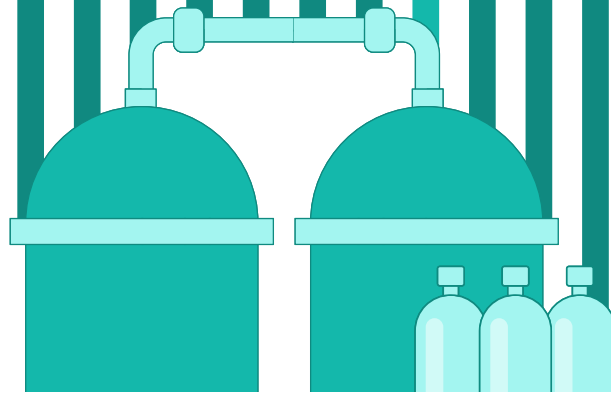
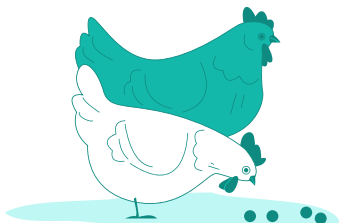
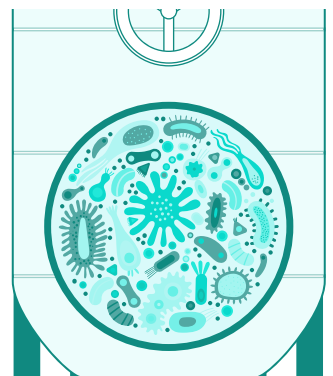




Advanced **Biotech**
for **Sustainability**

HARNESSING THE ECONOMIC AND ENVIRONMENTAL BENEFITS OF ADVANCED BIOTECHNOLOGY

MARCH 2025

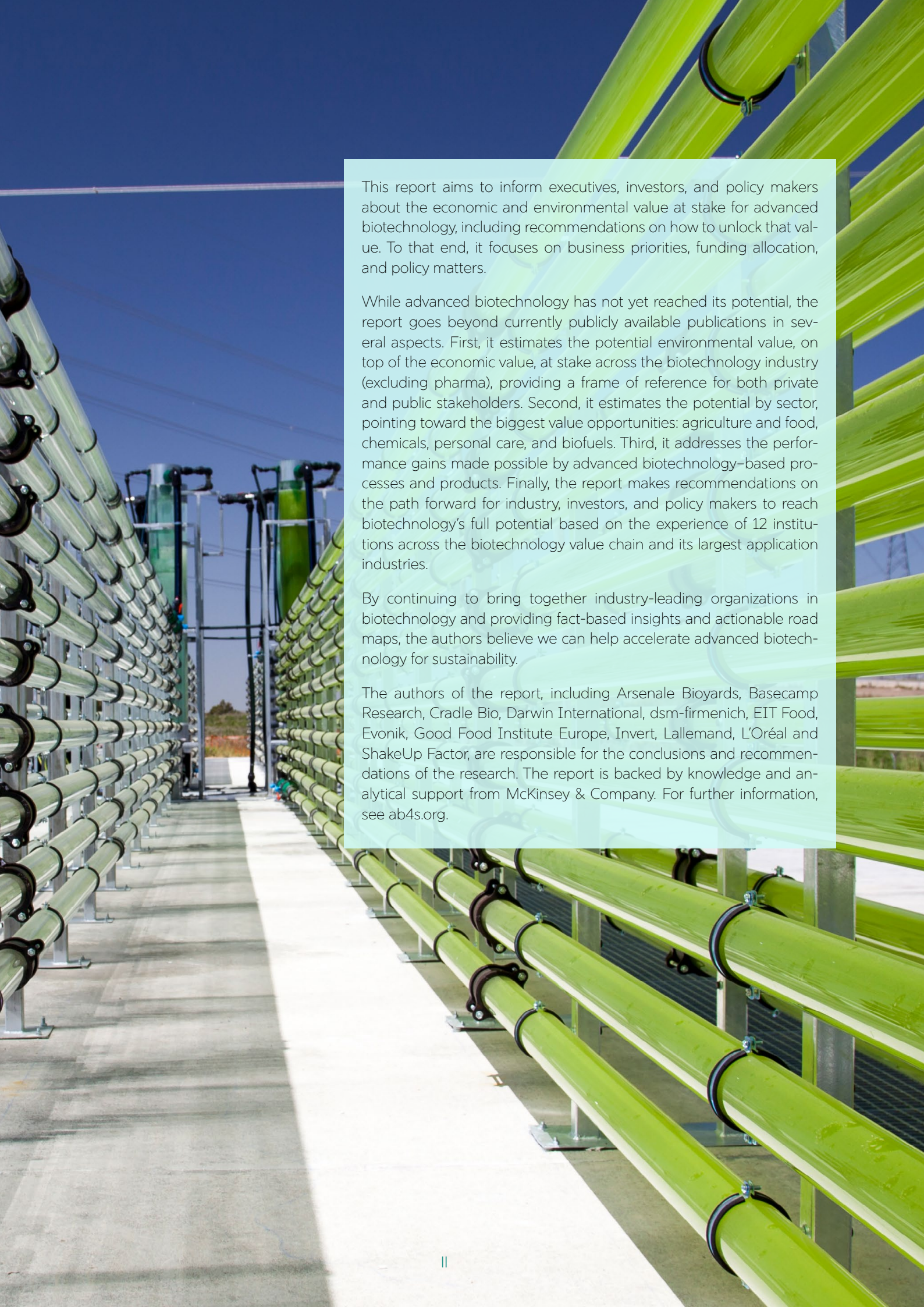




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This report aims to inform executives, investors, and policy makers about the economic and environmental value at stake for advanced biotechnology, including recommendations on how to unlock that value. To that end, it focuses on business priorities, funding allocation, and policy matters.

While advanced biotechnology has not yet reached its potential, the report goes beyond currently publicly available publications in several aspects. First, it estimates the potential environmental value, on top of the economic value, at stake across the biotechnology industry (excluding pharma), providing a frame of reference for both private and public stakeholders. Second, it estimates the potential by sector, pointing toward the biggest value opportunities: agriculture and food, chemicals, personal care, and biofuels. Third, it addresses the performance gains made possible by advanced biotechnology-based processes and products. Finally, the report makes recommendations on the path forward for industry, investors, and policy makers to reach biotechnology's full potential based on the experience of 12 institutions across the biotechnology value chain and its largest application industries.

By continuing to bring together industry-leading organizations in biotechnology and providing fact-based insights and actionable road maps, the authors believe we can help accelerate advanced biotechnology for sustainability.

The authors of the report, including Arsenale Bioyards, Basecamp Research, Cradle Bio, Darwin International, dsm-firmenich, EIT Food, Evonik, Good Food Institute Europe, Invert, Lallemand, L'Oréal and ShakeUp Factor, are responsible for the conclusions and recommendations of the research. The report is backed by knowledge and analytical support from McKinsey & Company. For further information, see ab4s.org.

PREFACE

In the face of unprecedented environmental challenges, the need to find sustainable and scalable solutions has never been more urgent. This report, *Harnessing the economic and environmental benefits of advanced biotechnology*, represents a collective effort by industry leaders to explore and advance the potential of biotechnology in creating a more sustainable future.

The promise of advanced biotechnology is profound: it can significantly advance the circular economy, deliver a reduction in greenhouse gas (GHG) emissions, and conserve natural resources, even as it delivers distinctive performance gains and creates substantial economic value. In past efforts, advanced biotechnologies have achieved neither the pace nor scale of their potential. Achieving a material shift in trajectory will require focused and strategic efforts across sectors from both advanced biotechnology players and supporting industries.

This report is a testament to the shared vision and commitment of the leaders and the institutions authoring the report. By providing fact-based insights and a unified framework that integrates financial and sustainability benefits, we aim to help set priorities and spark collaboration across the biotechnology value chain.

We hope this report serves as a catalyst for high ambition and bold action, as well as innovative partnerships that will drive the advanced biotechnology industry and its customers and partners forward, addressing some of the most pressing environmental risks of our time.

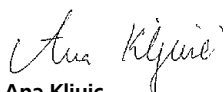
We extend our gratitude to all contributors and stakeholders who have supported this endeavor. Together, we can harness the power of advanced biotechnology to create a sustainable and resilient future.

Sincerely,

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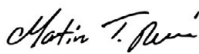
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The authors wish to give special thanks to all the experts who informed aspects of our research with their expertise and insights as well as the working groups involved.

**Backed by knowledge and
analytical support from
McKinsey & Company**



EXECUTIVE SUMMARY

Up to 60 percent of all physical inputs to the global economy . . . could be produced or replaced using biological methods.

Imagine a world in which biology is the basis of growth—where microbes are used to . . .

. . . feed the global population with tasty, nutritious, and protein-rich food while reducing emissions

. . . create consumer products that perform at a higher level while delivering a step change for the environment

. . . produce materials, chemicals, and fuels that are circular by design, perform better than the fossil alternative, and accelerate a transition to renewable feed-stocks

These are just some of the potential applications of advanced biotechnology, the subject of this report. As the world seeks solutions to improve livelihoods, grow economies, reduce supply chain vulnerabilities, and mitigate climate change risk, advanced biotechnology has the potential to deliver at-scale emission reductions and create significant improvement to lives and livelihoods.

Biotechnology has existed for millennia and is a cornerstone of our lives through fermentation, food conservation, medicines, and much more. In recent decades, technological breakthroughs in biotechnology have enabled new possibilities for sustainable bio-based solutions in many fields of industry, including food, cosmetics, medicine, chemistry, and even construction. We refer to this cutting edge in biotechnology science as advanced biotechnology. Advanced biotechnology leverages breakthroughs in biological sciences such as genetic engineering techniques, as well as advances in computing and engineering, to achieve the full potential use of microbes at scale. Up to 60 percent of all physical inputs to the global economy, encompassing both biological materials and nonbiological inputs, could be produced or replaced using biological methods.¹

1 *The Bio Revolution: Innovations transforming economies, societies, and our lives*, McKinsey, May 13, 2020.

While advanced biotechnology has demonstrated significant potential, it has not yet achieved the full scale of impact anticipated by industry leaders and stakeholders. We firmly believe that future goals can be more ambitious, positioning the industry on a more transformative trajectory. We believe it is critical to set bold ambitions for the future of bio-based products and rigorously embrace and evaluate their full life cycle impact, from resource sourcing and production to usage and end-of-life outcome.

This report outlines the state of advanced biotechnology in agriculture and food, chemicals, personal care, and fuels. It looks at what it would take to significantly scale up adoption of advanced biotechnology as a climate intervention. We focus on four advanced biotechnologies: precision fermentation, biomass fermentation, organism-as-a-product, and tissue-as-a-product. (For definitions of these and other terms, see the glossary.) While the concept of biotechnology and the excitement about it are not new, we take a fresh look, drawing on perspectives from practitioners and players in the industry to gauge advanced biotechnology's potential impact.

A significant part of advanced biotechnology's promise stems from its potential sustainability impact while also delivering tangible performance gains in the final product. It could support fully circular value chains, mitigate climate change, address freshwater shortages, reduce land use and deforestation, improve biodiversity and associated environmental pollution, enhance animal and human welfare, and address other sustainability challenges, largely by providing alternative pathways and products that reduce or eliminate GHG emissions. It can efficiently produce food, (bio)molecules, and fuels with a far smaller environmental footprint than conventional technologies by reducing emissions from conventional products and by providing low- or no-emission alternatives.

Until recently, however, advanced biotechnology solutions and products have not been able to compete with fossil-based products and solutions on scale or price. The biggest challenge for the industry is how to scale up industrially to produce goods more affordably for a growing global population and with a lower environmental impact and higher resilience to climate change and supply chain disruptions.

Our research suggests that the economic and environmental benefits of advanced biotechnology (excluding the pharmaceutical sector) could be substantial (exhibit).² The aspiration for 2040 includes the following:

- **Carbon abatement.** Reduce CO₂-equivalent emissions by three to four metric gigatons (Gt), equivalent to 5 percent or more of global emissions in 2022.³
- **Nature.** Free up about two million to four million square kilometers of land currently used for agriculture, about the size of India, which will also reduce chemical and plastic waste, and save on water use including about 250 billion to 500 billion cubic meters of freshwater annually.
- **Economic value.** Create about \$1 trillion in economic value across the value chain (about the size of Switzerland's economy), when measured through the full life cycle.

