect indigenous and lower-income communities, further increasing the necessity to include these peoples in the solutions generated[16,17]. Despite the serious and urgent climate issues we face, we are cautiously optimistic about the younger generation's awareness of climate problems and passion to solve them. Using engineering biology that is often scalable and easily accessible, the future workforce can be empowered to address challenges in climate-related research, technology development, commercialization efforts, and policymaking.

Our technical roadmap for engineering biology for climate and sustainability considers opportunities in both local and global contexts and provides research labs, industry, and governments worldwide with visions and potential biological solutions to climate problems. The companies, governments, and countries that seize the potential for the technological advancements and product- and process developments outlined in our roadmap can become global leaders in combating the climate crisis and accelerating bioeconomy development. Solving the climate crisis can be compatible with sustainable growth through interdisciplinary research and global collaboration as envisioned in the roadmap.

### Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

## DATA AVAILABILITY

To the extent of our knowledge, all materials and references provided in this paper are publicly available and accessible.

Received: 15 August 2023; Accepted: 23 November 2023;
Published online: 21 February 2024

## REFERENCES

1. Stanway, D. World hits record land, sea temperatures as climate change fuels 2023 extremes. *Reuters*. https://www.reuters.com/business/environment/climate-nears-point-no-return-land-sea-temperatures-break-records-experts-2023-06-30/ (2023).
2. Copernicus Climate Change Service. Copernicus: 2022 was a year of climate extremes, with record high temperatures and rising concentrations of greenhouse gases. *Copernicus*. https://climate.copernicus.eu/copernicus-2022-was-year-climate-extremes-record-high-temperatures-and-rising-concentrations (2023).
3. Bilefsky, D., Stack, L., & Isai, V. Quebec wildfires contribute to extreme fire season in Canada. *The New York Times*. https://www.nytimes.com/2023/06/07/world/americas/canada-wildfires.html?smid=url-share (2023).
4. Yasir, S. & Kumar, H. Deadly monsoon flooding and landslides Lash India. *The New York Times*. https://www.nytimes.com/2023/07/10/world/asia/india-monsoon-flooding-landslides.html?smid=url-share (2023).
5. Intergovernmental Panel on Climate Change. IPCC, 2022: Summary for Policymakers (eds Shukla, P. R. et al). In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022). https://www.google.com/url?q=https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SummaryForPolicymakers.pdf&sa=D&source=docs&ust=1689114782007392&usg=AOvVaw0G95FDi8N2mTPtw3UaUhh4.
6. Engineering Biology Research Consortium (EBRC). Engineering Biology for Climate & Sustainability: A Research Roadmap for a Cleaner Future. *Engineering Biology Research Consortium*. http://roadmap.ebrc.org (2022a).

7. Agrawal, D. et al. Carbon emissions and decarbonisation: the role and relevance of fermentation industry in chemical sector. *Chem. Eng. J.* **475**, 146308 (2023).
8. Lamb, W. F. et al. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environ. Res. Lett.* **16**, 073005 (2021).
9. Engineering Biology Research Consortium (EBRC). Social and Nontechnical Dimensions Case Studies. *Engineering Biology Research Consortium*. https://roadmap.ebrc.org/engineering-biology-for-climate-sustainability/social-and-nontechnical-dimensions-case-studies/ (2022b).
10. Carr, S. & Buan, N. R. Insights into the biotechnology potential of Methanosarcina. *Front. Microbiol.* **13**, 1034674 (2022).
11. Moon, T. S. SynMADE: Synthetic microbiota across diverse ecosystems. *Trends Biotechnol.* **40**, 1405–1414 (2022).
12. https://www.whitehouse.gov/briefing-room/statements-releases/2021/02/11/biden-harris-administration-launches-american-innovation-effort-to-create-jobs-and-tackle-the-climate-crisis/. The White House. Biden-Harris Administration Launches American Innovation Effort to Create Jobs and Tackle the Climate Crisis. *The White House* (2021).
13. Schmidt Futures. The U.S. Bloeconomy: Charting a Course for a Resilient and Competitive Future. *Schmidt Fut*. https://www.schmidtfutures.com/wp-content/uploads/2023/05/Bioeconomy-Task-Force-Strategy-4.14.22-4.pdf (2022).
14. BioMADE. New BioMADE Bioreactor Innovation Projects Aim to Supercharge the Future of Large-Scale Biomanufacturing. *BioMADE*. https://www.biomade.org/news/bioreactor-innovation-projects (2023).
15. Moon, T. S., Solomon, K., Borodina, I. & Vickers, C. Impacting future generations of synthetic biologists by ensuring diversity, equity, and inclusion. *Trends Biotechnol.* **41**, P1099–1105 (2023).
16. Environmental Protection Agency. Climate Change and the Health of Indigenous Populations. *EPA*. https://www.epa.gov/climateimpacts/climate-change-and-health-indigenous-populations (2022).
17. United Nations. Climate Change | United Nations For Indigenous Peoples. *United Nations* https://www.un.org/development/desa/indigenouspeoples/climate-change.html (2023).

