Charting the Future of Biotechnology

Graphic & Case Study Endnotes

i The Royal Swedish Academy of Sciences, "The Nobel Prize in Chemistry 2024," The Nobel Prize, October 9, 2024, https://www.nobelprize.org/prizes/chemistry/2024/press-release/.

ii John Jumper et al., "Highly Accurate Protein Structure Prediction with AlphaFold," *Nature* 596, no. 7873 (July 15, 2021): 583–89, https://doi.org/10.1038/s41586-021-03819-2.

iii Jun Zhang and Bing Chen, "Fighting SARS-CoV-2 with Structural Biology Methods," *Nature Methods* 19, no. 4 (April 8, 2022): 381–83, https://doi.org/10.1038/s41592-022-01448-9.

iv Research Collaboratory for Structural Bioinformatics, "RCSB PDB," RCSB Protein Data Bank, accessed February 4, 2025, https://www.rcsb.org/.

v Stephen K. Burley et al., "Protein Data Bank (PDB): The Single Global Macromolecular Structure Archive," *Methods in Molecular Biology* 1607 (2017): 627–41, https://doi.org/10.1007/978-1-4939-7000-1_26.

vi U.S. Department of Agriculture, National Agricultural Statistics Service, "USDA Releases 2022 Census of Agriculture Data," February 13, 2024, https://www.nass.usda.gov/Newsroom/2024/02-13-2024.php.; U.S. Department of Agriculture, National Agricultural Statistics Service, "2022 Census of Agriculture Highlights," February 2024, https://www.nass.usda.gov/Publications/Highlights/2024/Census22_HL_FarmProducers_FINAL.pdf.

vii Ann Steensland, "Troublesome Trends and System Shocks: 2022 GAP Report," Global Agricultural Productivity Report (Virginia Tech College of Agriculture and Life Sciences, 2022), https://globalagriculturalproductivity.org/wp-content/uploads/2022/11/2022-GAP_Report_final_110922.pdf.

viii World Organisation for Animal Health, "Animal Health through an Economic Lens," World Organisation for Animal Health, 2022, https://www.woah.org/en/article/animal-health-through-an-economic-lens/.; Adel Sarkozi, "Climate Change Fans Spread of Pests and Threatens Plants and Crops, New FAO Study," Food and Agriculture Organization of the United Nations, June 2, 2021, https://www.fao.org/newsroom/detail/Climate-change-fans-spread-of-pests-and-threatens-plants-and-crops-new-FAO-study/en?utm_source=chatgpt.com.

ix Douglas Broom, "This Is How War in Europe Is Disrupting Fertilizer Supplies and Threatening Global Food Security," World Economic Forum, March 1, 2023, https://www.weforum.org/stories/2023/03/ukraine-fertilizer-food-security/.

x Sarah E Bloch et al., "Harnessing Atmospheric Nitrogen for Cereal Crop Production," *Current Opinion in Biotechnology*, Energy Biotechnology • Environmental Biotechnology, 62 (April 2020): 181–88, https://doi.org/10.1016/j.copbio.2019.09.024.;
Diane Wray-Cahen et al., "Advancing Genome Editing to Improve the Sustainability and Resiliency of Animal Agriculture," *CABI Agriculture and Bioscience 3*, no. 1 (April 21, 2022): 21, https://doi.org/10.1186/s43170-022-00091-w.;
U.S. Department of Agriculture, "Biotechnology FAQs," U.S. Department of Agriculture, accessed February 4, 2025, https://www.usda.gov/farming-and-ranching/plants-and-crops/biotechnology/biotechnology-faqs.;
U.S. National Security Commission on Emerging Biotechnology, "Building the Future with Biotech: How Biotech Is Shaping the Agricultural Landscape" (U.S. National Security Commission on Emerging Biotechnology, May 2024), https://www.biotech.senate.gov/wp-content/uploads/2024/05/NSCEB_OP_Agriculture.pdf.