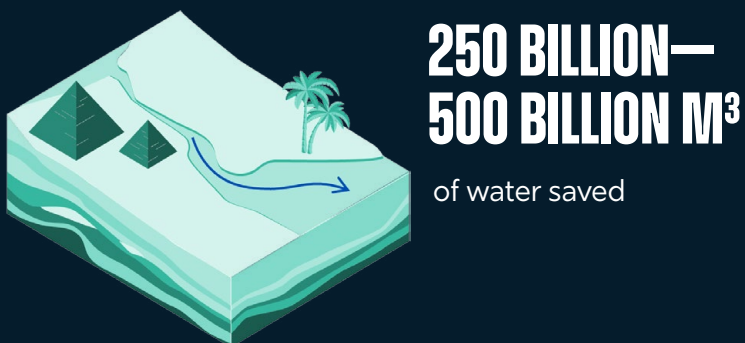
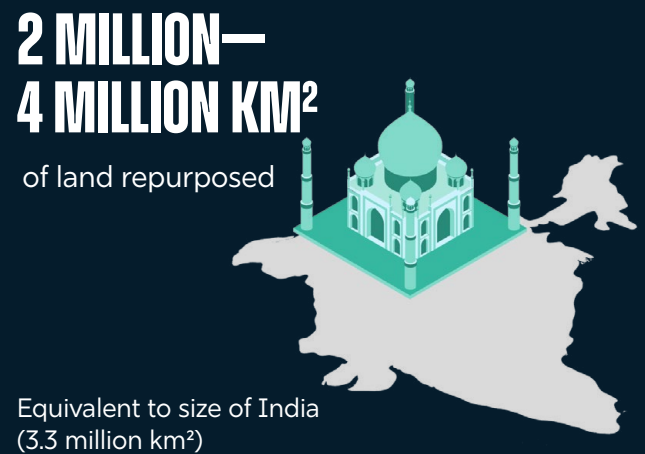
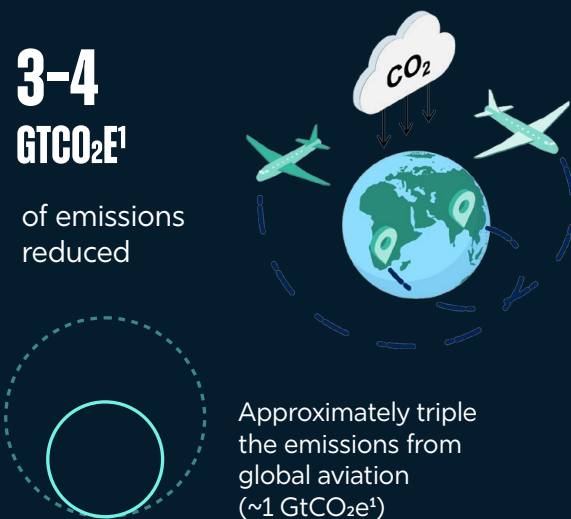
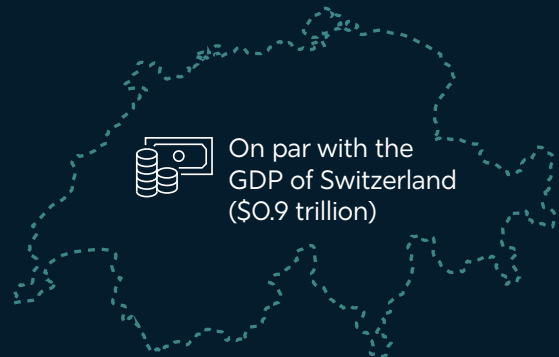
Our estimates for these 2040 aspirations are built with "full potential" methodology assuming a realistic best-case scenario in which non-physical roadblocks to technology adoption are removed (for example, feedstock availability, funding, public perception, and regulation) and excluding the impact from future bottlenecks. See the technical appendix for further details on limitations.

² See the methodology description in chapter 1 and the technical appendix for details of these calculations.

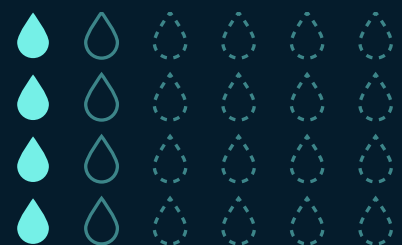
³ "GHG emissions of all world countries," European Commission, accessed September 12, 2024.

EXHIBIT

ADVANCED BIOTECHNOLOGY CAN PROVIDE NUMEROUS ECONOMIC AND ENVIRONMENTAL BENEFITS.



Equal to about 3× to 6× of all the water that flows through the Nile River annually (86 billion m³)



¹Metric gigatons of CO₂ equivalent.

In personal care and in industrial materials, we now see tangible cases in which advanced biotechnology is delivering products that customers value and that have additional performance advantages . . .

To create a flywheel effect and prompt a more ambitious adoption than currently seen, advanced biotechnology will also need to deliver real gains in functional performance. The pursuit of bio-derived drop-in molecules⁴ with a green premium has, to some extent, delayed the potential adoption of advanced biotechnologies. In personal care and in industrial materials, we now see tangible cases in which advanced biotechnology is delivering products that customers value and that have additional performance advantages through the full product life cycle.

To achieve this more ambitious adoption in a timely manner, the industry will need to drive down unit costs by achieving industrial-scale production, as some other cleantech segments have successfully achieved. For example, scaling onshore wind by a factor of 100 can lead to a cost reduction of approximately 80 percent.⁵ Industrial scale-up learnings could help the advanced biotechnology industry become cost competitive faster. That in turn would enable the industry to play in new markets and deliver the environmental impact we have sized.

ADVANCED BIOTECHNOLOGY'S LARGEST POTENTIAL IS IN AGRICULTURE AND FOOD, CHEMICALS, PERSONAL CARE, AND TRANSPORTATION FUELS

Our research assessed more than 500 use cases across sectors in which advanced biotechnology can make the largest sustainability and financial impact. We focus on four priority areas:

Agriculture and food. This sector contributes one-third of global GHG emissions, about half of global land use, and 70 percent of global water use.⁶ Advanced biotechnology can enhance the efficiency of crops and protein production—for instance, by producing drought-resistant and nitrogen-fixing crops and by producing alternative proteins via precision fermentation, biomass fermentation, or cultivated meat. Our research findings suggest that promoting the use of such products as an alternative to beef could reduce emissions and land use by up to 90 percent, depending on the scenario.⁷ In other cases, advanced biotechnology can reduce reliance on forage fish and intensive fishing or aquaculture practices through the production of algae oil. This serves as an alternative source of omega-3, which is traditionally obtained from fish oil, thereby supporting the preservation of marine ecosystems and wildlife.

Chemicals. Manufacturing of chemicals contributes about 4 percent of global GHGs.⁸ Plastics have a sustainability impact beyond how they are produced, including ocean pollution and microplastics that can end up in the food chain and beyond. Conventional fossil-based plastics release net carbon at their end of life. Advanced biotechnology can support the production of bioplastics such as polyhydroxyalkanoates (PHAs) and polylactic acid (PLA) through fermentation. It can improve plastic biodegradability through enzymatic depolymerization—that is, breaking down plastics (polymers) into building blocks for other plastics (monomers). Such advanced biotechnologies still face critical challenges, but PHA has the potential to reduce GHG emissions by as much as 75 percent compared with virgin conventional PET (polyethylene terephthalate) plastics.⁹

4 For example, chemicals derived from biomass, identical to their petroleum-derived counterparts (regardless of the feedstock). See “Drop-in chemicals,” European Commission, January 4, 2021.

5 For details, see McKinsey’s Platform for Climate Technologies.

6 Monica Crippa et al., “Food systems are responsible for a third of global anthropogenic GHG emissions,” *Nature Food*, March 2021, Volume 2, Number 6; Hannah Ritchie, Pablo Rosado, and Max Roser, “Environmental impacts of food production,” *Our World in Data*, 2022.

7 See the methodology description in chapter 1 and the technical appendix for details of these calculations.

8 Data from McKinsey’s EMIT database, 2021, based on EDGAR, Climate Trace, FAOSTAT, Global Carbon Project, and International Energy Agency. Estimate considers CO₂ equivalent without land use, land-use change, and forestry.

9 Forward-looking estimation as included in our analysis, considering existing research.

Personal care. Application of advanced biotechnology is already yielding material impact in the personal-care sector, and the segment could serve as a catalyst for other sectors to accelerate their progress. This has been achieved by focusing first on the full impact across the life cycle of materials and products, and then on functional performance advantages when replacing existing molecules with more-sustainable solutions (for example, biosurfactants that outperform current products). This approach has helped fuel consumer demand for more sustainable products currently seen in the market. This focus on life cycle and performance could form the basis of accelerated adoption beyond personal care—for example, in agricultural fertilizers and bio-derived fuels.

Transportation fuels. Transportation fuels contribute as much as 20 percent of global emissions.¹⁰ Various production pathways exist, with electrification already playing a significant role in reducing emissions for road transportation. However, electrification is not yet viable for all forms of transportation, such as long-distance and heavy-duty trucks, ships, and planes. Regarding the aviation sector, advanced biotechnology can play a role by partly substituting fossil fuel with sustainable aviation fuel through biomass fermentation, specifically alcohol-to-jet (AtJ), and by using feedstock that doesn't compete with food.¹¹ Using sustainable aviation fuel could reduce emissions by 50 percent or more compared with conventional kerosene.¹²

WHAT IT WOULD TAKE TO CAPTURE ADVANCED BIOTECHNOLOGY'S FULL POTENTIAL

If advanced biotechnology is to achieve the full market and sustainability potential we outline in this report, a fundamental rethink of the overall approach will be needed. There is no single solution; rather, several steps could be followed:

First, to build further proof points for the industry, prioritize resource allocation to advanced biotechnology products with the highest potential for accelerated adoption.

Second, derisk the scaling of advanced biotechnology production to increase success rates and reduce financing costs. An investment framework is required to finance the transition; investments needed would amount to at least an estimated \$500 billion by 2040 for fermentation alone. It will also be necessary to overcome regulatory obstacles, bridge talent gaps, and improve consumer awareness of the benefits of advanced biotechnology.

Third, improve cost effectiveness at scale, through execution and operational excellence. This can be achieved by strategies such as optimizing plant operations to minimize running costs; applying best practice capital investment methods to develop and commission additional capacity; and using flexible, modular design and shared capacity.

Numerous advanced biotechnology pathways are in development and fighting for the same resources, but few reach maturity because of resource competition.

10 "Driving the difference: Cars, trucks, and the road to net zero," McKinsey, November 21, 2021.

11 One company, LanzaTech, has already fueled a Virgin transatlantic flight with biojet fuel. See "Virgin Atlantic flies first transatlantic flight fueled by recycled carbon," Environment and Energy Study Institute, October 5, 2018.

12 See the methodology description in chapter 1 and the technical appendix for details of these calculations. See also "Sustainable Aviation Fuels (SAF)," European Union Aviation Safety Agency, accessed January 7, 2025.

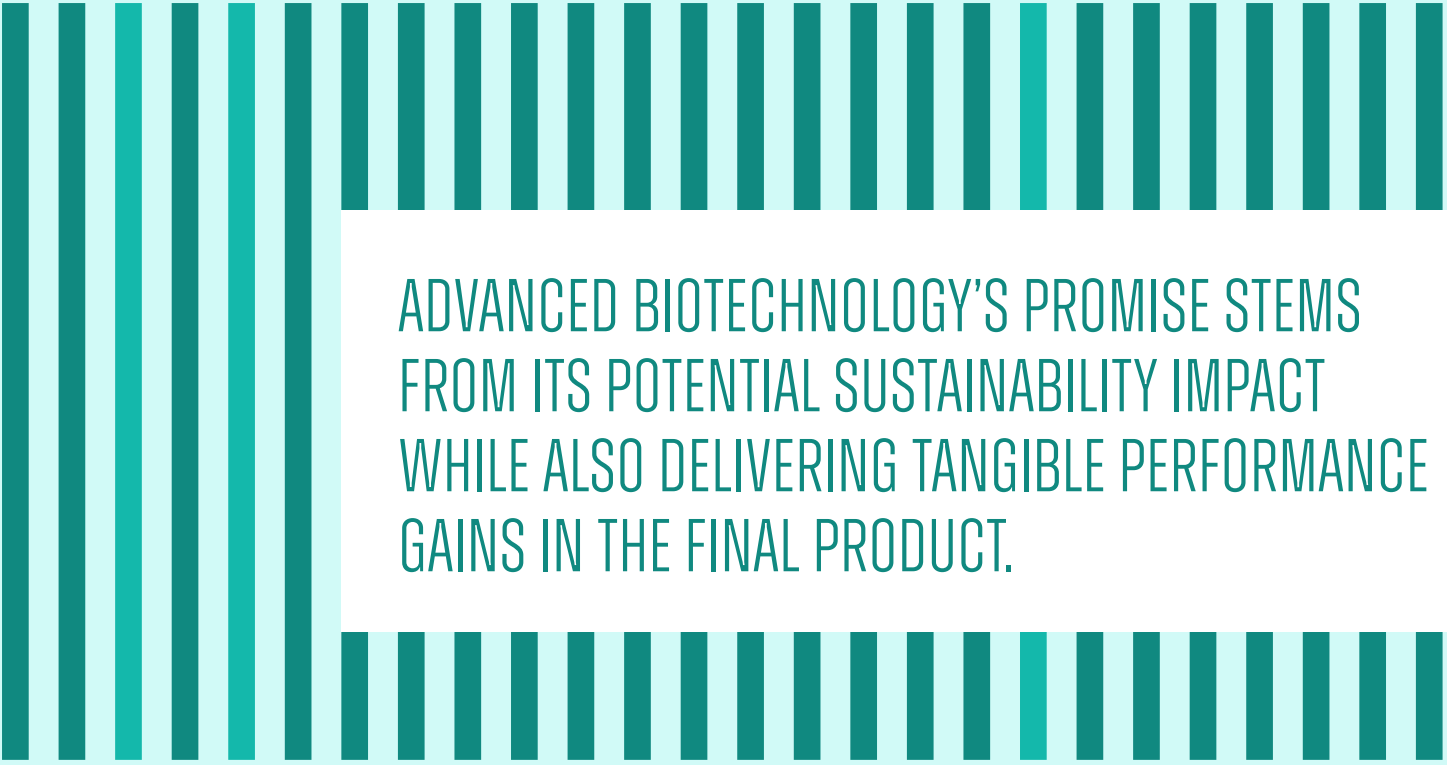
We also find that industrialization of advanced biotechnology at renewed pace and scale will rely on three enabling concepts:

- **Reduction of variables.** Minimize the variety of overall approaches across business and technology to focus resources efficiently. Numerous advanced biotechnology pathways are in development and fighting for the same resources, but few reach maturity because of resource competition. This leads to a dilution of effort and focus. Concentrating on fewer, more-promising technologies will ensure adequate attention and resources.
- **Standardization.** Create uniformity across processes, tools, roles, and technology to streamline operations, development, and scaling. This includes standardizing terminology, process tools, and methods; establishing uniform analytical techniques and process designs; and standardizing testing and measurement approaches. This standardization will play an important role in aligning investors, normalizing to standard processes, and accelerating lead times. It could, for instance, guide the holistic assessment of maturity level of projects and start-ups.

- **Shift to 'low-tech' deployment.** Transition advanced biotechnology from high-tech development to cost-effective, repeatable deployment of mature technology with mature and predictable supply chains while focusing on solutions that are easily replicable.



Advanced biotechnology is not a magic bullet for sustainability, but it does have significant potential to reduce environmental impact. With this report, we hope to contribute to shaping the agenda on these topics in three main respects. First, by providing fact-based, forward-looking insights into the potential of advanced biotechnology. Second, by tying together the financial and sustainability potential of advanced biotechnology into a unique framework to help organizations set priorities. Last, by providing a bold, unified vision of advanced biotechnology that is shared across the organizations authoring this report, which span various industries and steps in the value chain. In doing so, we hope to ignite fruitful collaboration to make that vision a reality.



ADVANCED BIOTECHNOLOGY'S PROMISE STEMS
FROM ITS POTENTIAL SUSTAINABILITY IMPACT
WHILE ALSO DELIVERING TANGIBLE PERFORMANCE
GAINS IN THE FINAL PRODUCT.



01 A FUTURE WITH ADVANCED BIOTECHNOLOGY

KEY TAKEAWAYS

- The market size for advanced biotechnology for non-pharma is \$200 billion to \$300 billion annually and could potentially reach \$700 billion to \$1.1 trillion by 2040. Broken down by sector, the market includes agriculture (\$205 billion to \$225 billion), food (\$130 billion to \$395 billion), chemicals (\$85 billion to \$100 billion), personal care (\$45 billion to \$75 billion), and transportation fuels (\$230 billion to \$320 billion).
- Advanced biotechnology has the potential to reduce carbon emissions by three to four metric gigatons, free two million to four million square kilometers of land, and save 250 million to 500 billion cubic meters of water annually. It also offers pollution reduction through bio-based ingredients and bioremediation, enhancing biodiversity.
- Technological, regulatory, and commercial advances—such as CRISPR-Cas9 gene editing, advances in sequencing technology, and AI-driven protein structure predictions—are shaping the biotechnology space.

Billions of years ago, microorganisms helped make Earth habitable for advanced organisms. They converted CO₂ to oxygen, fixed nitrogen, contributed to the formation of fertile soils, and played a role in regulating Earth's climate. Today, microorganisms are part of all life cycles on Earth in various ways, including the following:

- **Oxygen production.** Through photosynthesis, cyanobacteria release oxygen as a by-product. This ongoing process contributes significantly to maintaining the current levels of oxygen in Earth's atmosphere, which is essential for the survival of aerobic organisms including all animal life and humans.
- **Nitrogen fixation.** Bacteria such as rhizobium and azotobacter continue to convert atmospheric nitrogen into forms that plants can use. This ongoing process is crucial for plant growth and soil fertility, supporting agriculture and natural ecosystems, and closing natural elemental cycles.
- **Decomposition and nutrient cycling.** Microorganisms decompose organic matter, breaking it down into simpler compounds. This continuous process releases essential nutrients into the environment, ensuring their availability for other organisms and maintaining the balance of ecosystems.
- **Soil formation.** Fungi and bacteria break down rocks and minerals, releasing nutrients that contribute to the development of fertile soil. This process is essential for the formation of soil that can support plant life, which in turn supports entire ecosystems.

Through millions of years of evolution, microorganisms have typically evolved to reproduce with minimal inputs at high speed. For example, *Saccharomyces cerevisiae* (baker's yeast) can double in as little as 90 minutes.¹ Microorganisms are thus ideal "micro factories" that can be engineered to produce target products with low resource input and with minimal by-product. Biocatalytic reactions harness these microorganisms' quick metabolism and rapid reproduction time, with quick conversion to energy, biomass, and metabolites. For instance, genetically engineered *P. putida*, frequently used in bioremediation, has been shown to degrade more than 90 percent of selected pollutants in 48 hours.²

The types of applications that can be addressed with biotechnology range widely (Exhibit 1). Approximately 60 percent of all physical inputs to the global economy, including both biological materials (such as livestock for food) and nonbiological inputs (such as plastics and fuel), could be produced or replaced with alternatives using biological methods and sourced locally.³ People may use microorganisms and further advances in biotechnology as a means to live more sustainably, for instance, by reducing emissions generated by the production of goods that are used. For our research, we focused on a non-exhaustive selection of four types of advanced biotechnologies: precision fermentation, biomass fermentation, organism-as-a-product, and tissue-as-a-product.⁴ Each of these has the potential to effect significant positive change on society and on nature. For example, biofertilizers and biological crop protection applications of advanced biotechnology in agriculture and feed can reduce reliance on synthetic fertilizers and pesticides, improving soil health and reducing environmental impact.

1 Andrea A. Duina, Jill B. Keeney, and Mary E. Miller, "Budding yeast for budding geneticists: A primer on the *saccharomyces cerevisiae* model system," *Genetics*, 2014, Volume 197, Number 1.

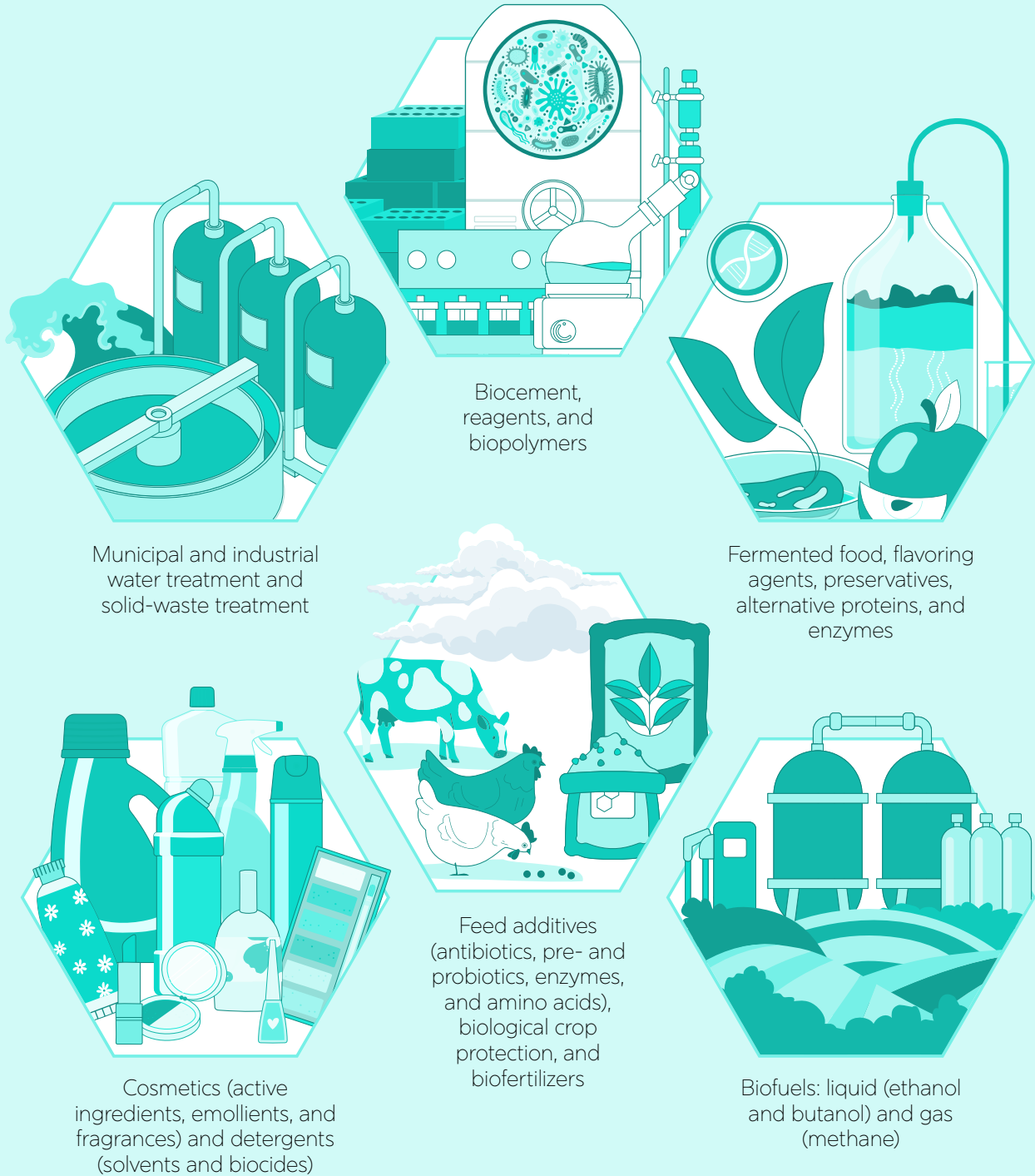
2 Yuping Liu et al., "Enhancing bioremediation potential of *pseudomonas putida* by developing its acid stress tolerance with glutamate decarboxylase dependent system and global regulator of extreme radiation resistance," *Frontiers in Microbiology*, September 2019, Volume 10.

3 *The Bio Revolution: Innovations transforming economies, societies, and our lives*, McKinsey, May 13, 2020.

4 See the glossary for definitions. These technologies map directly into the biomolecules and biosystems technologies identified in *The Bio Revolution*, May 13, 2020.

EXHIBIT 1

ADVANCED BIOTECHNOLOGY HAS APPLICATIONS ACROSS VARIOUS SECTORS.



ASSESSING THE FINANCIAL AND ENVIRONMENTAL POTENTIAL OF ADVANCED BIOTECHNOLOGY

The size of the market for advanced biotechnology is currently estimated at between \$200 billion and \$300 billion annually, according to our research. This mainly consists of certain segments for sustainable and bio-based alternatives to conventional production for which there is both demand and an attractive value proposition—for example, in the specialty chemicals or personal-care industry (such as enzymes, squalene, and hyaluronic acid). However, the potential market is far larger, with various opportunities for scaling advanced biotechnology to the next horizon.

In a full-potential scenario, we estimate that the total market size aspiration for these sectors could be between \$700 billion and \$1.1 trillion annually in 2040.

We have assessed the potential market size of advanced biotechnology in agriculture and food, chemicals, personal care, and transportation fuels. We selected these sectors based on two considerations: first, whether they encounter significant sustainability challenges, and second, whether advanced biotechnology has the potential to address these challenges. Advanced biotechnology is more

established in the agriculture and food sectors than in other sectors, but there remains room for further improvement. In the chemical industry, while we recognize that advanced biotechnology processes can be applied to a wide range of products,⁵ we focus on bioplastics, given the importance of plastic pollution⁶ and because we estimate that advanced biotechnology is below its potential in this segment. The personal-care sector operates downstream from the chemical sector but can significantly influence upstream sustainability improvements because of the higher margins that advanced biotechnology products can achieve in the industry. Last, while biofuels are a well-known solution to reduce greenhouse gas (GHG) emissions in transportation, we estimate that advanced biotechnology can play a role in addressing the expected increase in alternative fuel demand by 2040.⁷ Notably, we excluded the healthcare and pharma sector from our analyses. As a high-margin, low-volume industry, it faces distinct challenges—particularly in scaling and unit costs—that differ significantly from those of the industries we examined.⁸

In a full-potential scenario, we estimate that the total market size aspiration for these sectors could be between \$700 billion and \$1.1 trillion annually in 2040 (see Box 1, “Our methodology and its limitations,” and the technical appendix for details of this calculation).