## ACKNOWLEDGEMENTS

We wish to acknowledge and thank Kaitlyn Duvall and Cynthia Ni for their assistance in preparing this manuscript. The authors are especially thankful to the more than 90 individuals who contributed to the roadmap described herein. E.R.A. is supported by the National Science Foundation (MCB-2116166). T.S.M is supported by the Defense Advanced Research Projects Agency (N660012324032), American Institute of Chemical Engineers (Langer Prize for Innovation and Entrepreneurial Excellence), the United States Department of Agriculture (2020-33522-32319), U.S. Department of Energy (DE-SC0022003 and DE-SC0018324), U.S. Environmental Protection Agency (84020501), the National Institutes of Health (R01 AT009741), and the National Science Foundation (EF-2222403). N.R.B. is supported by awards from National Science Foundation (IOS-1938948 and QNN5RQTXQBT), US Department of Agriculture (NEB-30-138), Nebraska Center for Energy Sciences Research (Cycle 17) and Nebraska Soybean Board (23R-20-1/1 #714). K.V.S. is supported by the Office of Science's Biological & Environmental Research Program in the US Department of Energy (DE-SC0022206, DE-SC0022018, and DE-SC0023085), the National Science Foundation (CBET-2219276, MCB-2134603, MCB-2143856, and IOS-2128272), the National Institutes of Health (P20GM103446E), and the U.S. Department of Agriculture, Agricultural Research Service (Agreement No. 59-8072-1-002) via the Center for Food Safety Engineering at Purdue University. Members of the EBRC Technical Roadmapping Working Group can be found at https://ebrc.org/focus-areas/roadmapping/#wg. The content is solely the responsibility of the authors and does not necessarily reflect the official views of the funding agencies.

## AUTHOR CONTRIBUTIONS

E.R.A. wrote and revised the paper. T.S.M, N.R.B., K.V.S., and M.K. contributed to the conception of the paper and drafting. M.K. contributed to the revision of the paper. The EBRC Technical Roadmapping Working Group contributed to the conception of the paper and led the roadmapping effort described herein.

## COMPETING INTERESTS

N.R.B. has significant financial interest in RollingCircle Biotech, LLC, and Molecular Trait Evolution, LLC. M.K. is an employee of LanzaTech, a for-profit company that captures and transforms carbon. E.R.A., T.S.M., and K.V.S. declare no competing interests.

## INCLUSION AND ETHICS

The authors of this manuscript and the Engineering Biology Research Consortium (EBRC) are committed to diversity, inclusion, and equal opportunity in engineering biology, science and technology, and the bioeconomy. Please visit https://ebrc.org/ebrc-statement-of-ethics-in-engineering-biology-research/ to read the EBRC Statement of Ethics in Engineering Biology.

## ADDITIONAL INFORMATION

**Supplementary information** The online version contains supplementary material available at https://doi.org/10.1038/s44168-023-00089-8.

**Correspondence** and requests for materials should be addressed to Emily R. Aurand.