xi The White House, "Bold Goals for U.S. Biotechnology and Biomanufacturing: Harnessing Research and Development to Further Societal Goals" (The White House, March 2023), https://bidenwhitehouse.archives.gov/wp-content/uploads/2023/03/Bold-Goals-for-U.S.-Biotechnology-and-Biomanufacturing-Harnessing-Research-and-Development-To-Further-Societal-Goals-FINAL.pdf.

xii Kelly P. Nelson and Keith Fuglie, "Investment in U.S. Public Agricultural Research and Development Has Fallen by a Third Over Past Two Decades, Lags Major Trade Competitors," U.S. Department of Agriculture, Economic Research Service, June 6, 2022, https://www.ers.usda.gov/amber-waves/2022/june/investment-in-u-s-public-agricultural-research-and-development-has-fallen-by-a-third-over-past-two-decades-lags-major-trade-competitors.

xiii Kelly P. Nelson and Keith Fuglie, "China Is Largest Global Funder of Agricultural R&D," U.S. Department of Agriculture, Economic Research Service, July 18, 2022, https://www.ers.usda.gov/data-products/charts-of-note/chart-detail?chartId=104237.;
Jack Ellis, "Syngenta Group Launches after Taking $5.6bn Chinese Biz on Board," AgFunderNews, June 18, 2020, https://agfundernews.com/syngenta-group-relaunches-after-taking-5-6bn-chinese-biz-on-board.;
Heping Jia, "Merger of Sinochem and ChemChina, Long Rumored, Is Confirmed," *Chemical & Engineering News 98*, no. 35 (September 10, 2020), https://cen.acs.org/business/mergers-&-acquisitions/Merger-Sinochem-ChemChina-long-rumored/98/i35.;
Sun Yu, "China Chemical Merger to Create Group with $152bn Sales," *Financial Times*, April 1, 2021, https://www.ft.com/content/2d3664ca-89fc-4946-b2ec-969e3e81e452.;
Amy R. Beaudreault, "China's Growing Power for a Food Secure World," Center for Strategic & International Studies, January 8, 2020, https://www.csis.org/analysis/chinas-growing-power-food-secure-world.

xiv Paul Voosen, "Crop Savior Blazes Biotech Trail, but Few Scientists or Companies Are Willing to Follow," *The New York Times*, September 21, 2011, sec. Business, https://archive.nytimes.com/www.nytimes.com/gwire/2011/09/21/21greenwire-crop-savior-blazes-biotech-trail-but-few-scien-88379.html?pagewanted=1.

xv Suwenza Lius et al., "Pathogen-Derived Resistance Provides Papaya with Effective Protection against Papaya Ringspot Virus," *Molecular Breeding 3* (June 1997): 161–68, https://doi.org/10.1023/A:1009614508659.;

xvi Carol Gonsalves, David R. Lee, and Dennis Gonsalves, "Transgenic Virus-Resistant Papaya: The Hawaiian 'Rainbow' Was Rapidly Adopted by Farmers and Is of Major Importance in Hawaii Today," The American Phytopathological Society, August 1, 2004, https://www.apsnet.org/edcenter/apsnetfeatures/Pages/PapayaHawaiianRainbow.aspx

xvii Dennis Gonsalves, "The Papaya Story: A Special Case or a Generic Approach?," Biotechnology: Science and Society at a Crossroad (North American Agricultural Biotechnology Council, 2003), https://ecommons.cornell.edu/items/c2340827-c6a0-4bbb-a8db-da0327684bc9.