5 For a broader view on how the fermentation process can be used in various use cases in the chemical industry, see Jens Nielsen, Dina Petranovic, and Christian Brix Tillegreen, “Innovation trends in industrial biotechnology,” *Trends in Biotechnology*, October 2022, Volume 40, Number 10.

6 “Plastic pollution,” UN Environment Programme, accessed December 20, 2024.

7 For instance, in the aviation sector, the demand for sustainable fuel is projected to increase from 0 million metric tons per annum (Mtpa) in 2021 to 13 to 56 Mtpa by 2035 and to 69 to 200 Mtpa by 2050. In contrast, the overall global oil demand for aviation, which includes biofuels and synthetic fuels, is expected to grow at a CAGR of 2 percent until 2050. See “Global Energy Perspective 2023: Sustainable fuels outlook,” McKinsey, January 10, 2024.

8 The healthcare and pharma sector in the context of biotechnology-derived therapeutics primarily focuses on high-value, low-volume therapeutics aimed at improving health outcomes, which contrasts with the broader sustainability and industrial-scale challenges analyzed in this report.

BOX 1: OUR METHODOLOGY AND ITS LIMITATIONS

We calculated the potential impact of advanced biotechnology across several sustainability dimensions by analyzing the “full potential” impact of specific use cases such as dairy and beef cows, bioplastics and enzymatic depolymerization, rice production, and sustainable aviation fuel. As noted in the technical appendix, the full-potential methodology helps assess the impact of a technology by assuming a realistic best-case scenario in which nonphysical roadblocks to technology adoption are removed.

For each use case, we calculated the “improvement potential” of advanced biotechnology—that is, the difference it could make—by estimating, first, the sustainability impact, in terms of greenhouse gas emissions, land use, and water use, on the conventional pathway and its penetration rate within this production route; and second, the sustainability impact via an alternative pathway through advanced biotechnology and the market share it could capture. Both the conventional pathway and the alternative pathway will be required for advanced biotechnology to achieve its full potential for all sectors, because advanced biotechnology solutions often take time to scale and reach full market adoption. During this time, the conventional pathway continues to meet demand, ensuring market stability and supply chain continuity.

We then extrapolated the impact of advanced biotechnology to other segments of the four sectors examined, using three lenses: the technological feasibility of the solution to products in other segments; the difference in adoption rates because of conventional biotechnology alternatives, regulation, or consumer awareness; and different environmental baselines affecting relative improvement potential. For the market sizing of each of the four sectors, we broke each sector into segments (such as animal feed in agriculture) and assessed whether advanced biotechnology could play a role. We then developed three scenarios—slow, medium, or fast uptake of biotechnology solutions. For further detail, see the technical appendix.

We acknowledge several limitations to this research. First, we realize the full potential we calculated depends on both technological and nontechnological factors, such as public opinion and the regulatory action of governments. Second, we based our analysis on currently available technologies and their expected development. If fermentation processes can feed on other molecules than today at the same cost as current processes, this would increase the full sustainability and market potential even more. Further limitations are detailed in the technical appendix.

This total market size aspiration by 2040 can be broken down as follows (Exhibit 2):

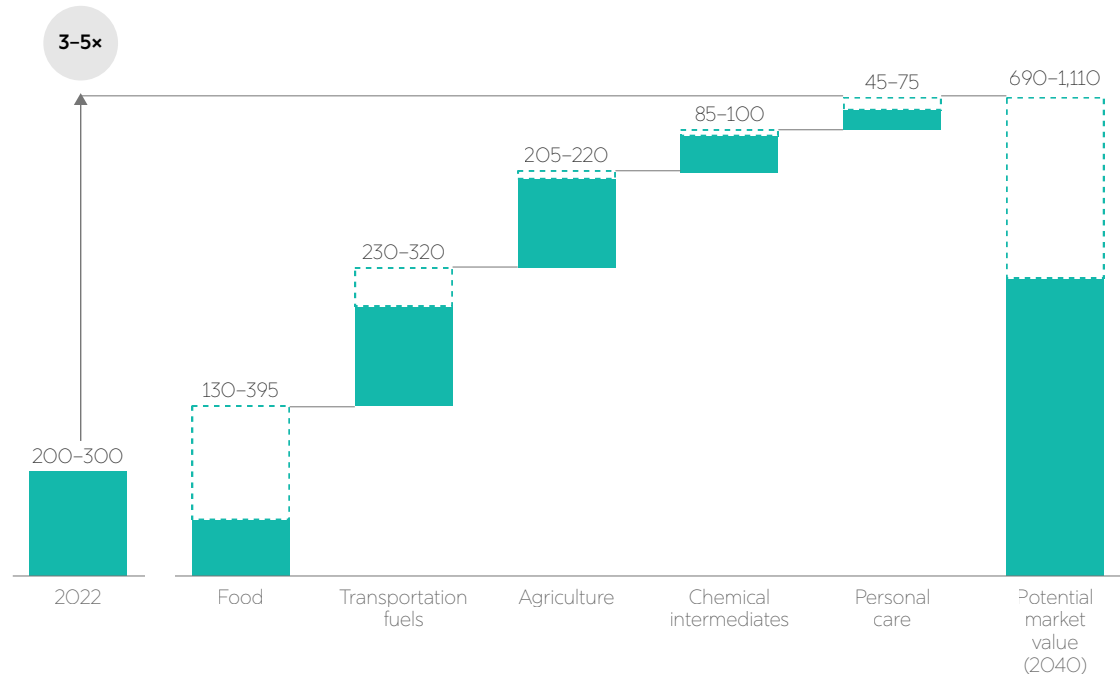
- **agriculture**, including improvements to yield and productivity of crops and animals, such as drought-resistant crops: \$205 billion to \$225 billion annually
- **food**, including alternative proteins such as fermented proteins (via precision or biomass fermentation) and cultivated meat (via tissue-as-a-product): \$130 billion to \$395 billion
- **chemical intermediates** for industrial applications, such as biopolymers and bulk and specialty chemicals: \$85 billion to \$100 billion
- **personal care** such as skin and facial care, fragrances, and hair and oral care: \$45 billion to \$75 billion; other sectors could look to personal care as an example of how to improve performance through a more sustainable solution
- **transportation fuels**, including liquid and gas biofuels such as fermented alcohols, aromatic hydrocarbons, or anaerobic digestion that can be further processed or directly blended with fuels and biogas or biomethane: \$230 billion to \$320 billion⁹

⁹ Note that these numbers reflect the global biofuels market, whereas the use case for sustainable aviation fuel is more narrowly focused on the biofuels produced with biotechnology in aviation. See the technical appendix for further details.

EXHIBIT 2

ADVANCED BIOTECHNOLOGY'S POTENTIAL MARKET VALUE IN 2040 IS ESTIMATED AT \$690 BILLION TO \$1,110 BILLION, WHICH IS THREE TO FIVE TIMES TODAY'S VALUE.

Potential market value of advanced biotechnology in 2040,¹ \$ billion



¹Ranges reflect the mid to high bound to indicate the full potential of advanced biotechnology.

Source: Enzymes Market, Marketsandmarkets; *The Bio Revolution: Innovations transforming economies, societies, and our lives*, McKinsey Global Institute, May 2020; McKinsey Vivid Economics Alternative Proteins Model

Beyond the potential market size, advanced biotechnology can have a direct sustainability impact. We focused our analysis on three of the nine “planetary boundaries”: climate change (GHG emissions), land-system change (land use), and freshwater change (water use).¹⁰ We selected these boundaries because they employ universally measurable methodologies. Based on this, we developed the following estimates:

Reducing carbon emissions. We estimated that advanced biotechnology has the potential to abate three to four metric gigatons of CO₂ equivalent (GtCO₂e) annually by 2040, or up to 14 percent reduction out of a 28 Gt in-scope baseline.¹¹ This is the equivalent of three to four

times the emissions of the entire aviation industry and about 5 percent of total global emissions in 2022.¹² Agriculture, chemicals, and fuels for transportation currently account for more than 50 percent of all GHG emissions.¹³

Optimizing land use. Advanced biotechnology has the potential to free up as much as four million square kilometers of land (or up to 6 percent of the 65 million square kilometers of global land usage for animal and plant farming)—equivalent to the size of India. Currently about 48 million square kilometers of the world’s habitable land—about 45 percent of the total—is used for agriculture, equivalent to five times the size of the United States.¹⁴ Advanced biotechnology in

¹⁰ The planetary boundaries framework proposed by Johan Rockström and colleagues in 2009 seeks to track Earth’s ability to support human life and development. It focuses on nine systems and processes that govern the stability of the Earth’s atmosphere, oceans, ice sheets, and ecosystems. See “Planetary boundaries,” Stockholm Resilience Center, accessed December 20, 2024; “Pulling back from the boundaries: An interview with Johan Rockström,” McKinsey, July 26, 2024.

¹¹ See chapter 1 and the technical appendix for details about the methodology and baseline used.

¹² “GHG emissions of all world countries,” European Commission, accessed September 12, 2024.

¹³ Agriculture, chemicals, and fuels for transportation account for 28 metric gigatons of CO₂ equivalent (GtCO₂e) in our analysis, whereas global GHG emissions in 2023 have reached 53 GtCO₂e. See “GHG emissions,” accessed September 12, 2024.

¹⁴ Hannah Ritchie and Max Roser, “Half of the world’s habitable land is used for agriculture,” Our World in Data, February 16, 2024.

agriculture has the potential to reduce by 3 to 6 percent the land used for agriculture if its full potential were applied today. In practice, this land-use reduction potential could be repurposed in different ways: society could leverage some of the freed-up land to grow feedstocks for other sectors, thereby improving overall farming output, or for land restoration to ensure more resilient ecosystems. By contrast, in two of the other sectors we examined—chemicals and transportation fuels—land use could increase with advanced biotechnology because of the switch from using fossil fuels to biomass in feedstock, assuming current agricultural productivity. Reducing (or not increasing) overall land footprint, while switching to circular feedstocks, in these sectors would require using advanced biotechnology to boost upstream agricultural productivity (not included in our calculations), making specific commitments also on land footprint, biodiversity, or both. Advanced biotechnology enables the transition to circular feedstocks by creating bio-based alternatives to fossil-derived inputs and by using agricultural residues, waste streams, and renewable resources more efficiently. These innovations reduce dependency on virgin materials and minimize environmental impact.

Reducing water use. Advanced biotechnology could potentially save 250 billion to 500 billion cubic meters of water annually (or up to 9 percent of the 5,650 billion cubic meters in scope).¹⁵ This is equivalent to between three and six times all the water that flows through the Nile every year. It could do so by providing an alternative to conventional agriculture, which is the largest user of freshwater.¹⁶ This reduction in water use would improve people's livelihoods and help reduce stress on water ecosystems. In practice, most of the potential for reduced water usage comes from agriculture, where we estimate that 70 billion to 150 billion cubic meters could be saved from animal farming and 190 billion to 335 billion cubic meters from plant farming. For instance, aerobic rice, beyond its impact in reducing GHG emissions, is estimated to require

about half as much water as conventional rice.¹⁷ By contrast, we estimate that scaling advanced biotechnology in chemicals could require up to 105 billion cubic meters of additional water use because bioprocesses usually occur in water-based environments.

Reducing pollution. While the primary approach to pollution reduction is to target the sources of environmental discharge, advanced biotechnology could provide support for this effort in two ways. First, it could encourage the shift away from inputs that could be more harmful to the environment—for example, by providing bio-based ingredients that degrade more effectively or environmental properties such as biofertilizers (an alternative for conventional pesticides and fertilizers, which significantly contribute to soil and water pollution¹⁸). Second, it could address pollution through bioremediation—that is, the degradation of persistent compounds present in the environment by microorganisms, specifically to break down plastics or clean up soils and improve biodiversity of land and marine life.

Improving food safety and security. Advanced biotechnology could help reduce pressure on demand for food without affecting affordability at a time when the world's population is increasing and consumption is rising as more people move into the middle class. Food production everywhere needs to increase, but doing so will require greater efficiency. Precision- or biomass-fermentation processes could help—for example, with production of dairy proteins. Advanced biotechnology could make food production more resilient to shocks: chickens can catch bird flu and harvests can fail, but advanced biotechnology production output could be less dependent on weather and less exposed to other disruptions, including supply chain snarls, pandemics, and geopolitical events. It could also offer consumers animal-free alternatives with similar taste, texture, or nutrients that would not require substantial diet shifts. Moreover, advanced biotechnology can supply products with

15 See the technical appendix and chapter 1 for detailed methodology (including the baseline level).

16 "Environmental impacts of alternative proteins," Good Food Institute, accessed December 20, 2024.

17 Shu Fukai and Jaquie Mitchell, "Factors determining water use efficiency in aerobic rice," *Crop and Environment*, March 2022, Volume 1, Number 1.

18 Wasim Aktar, Ashim Chowdhury, and Dwaipayan Sengupta, "Impact of pesticides use in agriculture: Their benefits and hazards," *Interdisciplinary Toxicology*, March 2009, Volume 2, Number 1.

additional nutritional and health benefits, as well as lower environmental pollution, by leveraging techniques such as precision fermentation to produce pure, essential molecules, such as amino acids, vitamins, oligosaccharides, and enzymes, which are contaminant-free compounds, and alternatives for fish oil without pollutants such as heavy metals and microplastics.

Geopolitical independence. Because food supply risks are often intertwined with geopolitical dependencies, governments are looking for ways to limit these risks. Several wealthy states with limited arable land are highly dependent on foreign produce, including beef and dairy products. Advanced biotechnology can help regions and governments achieve strategic autonomy because of its relative independence; feedstock, which can typically be altered, is the main supply requirement.

TECHNOLOGICAL, REGULATORY, AND COMMERCIAL ADVANCES ARE SHAPING THE BIOTECHNOLOGY SPACE

Recent technological advances, such as new genomic techniques, and the integrated deployment of these advances have opened a realm of opportunities to produce molecules in a more efficient, fast, and cost-effective way.

On the technology front, genetic engineering and strain development are advancing. For example, the CRISPR-Cas9 gene-editing system, published in 2012, allows scientists to selectively modify genes with extraordinary precision and speed.¹⁹ Combined with other modern genomic techniques, this enables the targeted alteration of organisms—for example, to introduce novel traits or to increase or decrease already existing functions.

AI and automation can already play a role in speeding up the modification of microorganisms for a broad variety of application fields.

By analyzing large data sets to identify optimal gene sequences and predict successful modifications, AI increases the likelihood of finding solutions that succeed in field and laboratory trials. While these trials remain necessary, AI significantly enhances the efficiency and probability of success. For instance, in agricultural biotechnology, AI-driven genomic techniques can identify and test gene sequences that enhance crop resistance to pests or improve yield, leading to better outcomes in less time.²⁰ This integration of AI and genomic techniques opens a path to many new applications and new feedstocks in a shorter amount of time and at a more competitive cost.

Finally, cultivation and fermentation technologies are advancing, enabling the development of new products.²¹ For example, fermentation can improve the nutritional value of alternative proteins, used in plant-based meats. In contrast, cultivated meats are produced by culturing animal cells to create meat that is molecularly identical to conventional meat. Deploying these technologies simultaneously could potentially accelerate the scaling of advanced biotechnology: with multiple viable solutions, there would be broader positive reinforcement from the multis-takeholder ecosystem needed for scaling.

On the regulatory front, new regulations and policies worldwide are being put in place or are under discussion and revision. It remains to be seen what their impact on the sector will be, including their effects on certain bio-solutions, whether they would create go-to-market opportunities, and provide access to funding and support. For example, the United States has increased investments to more than \$3.5 billion since 2022 under the Bioeconomy Executive Order, which also encompasses the National Biotechnology and Biomanufacturing Initiative (NBBI),²² and in 2024, the European Union announced a plan to boost biotechnology and biomanufacturing.²³

19 Adam Cribbs and Sumeth Perera, “Science and bioethics of CRISPR-Cas9 gene editing: An analysis towards separating facts and fiction,” *Yale Journal of Biology and Medicine*, December 2017, Volume 90, Number 4.

20 Sarah Hearne et al., “Artificial intelligence in plant breeding,” *Trends in Genetics*, October 2024, Volume 40, Number 10.

21 “The science of fermentation,” Good Food Institute, accessed December 20, 2024.

22 “White House releases report on growing U.S. biomanufacturing capacity for the American bioeconomy,” White House, November 15, 2024.

23 For EU initiatives, see “Commission takes action to boost biotechnology and biomanufacturing in the EU,” European Commission, March 19, 2024. For US initiatives, see “Executive order on advancing biotechnology and biomanufacturing innovation for a sustainable, safe, and secure American bioeconomy,” White House, September 12, 2022.

Finally, in terms of commercialization, advanced biotechnology is reaching an inflection point with a strong consumer push for sustainable products in recent years. Growing consumer awareness about sustainability is driving this demand for sustainable products and reducing dependency on fossil fuels. A 2023 McKinsey survey found that 28 percent of consumers are willing to pay a price premium for environmentally friendly products, with this willingness particularly high among younger generations: 48 percent of millennials and 49 percent of Gen Z consumers expressed readiness to spend more on sustainable goods.²⁴ However, it is still unclear whether declared intentions translate into concrete purchase decisions on a broad scale.²⁵ Economic pressures have led many consumers to prioritize affordability, and educating consumers will be necessary to ensure adoption of biotechnology products. Currently, consum-

er adoption requires acceleration because of mixed attitudes toward these technologies. For example, in the United States, public opinion polls about biotechnology food products indicate support for mandatory labeling and also suggest a general lack of knowledge.²⁶

Companies have also been making commitments to sustainability targets, helping propel this market push for sustainable alternatives. The Science Based Targets Initiative (SBTi) is one leading driver; as of November 2024, the SBTi had validated the GHG reductions of more than 9,400 companies.²⁷ Other initiatives, such as the Science Based Targets Network (SBTN) and the Taskforce on Nature-related Financial Disclosures (TNFD) address broader sustainability issues, including biodiversity and nature-related risks, and are also gaining traction.²⁸

24 *The Week in Charts*, "Buying into sustainability," McKinsey, October 20, 2023.

25 McKinsey Global Consumer Sentiment survey, Q3 2024.

26 Elise Golan, Demcey Johnson, and Robbin Shoemaker, "Consumers and the future of biotech foods in the United States," Economic Research Service, November 1, 2023.

27 "Companies taking action," SBTi, accessed November 2024.

28 "Empowering companies and cities for credible nature action," Science Based Targets Network, accessed December 20, 2024; TNFD website.



RECENT TECHNOLOGICAL ADVANCES, SUCH AS
NEW GENOMIC TECHNIQUES, AND THE INTEGRATED
DEPLOYMENT OF THESE ADVANCES HAVE OPENED A
REALM OF OPPORTUNITIES TO PRODUCE MOLECULES IN
A MORE EFFICIENT, FAST, AND COST-EFFECTIVE WAY.



02 ADVANCED BIOTECHNOLOGY'S POTENTIAL ACROSS SECTORS

KEY TAKEAWAYS

- **Agriculture and food:** Advanced biotechnology could improve the security of supply, reduce emissions by 2.8 to 3.3 metric gigatons of CO₂ equivalent (GtCO₂e), decrease land use by 2.2 million to 3.9 million squared kilometers, and save 260 billion to 490 billion cubic meters of water, using precision and biomass fermentation and cultivated meat, applied in use cases such as alternative proteins and algae-derived oils.
- **Chemicals:** Advanced biotechnology could reduce reliance on fossil feedstocks and lower emissions by 0.1 to 0.3 GtCO₂e, while slightly increasing land and water usage, with bio-based chemicals and enzymes such as bio-based plastics (PHA) and microbial fertilizers.
- **Personal care:** Advanced biotechnology can reduce reliance on fossil-derived materials and enhance the life cycle and functional performance of products through bio-based ingredient alternatives such as biosurfactants.
- **Transportation fuels:** Advanced biotechnology can produce biofuels such as sustainable aviation fuels through fermentation or anaerobic digestion, potentially reducing emissions up to 0.4 GtCO₂e while slightly increasing land and water usage.
- **Increased efficiency:** Advanced biotechnology is able to create superior production systems (for example, cutting out a number of steps) by using resources more efficiently.
- **New opportunities:** Advanced biotechnology provides opportunities to build new businesses in at-scale markets by addressing niche high-value applications that eventually become cost-competitive with lower-value mass applications.

We assessed the sustainability potential of a range of industry sectors to determine the ones for which advanced biotechnology could have the biggest potential environmental impact. Four sectors stood out: agriculture and food, chemicals, personal care, and transportation fuels (Exhibit 3).²⁹ These four jointly contribute about 50 percent of GHG emissions.³⁰

Beyond reducing emissions, advanced biotechnology offers transformative potential to enhance sustainability across sectors. It can address critical challenges such as optimizing nutrient applications, preserving biodiversity, and promoting circularity. Additionally, it can improve product performance by complementing and enhancing existing solutions rather than replacing them, paving the way for both environmental and economic progress.

This chapter provides an in-depth examination of the potential for advanced biotechnology in each of these sectors, including illustrative use cases.

- In agriculture and food, our analysis found that advanced biotechnology can significantly reduce emissions and use of land, water, conventional fertilizers, and pesticides throughout the value chain. This can be achieved through several mechanisms, including more-efficient use of resources, the use of feed additives that improve digestibility and reduce emissions, and the development of alternative protein sources with a lower environmental impact than traditional animal agriculture. Through these mechanisms, advanced biotechnology can enhance resource efficiency, leading to more sustainable agricultural practices. By 2040, according to our analysis, fermented foods could capture about 20 percent of the total

market value of cultivated and fermented proteins, while cultivated foods could capture about 80 percent of this market value because of its higher price. In agriculture, improvements in yield and quality for livestock could capture about 80 percent of the market, with the largest share driven by advances in animal feed and selective breeding.

- In the chemical sector, advanced biotechnology solutions could help reduce the use of fossil sources by using renewable feedstocks, decrease the environmental impact of the manufacturing process, and improve the end of life of products through biodegradability and lower toxicity. Within this sector, chemicals for food and nutrition, such as amino acids, peptides, and organic acids, could capture about 40 percent of the market value by 2040, according to our analysis, while chemicals for materials and enzymes could also capture about 40 percent of the market, including applications such as amylase and protease.
- In the personal-care sector, advanced biotechnology solutions can help reduce emissions by increasing the feedstock efficiency of existing ingredients and by providing bio-based alternatives to these ingredients altogether. This could support circularity and biodegradability at the product's end of life.³¹ Additionally, advanced biotechnology can enhance product functionality and sustainability by offering bio-based alternatives that complement existing solutions. Beauty and care products will capture about 65 percent of the market value in this sector by 2040, according to our analysis, with probiotics and prebiotics forming the rest of the market value.

29 No sustainability impact assessment has been conducted for the personal-care sector to avoid double counting, because it operates downstream in the chemical industry.

30 Agriculture, chemicals, and fuels for transportation account for 28 GtCO₂e in our analysis, whereas global GHG emissions in 2023 reached 53 GtCO₂e. See "GHG emissions," accessed September 12, 2024.

31 Emission reductions are used to showcase the potential impact of advanced biotechnology. While life cycle assessments (LCAs) offer a more comprehensive evaluation of environmental benefits, these are inherently product-specific and vary significantly depending on application and use case.

EXHIBIT 3

ADVANCED BIOTECHNOLOGY COULD SUBSTANTIALLY REDUCE ENVIRONMENTAL STRESS.

Potential of reducing impact on planetary boundaries from advanced biotechnology solutions



Note: Figures may not sum to totals, because of rounding.

Source: Food and Agriculture Organization; Intergovernmental Panel on Climate Change; Our World in Data; McKinsey analysis

- In the transportation fuel sector, several sustainable production pathways exist, including Power-to-X, Fischer-Tropsch gasification, renewable natural gas, and green ammonia. Advanced biotechnology can play a role in this—it could produce biofuels through fermentation or anaerobic digestion for applications including sustainable aviation fuel (SAF). Alcohol-to-jet fuels through fermentation could capture about 40 percent of the biofuels produced through advanced biotechnology market value by 2040, according to our analysis, while anaerobic digestion into biogas could account for about 60 percent of the market value.

Our findings contain some overarching learnings for the successful development of advanced biotechnology. We identify current limitations and necessary advancements to integrate advanced biotechnology into the four focus areas.

While it is possible to reduce emissions in conventional pathways, alternative production pathways are required to leapfrog to a net-zero world. To drive these initiatives and overcome challenges associated with sustainable development requires an interplay among technological advances, financial mechanisms, and adequate policies.

Advanced biotechnology could have a big role in both driving innovation . . . and potentially reaching commercial scale over time . . .

First, to fully capture material sustainability improvements, fermentation technologies including upstream and downstream processing will need to improve the technology and eco-

nomics of alternative feedstocks. Existing sugar feedstocks alone will not suffice as an alternative. Advanced biotechnology could have a big role in both driving innovation by addressing niche high-value applications and potentially reaching commercial scale over time, eventually becoming cost competitive with lower-value mass applications.