xviii U.S. Department of Agriculture, *Notice: Cornell University and University of Hawaii; Availability of Determination of Nonregulated Status for Papaya Lines Genetically Engineered for Virus Resistance*, 61 Fed. Reg. 48,663 (Sept. 16, 1996), available at https://www.govinfo.gov/content/pkg/FR-1996-09-16/pdf/96-23663.pdf (last visited Feb. 20, 2025).;
U.S. Food and Drug Administration, *Biotechnology Consultation Agency Response Letter BNF No. 000042* (Sept. 19, 1997), available at https://wayback.archive-it.org/7993/20171031094445/https://www.fda.gov/Food/IngredientsPackagingLabeling/GEPlants/Submissions/ucm161101.htm (last visited Feb. 20, 2025).;
U.S. Environmental Protection Agency, *Coat Protein of Papaya Ringspot Virus and the Genetic Material Necessary for its Production; Exemption From the Requirement of a Tolerance*, 62 Fed. Reg. 44,572 (Aug. 22, 1997), available at https://www.govinfo.gov/content/pkg/FR-1997-08-22/pdf/97-22395.pdf (last visited Feb. 20, 2025).

xix Carol Gonsalves, David R. Lee, and Dennis Gonsalves, "Transgenic Virus-Resistant Papaya: The Hawaiian 'Rainbow' Was Rapidly Adopted by Farmers and Is of Major Importance in Hawaii Today," The American Phytopathological Society, August 1, 2004, https://www.apsnet.org/edcenter/apsnetfeatures/Pages/PapayaHawaiianRainbow.aspx.

xx Jean B. Ristaino et al., "The Persistent Threat of Emerging Plant Disease Pandemics to Global Food Security," *Proceedings of the National Academy of Sciences* 118, no. 23 (May 21, 2021): e2022239118, https://doi.org/10.1073/pnas.2022239118.;
Centers for Disease Control and Prevention, "H5 Bird Flu: Current Situation," Avian Influenza (Bird Flu), February 19, 2025, https://www.cdc.gov/bird-flu/situation-summary/index.html.;
World Organisation for Animal Health, "African Swine Fever," World Organisation for Animal Health, accessed February 19, 2025, https://www.woah.org/en/disease/african-swine-fever/.

xxi U.S. Small Business Administration, "Course 1, Tutorial 1: What Is the Purpose of the SBIR & STTR Programs?," November 2020, https://www.sbir.gov/sites/all/themes/sbir/dawnbreaker/img/documents/Course1-Tutorial1_v2.pdf.

xxii U.S. Small Business Administration, "Award Data," Portfolio, accessed February 6, 2025, https://www.sbir.gov/awards?company_name=genomatica&keywords&topic_code&ri&agency&program&phase&year&state&demographic&page=0.