Second, financing mechanisms are essential for making advanced biotechnology solutions cost competitive and supporting their implementation. Currently, sustainable products are often more expensive—partly because of the mature and industrialized state of the agriculture and fossil fuel industries, as well as the exclusion of climate impact costs from their pricing. To bridge this gap, cofinancing solutions—such as subsidies and performance- and sustainability-linked loans and bonds—may be needed. These mechanisms provide incentives for sustainable practices, offset initial costs, and provide future price stability, thereby promoting the adoption of sustainable solutions.

Third, regulatory and policy approaches can help foster advanced biotechnology innovation and development. One goal could be to derisk biotechnology developments through support for the research, development, production, and marketing of biotechnological production, thereby helping ensure that advanced biotechnology's potential impact can become a reality.³² Exhibit 4 provides a high-level summary of the use cases by sector discussed in the report. The individual sector write-ups below provide more details and sources.

32 An example of how policy can accelerate innovation and adoption of new technologies in non-biotechnology-related fields is Norway's move to exempt electric vehicle drivers from toll and parking charges, which has spurred electric vehicle sales. See Felix Richter, "How Norway is racing ahead on EVs," World Economic Forum, January 6, 2023.

EXHIBIT 4

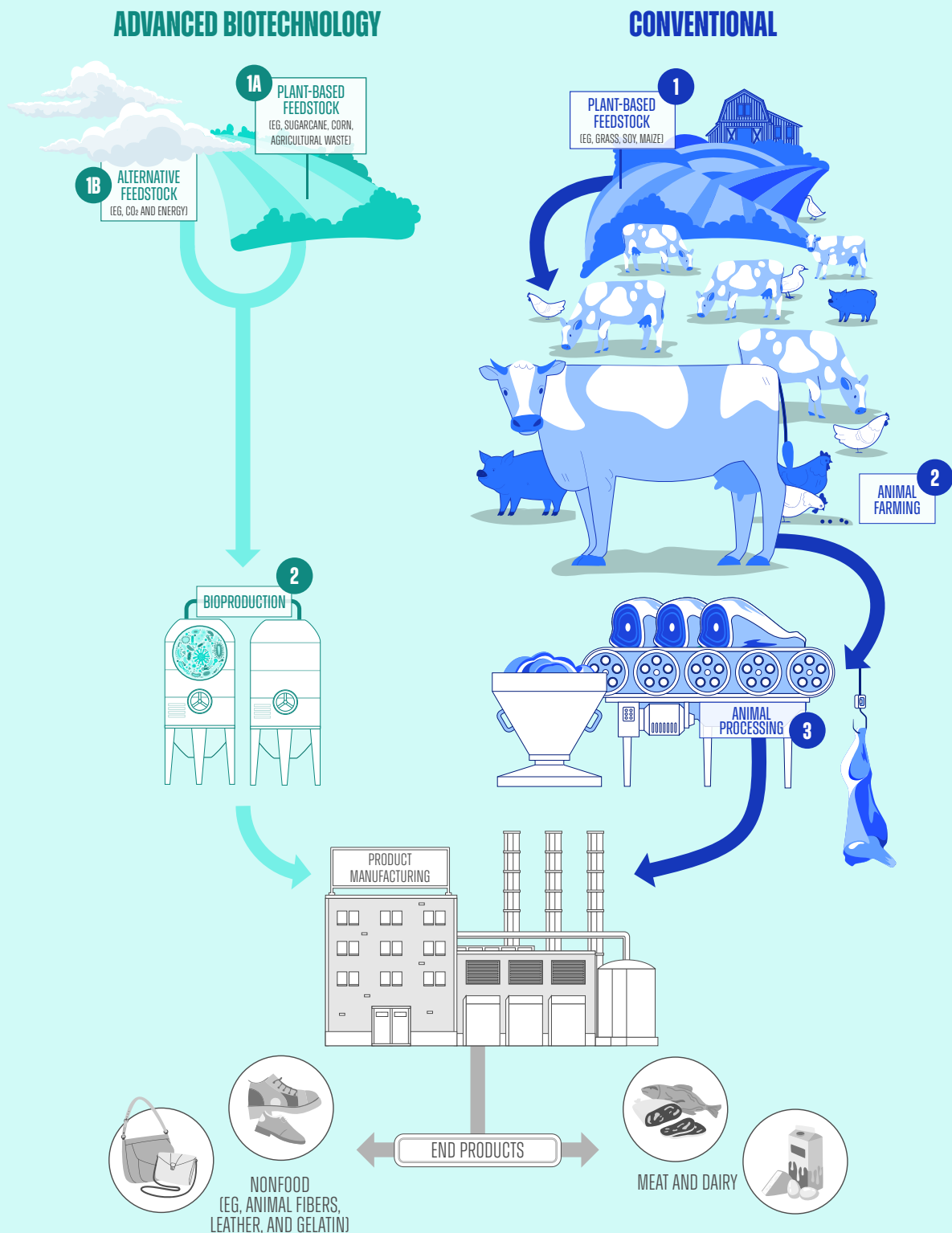
ADVANCED BIOTECHNOLOGY PROVIDES ALTERNATIVES ACROSS THE FOUR SECTORS.

Sector and use case		Product		Potential (environmental) impact
		Conventional	Alternative	
FOOD AND AGRICULTURE	MEAT AND DAIRY	 Animal-derived protein	 Alternative protein	- Lower greenhouse gas (GHG) emissions (especially from methane) - Less land and water required due to more efficient feedstock conversion to protein
	FISH OIL	 Fish-derived omega-3	 Algae-derived omega-3	- Lower GHG emissions - Reduce the reliance on forage fish as traditional source of omega-3 - Provide a stable, predictable, and secure supply
CHEMICALS	PLASTICS	 Fossil-based plastic	 Bio-based plastics (PHA)	- Lower life cycle GHG emissions - Biodegradable alternatives in marine and land environments - Improved end of life and versatile
	FERTILIZER	 Nitrogen fertilizer	 Microbial fertilizer	- Lower life cycle GHG emissions - Less water use - Enabled restoration of degraded soils with limited ecosystem disruption - Reduced nitrogen effluents
PERSONAL CARE	SURFACTANTS	 Fossil-based surfactants	 Bio-based surfactants	- Lower life cycle GHG emissions - Improved well-being of consumers (eg, relieved skin irritation) - Improved end of life
TRANSPORT FUELS	AVIATION FUEL	 Kerosene	 Alcohol-to-jet	- Lower GHG emissions from global aviation fuel - More land and water required (depending on feedstock) - Diverse range of feedstock

2A AGRICULTURE AND FOOD: REDUCING THE ENVIRONMENTAL FOOTPRINT

EXHIBIT 5

IN FOOD AND AGRICULTURE, ADVANCED BIOTECHNOLOGY HAS GREAT POTENTIAL TO COMPLEMENT CONVENTIONAL TECHNOLOGIES BY PRODUCING END PRODUCTS MORE RESOURCE-EFFICIENTLY.



The case for advanced biotechnology

The agriculture and food sectors have been subject to a range of economic, geopolitical, and climate-related shocks in recent years. These include sharp increases in food prices,³³ geopolitical disruptions to supply stemming from Russia's invasion of Ukraine, and severe weather events linked to climate change. At the same time, the demand for food is expected to continue to rise.³⁴ In this context, the food sector is looking for opportunities to build in climate resilience and decouple supply chains from seasonal and geopolitical supply chain shocks, to guarantee food security and safety for consumers at affordable prices. Moreover, consumers—especially in Europe and the United States—are becoming more conscious of the environmental impact of their food. However, consumer sentiment is mixed: while some surveys suggest that approximately 30 percent of consumers plan to spend more on environmentally friendly food products and that many consumers are shifting toward incorporating more environmentally friendly products in their diets, economic pressures have also led many to prioritize affordability.³⁵ Governments are also striving to establish regional food sovereignty and independence.³⁶

Livestock are a major contributor to GHG emissions, land use, and water; they account for 14.5 percent of global GHG emissions and use 27 percent of the world's land (which translates to 77 percent of all agricultural land).³⁷ GHG emissions and land use vary widely across food

sources. For example, depending on the feedstock, aquaculture generates less than 10 percent of the GHG emissions produced by beef.³⁸ Beef (herd) requires 164 square meters of land per 100 grams of protein, whereas farmed fish needs just four square meters per 100 grams of protein.³⁹ This land-use metric includes not only the physical space occupied by the animals or aquaculture infrastructure but also the land needed to produce feed, such as soy or other crops. Cattle alone contribute about two-thirds of livestock GHG emissions.⁴⁰ Among crops, rice has one of the highest environmental footprints. This is because of the sheer size of production as well as the need to flood rice fields, which releases methane into the air.

Advanced biotechnology can enhance the sector's resilience by developing drought- and disease-resistant crops and animal-free protein alternatives.

How advanced biotechnology could address the challenges

Advanced biotechnology can improve the efficiency of food and agriculture practices by enhancing natural processes. Advanced crop breeding can fix nitrogen, improving soil fertility and reducing the need for synthetic fertilizer use.⁴¹ For example, biotechnology-enabled feed additives can inhibit methane-producing microbes in the digestive system, reducing GHG emissions.⁴²

33 Inflation-adjusted FAO Food Price Index.

34 The World Resources Institute estimates that demand for food will increase by 56 percent from 2010 to 2050 based on "usual" growth of the population to ten billion in 2050. See Craig Hanson et al., "How to sustainably feed 10 billion people by 2050, in 21 charts," World Resources Institute, December 5, 2018.

35 *The agricultural transition: Building a sustainable future*, McKinsey, June 27, 2023.

36 Gustavo Gordillo and Obed Mendez Jeronimo, *Food security and sovereignty*, FAO, 2013.

37 *Livestock solutions for climate change*, FAO, 2017; "50% of all land in the world is used to produce food," World Economic Forum, December 11, 2019.

38 Our analysis shows that cows emit 6.50 GtCO₂e, whereas aquaculture only generates 0.25 GtCO₂e. See Heidi K. Alleway et al., "Climate-friendly seafood: The potential for emissions reduction and carbon capture in marine aquaculture," *BioScience*, February 2022, Volume 72, Number 2.

39 "Land use per 100 grams of protein," Our World in Data, accessed December 20, 2024.

40 *Livestock solutions*, 2017.

41 The Engineering Nitrogen Symbiosis for Africa (ENSA) project, supported by the Bill & Melinda Gates Foundation, aims to enhance nitrogen fixation in nonleguminous crops. By enabling these crops to form beneficial relationships with nitrogen-fixing bacteria, ENSA seeks to improve soil fertility and reduce reliance on synthetic fertilizers.

42 Jane Byrne, "US study supports methane emission reduction claims for DSM feed additive," FeedNavigator, June 25, 2020; "Background information on Bovaer, the feed additive that enables farmers to achieve consistent methane emission reductions by on average 30% for dairy cows and on average 45% for beef cattle," DSM, March 2023.

Advanced biotechnology can enhance the sector's resilience by developing drought- and disease-resistant crops and animal-free protein alternatives. Genetic engineering and CRISPR technologies enable precise modifications to enhance stress tolerance and resistance to pests and pathogens. Bio-solutions, such as alginates derived from brown algae, bio fungicides, or amino acids, are developed to condition soil and enhance growth.⁴³ These innovations can produce crops and livestock that are more resilient, reducing reliance on chemical inputs and improving yields (see Box 2, "Approach to genetically modified crops").

Advanced biotechnology can also drive development and adoption of animal-free and sustainable alternatives.⁴⁴ It can do this through various processes including precision fermentation for more environmentally efficient production of egg, dairy, or fungal proteins through precision or biomass fermentation as well as tissue-cultured technology for cultivated meat. These advanced biotechnology solutions can help enhance product features, such as higher protein content or improved nutritional profiles,

while meeting consumer expectations of taste and texture that are consistent with traditional products at acceptable price points.⁴⁵ For example, a 2024 report by the Good Food Institute found that more than 60 percent of US consumers expressed a willingness to try cultivated meat. After consumers were given a description of cultivated meat that emphasized how it can look, cook, and taste the same as conventional meat, the share who said they found cultivated meat very or somewhat appealing rose from 19 percent to 31 percent.⁴⁶

Farmers and industry are already working on reducing this environmental footprint. Changing farming practices, electrifying machinery, and other measures have the potential to reduce emissions by about 15 percent.⁴⁷

The following two use cases, focusing on cattle and sustainable sources of omega-3 fatty acids, illustrate some of the opportunities as well as challenges that advanced biotechnology can offer.

BOX 2: APPROACH TO GENETICALLY MODIFIED CROPS

In the 1990s, genetic engineering emerged commercially to improve the traits of plants beyond traditional breeding. Historically, the first wave of genetically engineered crops has been referred to as genetically modified organisms (GMOs), or organisms with foreign (transgenic) genetic material introduced. This is not encompassed in the potential of advanced biotechnology in this report.