xxiii	Genomatica Inc., Form S-1 Registration Statement (filed August 23, 2011), from Securities and Exchange Commission website, https://www.sec.gov/Archives/edgar/data/1143301/000119312511230125/ds1.htm, accessed February 6, 2025.; "The Better BDO: Geno Bio-BDO," Geno, accessed February 6, 2025, https://www.genomatica.com/bdo/.; "Lululemon Partners with Genomatica on Plant-Based Nylon," Geno, August 18, 2021, https://www.genomatica.com/news-content/lululemon-partners-with-genomatica-on-plant-based-nylon/.; "L'Oréal Becomes Third Global Company to Invest in Geno-Led Venture for Sustainably Sourced Ingredients," Geno, March 20, 2023, https://www.genomatica.com/news-content/loreal-becomes-third-global-company-to-invest-in-geno-led-venture-for-sustainably-sourced-ingredients/.
xxiv	U.S. Department of Defense, "DoD Releases Seven Awards for Distributed Bioindustrial Manufacturing Program," U.S. Department of Defense, August 24, 2024, https://www.defense.gov/News/Releases/Release/Article/3878835/dod-releases-seven-awards-for-distributed-bioindustrial-manufacturing-program/.
xxv	Evan Halper, "Amid Explosive Demand, America Is Running out of Power," *The Washington Post*, March 7, 2024, https://www.washingtonpost.com/business/2024/03/07/ai-data-centers-power/.
xxxi	Hannah Ziegler, "Can the Tire Industry Be Sustainable? Guayule Farmers Say Yes.," *Washington Post*, October 22, 2024, https://www.washingtonpost.com/business/interactive/2024/guayule-us-rubber-new-sustainable-tires/.
xxxiii	Hannah Ziegler, "Can the Tire Industry Be Sustainable? Guayule Farmers Say Yes.," *Washington Post*, October 22, 2024, https://www.washingtonpost.com/business/interactive/2024/guayule-us-rubber-new-sustainable-tires/.
xxxiv	"Pharma Isn't Ready for OTC Narcan Demand," *Antheia* (blog), September 25, 2024, https://antheia.bio/pharma-isnt-ready-for-otc-narcan-demand/.
xxxv	Drug Enforcement Administration, "Opium Poppy," DEA Museum, accessed February 6, 2025, https://museum.dea.gov/exhibits/online-exhibits/cannabis-coca-and-poppy-natures-addictive-plants/opium-poppy.
xxxvi	Antheia, "Thebaine" (Antheia, August 2023), https://antheia.bio/wp-content/uploads/2023/08/Thebaine_ProductSheet.pdf.
xxxvii	SynBioBeta, "Tandem Repeat Secures $1.5M DoD Grant to Scale Protein-Based Fibers - SynBioBeta," SynBioBeta, August 29, 2024, https://www.synbiobeta.com/read/tandem-repeat-secures-1-5m-dod-grant-to-scale-protein-based-fibers.; "Squitex," Microfiber Innovation Challenge, accessed February 6, 2025, https://www.microfiberinnovation.org/innovation/squitex.
xxxviii	United Nations Environment Programme, "Beat Plastic Pollution," UN Environment Programme, accessed February 18, 2025, http://unep.org/interactive/beat-plastic-pollution/.
xxxix	Ecovative, "Our Process," Mushroom Packaging, accessed February 6, 2025, https://mushroompackaging.com/pages/our-process.
xl	Cesio Surfactants Europe, "How Surfactants Are Made," Cesio Surfactants Europe, accessed February 6, 2025, https://www.cesio.eu/index.php/about-surfactants/how-surfactants-are-made.; Craig Bettenhausen, "The Chemistry of Cold-Water Washing," *Chemical & Engineering News* 102, no. 3 (January 28, 2024), https://doi.org/10.1021/cen-10203-feature1.
xli	Craig Bettenhausen, "The Chemistry of Cold-Water Washing," *Chemical & Engineering News* 102, no. 3 (January 28, 2024), https://doi.org/10.1021/cen-10203-feature1.; Peter Dybdahl Hede, "A Beginner's Guide to Enzymes in Detergents," Novozymes, May 7, 2020, https://biosolutions.novozymes.com/en/dish/insights/article/beginners-guide-enzymes-detergents.
xlii	Jasmin Jessen, "P&G Partners with Biotech Start-Up for Cold Wash Technology," ClimateTech Digital, September 24, 2024, https://climatetechdigital.com/climate-technology/p-g-bio-ai-for-enhanced-cold-water-cleaning.; Procter & Gamble, "Tide's #TurnToCold Highlights the Benefits of Cold Water Washing," The P&G Blog, August 4, 2022, https://us.pg.com/blogs/benefits-tide-cold-water-washing/.

xliii Bryan Pietsch, Grace Moon, and Taylor Telford, "U.S. Baby Formula Shortage Is Worrying Parents. Here's What to Know.," *Washington Post*, May 11, 2022, https://www.washingtonpost.com/business/2022/05/11/baby-formula-shortage-similac-alimentum-elecare-fda/;
Karla Damian-Medina et al., "Cross-Sectional Analysis of Infant Diet, Outcomes, Consumer Behavior and Parental Perspectives to Optimize Infant Feeding in Response to the 2022 U.S. Infant Formula Shortage," *Nutrients* 16, no. 5 (January 2024): 748, https://doi.org/10.3390/nu16050748.