More recently, advances in genetic engineering (such as the emergence of gene editing tools such as CRISPR) have enabled even more specific and targeted modifications (without using foreign genetic materials). The use of these techniques—for instance, for the modification of crops—may offer benefits in agriculture such as increased crop productivity, improved nutritional quality, reduced need for chemical inputs, or improved stress tolerance (the latter being critical to adapt to the impact of climate change). Such potential will have to be achieved by ensuring overall improved environmental impact and compliance with local regulations.

43 Further details on bio-solutions (for example, biofertilizer and biostimulants) are included in chapter 2B on chemicals.

44 For example, a 2020 *McKinsey Quarterly* article states that proteins produced from ruminant livestock (cows and sheep) are 30 times more GHG intensive than those from vegetable proteins. See "Feeding the world sustainably," *McKinsey Quarterly*, June 2, 2020.

45 Karson Hilgendorf et al., "Precision fermentation for improving the quality, flavor, safety, and sustainability of foods," *Current Opinion in Biotechnology*, April 2024, Volume 86.

46 "Looking ahead to U.S. cultivated meat adoption," Good Food Institute, February 2024.

47 *The agricultural transition*, June 27, 2023.

Use case: Beef and dairy cattle

Dairy and beef cattle present a significant opportunity for advanced biotechnology given their environmental footprint and substantial land use. They emit about 6.5 GtCO₂e per year—more than 10 percent of all global GHG emissions⁴⁸—most of which is methane.⁴⁹ Cattle land use amounts to more than 30 million square kilometers globally, or about three times the size of the entire European continent. Total land use of livestock equals 35 percent of habitable land—32 million square kilometers of grazing land and another six million square kilometers of cropland for animal feed.⁵⁰ The conversion efficiency of agricultural produced feedstock into protein varies significantly by animal. For example, producing one kilogram (kg) of beef protein requires roughly 100 kg of animal feed, whereas chicken requires roughly 13 kg of animal feed for the same amount of protein.⁵¹ Biomass fermentation is about 15 times more efficient than beef, needing only 8.2 kg of feedstock to produce 1.0 kg of protein.⁵²

Advanced biotechnology's sustainability potential

Advanced biotechnology can play a major role in reducing the environmental impact of cattle, both within the conventional production pathway of beef and dairy production and within an alternative pathway. The latter includes using

tissue-as-a-product for cultivated-meat production, precision fermentation for dairy protein production, and both biomass fermentation and precision fermentation for meat replacements.

For the conventional pathway, our analysis suggests that advanced biotechnology could reduce the environmental footprint of dairy production by about 30 percent through selective breeding, feed additives, manure management, and advanced crop breeding. However, the conventional livestock industry faces several ethical concerns (such as animal welfare) and health issues (such as zoonoses), along with challenges associated with supply security. Selective cattle breeding for genetic markers linked to reduced enteric fermentation can reduce methane emissions from cattle by approximately 20 percent over ten years by selecting for traits such as feed efficiency and lower methane production.⁵³

Feed additives such as 3-NOP, which is produced via chemical synthesis, can reduce enteric methane emissions by as much as 30 to 40 percent. These additives work by inhibiting the enzymes responsible for methane production in cattle's digestive systems.⁵⁴

Advanced biotechnology could reduce the environmental footprint of dairy production by about 30 percent.

48 Global GHG emissions in 2023 reached 53 GtCO₂e. "GHG emissions," accessed September 12, 2024.

49 The majority of emissions originate from cows' digestive system, which naturally produces enteric methane as a by-product. This methane is released into the atmosphere through eructation and increases atmospheric temperature approximately 80 times more than CO₂ on a 20-year outlook. However, it does have a shorter atmospheric lifetime than other GHGs, making it an effective target to lower the global temperature. See *The agricultural transition*, June 27, 2023. Additionally, note that crop cultivation required to feed those cows is also a source of emissions because nitrogen fertilizers emit nitrogen oxides, which have 273 times higher global warming potential than carbon dioxide over a 100-year period. See Emily Joiner and Michael A. Toman, "Agricultural greenhouse gas emissions 101," *Resources for the Future*, September 8, 2023.

50 "Half of the world's habitable land is used for agriculture," February 16, 2024.

51 Beef requires 25.0 kg of animal feed to produce one kilogram of meat, whereas chicken requires 3.3 kg of animal feed to produce 1.0 kg of meat. Assuming a protein-to-meat ratio of 25 percent, this translates to 100 kg of animal feed required to produce one kilogram of beef protein and 13 kg of animal feed required to produce one kg of chicken protein. See Hannah Ritchie, Pablo Rosado, and Max Roser, "Meat and dairy production," *Our World in Data*, updated December 2023.

52 Based on the use of maize as a feedstock and an average 15 percent moisture content. See supplementary material to Andrew J. Fletcher et al., "Modeling the feasibility of fermentation-produced protein at a globally relevant scale," *Frontiers in Sustainable Food Systems*, July 2024, Volume 8; R. L. Nielson, "Converting wet corn weight to dry corn weight," *Corny News Network*, Purdue University, December 2024.

53 "Mitigation of greenhouse gases in dairy cattle through genetic selection," *ScienceDaily*, July 22, 2020.

54 3-NOP works by inhibiting a specific enzyme called methyl-coenzyme M reductase (MCR), which is essential in the final step of methane production in the rumen. By blocking this enzyme, 3-NOP significantly reduces the amount of methane that the microbes can produce, thereby lowering the methane emissions released into the atmosphere when the animal exhales or burps. Importantly, the use of 3-NOP does not negatively affect the overall health or productivity of the animals, making it an attractive option for farmers looking to reduce their environmental footprint. See "US study supports," June 25, 2020; "Background information on Bovaer," March 2023; "Outcome of assessment of 3-Nitrooxypropanol '3-NOP' - Assessment," Food Standards Agency, March 31, 2023.

Improved manure management, including anaerobic digestion, can reduce methane emissions from manure by 25 to 68 percent, depending on the specific conditions and storage practices. This process converts organic waste into biogas, which can be used as a renewable energy source, significantly reducing methane emissions from stored manure.⁵⁵

For animal feed, microbial fertilizers, also known as biofertilizers, are preparations containing living microorganisms that enhance plant growth by increasing the availability or uptake of primary nutrients. These microorganisms can fixate nitrogen. They can be produced with less than 5 percent of the GHG emissions of conventional fertilizers.⁵⁶

Embracing a fully alternative pathway using advanced biotechnology to produce animal-free or alternative dairy and cultivated meat would amount to a significant step change. Three technologies are possible. First, precision fermentation can substitute

for dairy proteins such as casein and whey (among others); these dairy proteins are at low concentration in milk, so purpose-made molecules enable production of higher volumes. Second, biomass fermentation from microorganisms—such as fungi, yeast microalgae, and bacteria—can substitute for meat products. Third, tissue-as-a-product can be used to produce cultivated meat, offering an alternative to animal-derived meat.

Precision fermentation outputs can be further processed in isolation to provide animal-free alternatives for milk, cheese, yogurt, butter, cream, protein supplements, and heme (a molecule that imparts a meaty flavor and color), as well as cooking and baking ingredients. These include casein and beta-lactoglobulin, the major protein in whey. They also include lactoferrin, a whey

protein constituent that is used in specialty applications including infant nutrition, as well dairy fats, and lactose. Alongside traditional dairy alternatives, these proteins can fortify everyday foods or provide alternatives to land-consuming crops or milk derivatives, offering a broader opportunity to enhance normal diets and reduce environmental impact. In another example, some companies use genetically engineered yeast or other microorganisms to produce ingredients for plant-based meat analogs (for example, genetically engineered yeast to produce heme).

Biomass fermentation uses the efficient conversion of feedstock into protein-rich microorganisms to produce meat alternatives that mirror the taste and texture of traditional meat. Microorganisms can convert a wide array of carbon molecules into protein, which is stored inside the cells. If these carbon sources are sustainably derived, the protein can be produced with only a limited claim on land.⁵⁷ Additionally, microorganisms' rapid and efficient growth offers a unique opportunity to produce new protein at scale. While biomass fermentation is commonly associated with alternative meat products, its broader potential lies in producing versatile proteins that can serve as ingredients in fortified foods, improve nutritional value, or substitute for conventional soy or whey protein. While alternative-meat products have garnered attention, consumer adoption has been limited because of concerns over flavor, texture, and price. By addressing those concerns, alternative proteins may hold greater promise in new applications, such as soy protein or whey protein replacements, or as ingredients in fortified foods designed to improve nutritional value. For example, mycoprotein is used as a key ingredient in meat substitutes.

One example of a tissue-as-a-product output is cultivated meat. This meat is produced directly from animal cells. The process of cultivating meat uses the basic elements needed to build muscle and fat and enables the same biological process that happens inside an animal.

Precision-fermented proteins could generate less than 5 percent of the emissions associated with conventional proteins and reduce required water and land use of conventional proteins by more than 95 percent.

55 Tyler J. Barzee et al., "Anaerobic digestion and alternative manure management technologies for methane emissions mitigation on Californian dairies," *Atmosphere*, January 2023, Volume 14, Number 1.

56 "Microbial fertilizer," Innovation Commission, November 2023.

57 Fatemeh Ahmadi et al., "Recent advances and challenges in single cell protein technologies for food and feed production," *Science of Food*, September 2024, Volume 8.

Currently, cultivated meat is mainly produced using animal-derived media constituents (that is, the liquid these cells are grown in) sourced from the pharmaceutical industry.⁵⁸ These constituents are currently the largest cost driver of cultivated-meat production. Research is ongoing to find the right feedstock to create a more-affordable supply chain with animal-free and food-grade ingredients.⁵⁹ This can include hybrid products that combine plant-based and cell-based ingredients to achieve better taste, texture, and affordability.

The sustainability impact of such alternative production pathways can be significant. As an example, precision-fermented proteins could generate less than 5 percent of the emissions associated with conventional proteins and reduce required water and land use of conventional proteins by more than 95 percent (because growing fermentation feedstock and maintaining fermentation facilities require significantly less space).⁶⁰ Moreover, these environmental benefits could be further enhanced once alternative feedstocks such as CO₂ or platform molecules (biomass-derived molecules that could be used as building blocks) become accessible in existing bioprocesses, or when energy sources become more sustainable. Such progress could expand the applications of these processes beyond traditional meat or dairy substitutes to transform broader food systems.

Precision-fermented dairy proteins are structurally and functionally indistinguishable from animal-based dairy proteins, so their taste, texture, and nutritional profile can closely resemble those of their animal-based counterparts. Conventional proteins in recipes from food ingredient producers can be replaced with precision-fermented alternatives. However, scaling and consumer perception remain a challenge. Achieving cost comparability with traditional dairy products would require continued innovation, both in advanced biotechnology and in efficient industrial production processes. While there is growing interest in sustainable and al-

ternative protein sources, consumer awareness and acceptance of precision-fermented dairy are still in the early stages. Regulatory approaches differ significantly across countries and regions. In the European Union, there are currently no approved alternative proteins derived from precision fermentation, and new fermentation products are evaluated under the Novel Food Regulations. The United States employs a regulatory framework, assessing precision fermentation under the dedicated Generally Recognized as Safe framework. To date, the FDA has issued numerous “no question” letters to alternative proteins, effectively granting direct market entry. These regulatory differences significantly affect the ease of market entry and the speed of adoption.⁶¹

Use case: Alternatives to fish oil as sources of omega-3 fatty acids

Fish oil is the principal source of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), omega-3 fatty acids that are used mainly in fish feed. They can be taken as food supplements for humans or used in pet food. Omega-3 fatty acids are crucial for maintaining heart health and joint and muscle function in humans, and for promoting health and growth in fish. Since neither humans nor fish can naturally produce enough of these nutrients, they must obtain them through their diet. Global demand for EPA and DHA is on the rise, but the supply of fish oil is finite.⁶² Reducing pressure on marine environments by supplying a sustainable alternative can reduce reliance on marine resources, meet the growing demand for essential nutrients, and support both industry growth and environmental balance.

The fish oil market is subject to frequent supply and price fluctuations because production capacity is dependent on environmental circumstances, particularly weather phenomena such as El Niño. Future supply issues might develop as expected increases in ocean temperatures reduce availability of food sources for wild fish.

58 Media mimics the natural environment and includes all the growth factors that the cells need to grow into meat. One ingredient has traditionally been fetal bovine serum, a blood serum from fetal cows, which is both expensive and derived from animals. A number of companies are working to replace this with less expensive substances that are not derived from animals.

59 *Cultivated meat and seafood*, Global Food Institute, April 2024.

60 See the methodology description in chapter 1 and the technical appendix for details of these calculations.

61 Hannah Lester, “ATOVA regulatory focus: Precision fermentation,” Atova, February 9, 2023.

62 *Sustainable development report 2023*, Veramaris, 2023.