xliv "Checkerspot Unveils 'Breakthrough' for Baby Formula: Human Milk Fat Analog Made Using Microalgae Fermentation," *Vegconomist*, January 31, 2024, https://vegconomist.com/fermentation/checkerspot-baby-formula-human-milk-fat-analog-microalgae-fermentation/;
Jenna Gallegos, "Where Infant Formula Falls Short Synthetic Biology Comes Up Strong," SynBioBeta, August 24, 2023, https://www.synbiobeta.com/read/where-infant-formula-falls-short-synthetic-biology-comes-up-strong.

xlv Linda R. Rowan, "Critical Mineral Resources: National Policy and Critical Minerals List" (Congressional Research Service, April 8, 2024), https://crsreports.congress.gov/product/pdf/R/R47982/3.

xlvi Keith Bradsher, "China Tightens Its Hold on Minerals Needed to Make Computer Chips," *The New York Times,* October 26, 2024, sec. Business, https://www.nytimes.com/2024/10/26/business/china-critical-minerals-semiconductors.html.

xlvii Steven Arcidiacono et al., "The Current State and Future Direction of DoD Gut Microbiome Research: A Summary of the First DoD Gut Microbiome Informational Meeting," *Standards in Genomic Sciences* 13, no. 5 (March 20, 2018), https://doi.org/10.1186/s40793-018-0308-0.;
John Cryan, "Understanding the Multidirectional Axes of Communication between the Gut Microbiome and the Brain to Augment Human Performance" (Air Force Research Laboratory, April 23, 2020), https://apps.dtic.mil/sti/pdfs/AD1104391.pdf.

xlviii Benjamin Shemer et al., "Detection of Buried Explosives with Immobilized Bacterial Bioreporters," *Microbial Biotechnology* 14, no. 1 (January 2021): 251–61, https://doi.org/10.1111/1751-7915.13683.

xlix Joseph Flaig, "FEATURE: Building Biological Batteries Using DNA, Seaweed and Beeswax," *Institution of Mechanical Engineers*, December 1, 2023, https://www.imeche.org/news/news-article/feature-building-biological-batteries-using-dna-seaweed-and-beeswax#:~:text=Enhanced%20safety%20is%20another%20potential,has%20a%20lot%20of%20advantages.%E2%80%9D.

l National Academies of Sciences, Engineering, and Medicine, "Strategic Report on Research and Development in Biotechnology for Defense Innovation" (Washington, D.C., 2025), https://nap.nationalacademies.org/catalog/27971/strategic-report-on-research-and-development-in-biotechnology-for-defense-innovation.

li National Academies of Sciences, Engineering, and Medicine, "Strategic Report on Research and Development in Biotechnology for Defense Innovation" (Washington, D.C., 2025), https://nap.nationalacademies.org/catalog/27971/strategic-report-on-research-and-development-in-biotechnology-for-defense-innovation.

lii CHIPS and Science Act 15 U.S.C. §3722a (2023).

liii National Institute of Standards and Technology, "NIST Bioeconomy Lexicon," December 9, 2022, https://www.nist.gov/bioscience/nist-bioeconomy-lexicon.

liv Kevin Olsen, "The First 110 Years of Laboratory Automation: Technologies, Applications, and the Creative Scientist," *Journal of Laboratory Automation* 17, no. 6 (December 2012): 469–80, https://doi.org/10.1177/2211068212455631.

lv Emerald Cloud Lab, "Emerald Cloud Lab," 2025, https://www.emeraldcloudlab.com/.

lvi Jennifer Wong Leung, Stephan Robin, and Danielle Cave, "ASPI's Two-Decade Critical Technology Tracker: The Rewards of Long-Term Research Investment" (Australian Strategic Policy Institute, August 2024), https://ad-aspi.s3.ap-south-east-2.amazonaws.com/2024-08/ASPIs%20two-decade%20Critical%20Technology%20Tracker_1.pdf?VersionId=1p.Rx9MluZyK5A5w1SDKIpE2EGNB_H8r,.