Over the past decade, fish oil has faced several supply shortages, and prices have increased by almost 200 percent.⁶³

More broadly, about 50 percent of fish oil already uses fish trimmings and by-products, which reduces its marine footprint. Oils using such trimmings and by-products typically contain lower concentrations of EPA and DHA compared with alternatives such as algae oil.

It is possible to produce alternative oils, such as canola, which requires genetic seed modification, to produce omega-3. However, these seed oils have low DHA concentrations compared with fish oil and, so far, do not contain EPA in relevant concentrations. This means that they do not provide the same health benefits and nutritional value as fish oil, including anti-inflammatory properties and cardiovascular protection, potentially limiting their effectiveness. Some companies are seeking to commercialize an EPA containing genetically modified seed oil. Another alternative includes the production of omega-3 for fish feed using genetically modified yeast, which is commercially available but faces economic challenges.⁶⁴

Advanced biotechnology production of algae oil as a reliably available and sustainable alternative

Algae oil naturally contains high levels of DHA and EPA: a 65 percent EPA and DHA concentration delivers a potency that is up to five times that of traditional fish oil sources.⁶⁵ Advanced biotechnology production of algae oil using biomass fermentation provides a stable and secure supply of EPA and DHA because it is a nonfinite

sustainable alternative. Algae oil offers significant potential for reducing emissions compared with other fish oil substitutes. For example, algae oil can reduce up to 52 kg of CO₂e per kg DHA, compared with 15 kg CO₂e per kg DHA for fish oil, according to 2021 research on fish oil substitutes.⁶⁶ However, the climate impact of algae oil depends on specific production methods and contexts to fully compare its footprint to fish oil across various scenarios.

The fermentation process involves screening specific microalgae and selecting strains that naturally produce high levels of omega-3 fatty acids in fermentation tanks. The algae produce oil rich in omega-3 fatty acids. Once the algae have grown and accumulated oil, the oil is extracted and purified.

One highly concentrated alternative, currently in the market, can provide one metric ton of algae oil with the same amount of EPA and DHA as up to 66 metric tons of forage fish.⁶⁷ By partially substituting fish oil with algae and vegetable oil, aquafeed producers can produce one kg of farmed fish using less than one kg of forage fish (compared with the current need of more than one kg of forage fish), while maintaining nutritional quality.⁶⁸

When algae oil is used directly for human consumption rather than being fed to fish, it provides consumers with a fully vegan option. It is the only vegan option available in Europe, where regulations apply to products coming from genetically modified organisms.⁶⁹

63 "2023 report: Fishmeal and fish oil in the EU," European Fishmeal and Fish Oil Producers, October 3, 2023.

64 A major limitation to using algal oil in aquafeeds is that it can be expensive to extract from the biomass compared to current fish oil prices. M. B. Betancor, M. Sprague, and D. R. Tocher, "Microbial and genetically engineered oils as replacements for fish oil in aquaculture feeds," *Microbiology Letters*, July 2017, Volume 39.

65 *Sustainable development*, 2023.

66 Furthermore, the research also showed that algae oil has lower climate impact compared to other fish oil substitutes, such as canola oil and linseed. See Louise Bartek et al., "Life cycle assessment of fish oil substitute produced by microalgae using food waste," *Sustainable Production and Consumption*, July 2021, Volume 27.

67 "Algal oil features and benefits," Veramaris, accessed December 23, 2024.

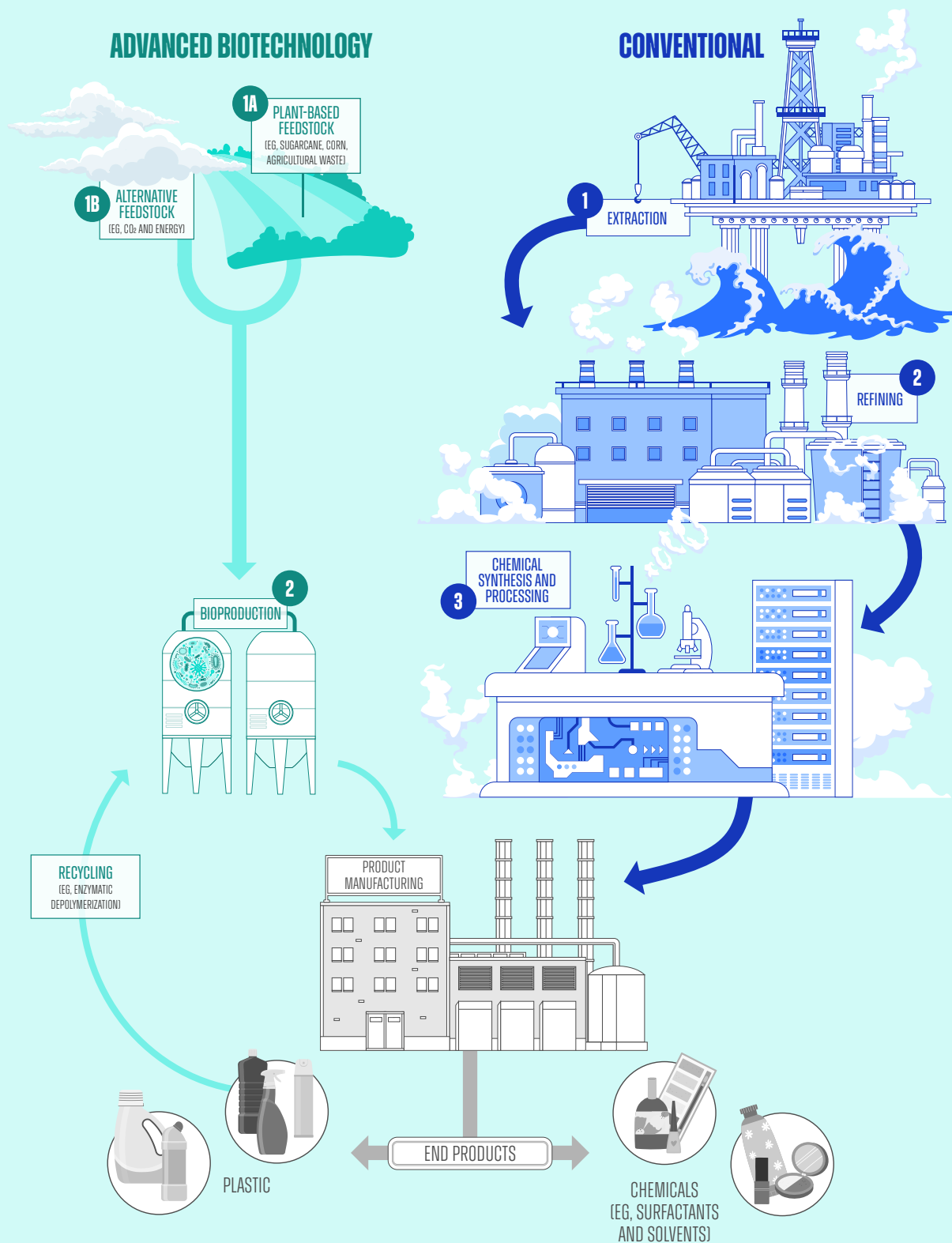
68 Ian Carr et al., "Algal oil gives control of long-chain omega-3 levels in full-cycle production of Atlantic salmon, without detriment to zootechnical performance and sensory characteristics," *Journal of the World Aquaculture Society*, August 2023, Volume 54, Number 4.

69 "More than 20 algae species can now be sold as food or food supplements in the EU," European Commission, February 26, 2024; "GMO legislation," European Commission, accessed December 23, 2024.

2B CHEMICALS: DECOUPLING FROM FOSSIL FEEDSTOCKS

EXHIBIT 6

IN CHEMICALS, ADVANCED BIOTECHNOLOGY HAS GREAT POTENTIAL TO COMPLEMENT CONVENTIONAL TECHNOLOGIES BY SIGNIFICANTLY REDUCING GREENHOUSE GAS EMISSIONS.



The case for advanced biotechnology's role

The chemical sector is highly dependent on oil, gas, and coal as a feedstock and energy source for production. As a result, the manufacturing of chemicals generates about two GtCO₂e emissions yearly, including Scope 1 and 2 emissions, or about 4 percent of global emissions.⁷⁰ CO₂ and other GHGs are released during production, and the fossil carbons end up as CO₂ in the atmosphere.

Land and water usage is less of a challenge in chemicals, in which the fossil fuel and production steps require limited land usage. Water usage is also smaller than, for example, in the agricultural sector.⁷¹ However, alongside air pollution (particulate matter or GHG emissions), manufacturing in the chemical sector can pollute land and water, and the fossil extraction and distribution process affects ecosystems. For example, soil can be contaminated with PFAS pollution and water with microplastic pollution (primarily from discarded or end-of-life products). In agriculture, fertilizer runoff can cause eutrophication.⁷²

The chemical sector has made commitments to reduce its environmental footprint—mainly cutting GHG emissions from chemical processes (that is, energy consumption) and the waste component of chemicals. To date, more than 200 companies in the chemical industry have committed to targets to reduce GHG emissions approved by the SBTi.⁷³

Consumers are also demanding more sustainable alternatives such as bio-based, natural, low-CO₂-emission products; reusable packaging; and biodegradable plastics. While transitioning

to bio-based chemicals presents important environmental benefits, such as reductions in life cycle carbon emissions, it also requires careful management of the land and water resources required for production.

Here we examine two use cases that address these challenges: bioplastics and plastic recycling, and alternatives to nitrogen-based fertilizers. Bioplastics can be distinguished as bio-sourced (made of) or biodegradable (end of life), depending on the context. In this report, bioplastics mainly refer to bio-sourced plastics. This does not mean that they are automatically biodegradable, as some are biodegradable while others are not.

Use case: Bioplastics and plastic recycling

Plastics are prevalent throughout the global economy. Their benefits include reducing food waste by providing airtight packaging that extends shelf life and lowering emissions through lightweight materials that reduce transportation fuel consumption. However, the production of plastics is associated with high resource use (even though plastics often have a favorable ratio of material usage per milliliter, making them more efficient than alternative materials in many applications).⁷⁴ Circular solutions, including the use of advanced biotechnology, can help tackle the challenge. Their availability and the effectiveness of alternatives depend heavily on the application or end-use segment. For instance, in packaging, depending on specific end uses, there are alternatives such as cardboard, glass, reusable, and recycled plastics that can provide similar functionalities with a lighter environmental footprint, in select use cases.

70 Andrés González-Garay, Niall Mac Dowell, and Nilay Shah, “A carbon neutral chemical industry powered by the sun,” *Discover Chemical Engineering*, May 2021, Volume 1, Number 2.

71 Note that these implications could change if the industry transitions to bio-based materials or fuels. The impact on land and water usage becomes more significant because the necessary feedstock must be cultivated. However, the extent of this impact largely depends on the type of feedstock used. First-generation feedstocks (such as corn or sugar) typically require substantial land and water resources and may compete with food production. In contrast, second-generation feedstocks (such as nonfood biomass or agricultural residues) use waste materials and generally have a lower impact on land and water usage.

72 PFAS, or per- and polyfluoroalkyl substances, are human-made chemicals widely used in various industrial and consumer products for their water- and grease-resistant properties. They are sometimes known as “forever chemicals” because they do not break down in the environment and can accumulate over time in soil, water, and air, as well as in the bodies of humans and animals. They have been linked to various health issues, including cancer, liver damage, thyroid problems, and immune system effects.

73 “Target dashboard (beta),” SBTi, accessed December 23, 2024.

74 See Roland Geyer, Jenna R. Jambeck, and Kara Lavender Law, “Production, use, and fate of all plastics ever made,” *Science Advances*, July 2017, Volume 3, Number 7; *Plastics and sustainability: A valuation of environmental benefits, costs, and opportunities for continuous improvement*, American Chemistry Council, July 2016.

These alternatives can come with other environmental costs, including higher water consumption for cardboard, higher energy consumption for glass production, and higher fuel consumption for transport due to materials that are heavier than plastics. Finding suitable alternatives is more challenging for more demanding applications such as engineering plastics used in automotive parts, electrical components, wind energy, and industrial machinery. These applications often require materials that offer specific performance characteristics, making the transition to more sustainable options less straightforward. In the case of cosmetics products for instance, the material and packaging choices are important for the performance through application of the formula, dosages, and consumer experience.

Annual plastic use of about 340 million metric tons (Mt) in 2019 is set to almost double by 2050 to about 580 Mt.⁷⁵ The manufacturing of plastics, including conversion from fossil sources and end-of-life emissions, generates approximately 1.8 GtCO₂e, which is 3.4 percent of 2019 global emissions. Emissions are expected to double by 2060, resulting in more than four GtCO₂e of GHG emissions.⁷⁶

CO₂ emissions from plastics originate from plastic production (about 65 percent), converting polymers into products (about 20 percent) and waste treatment and end of life (about 15 percent).⁷⁷

Between 1950 and 2015, approximately 79 percent of all disposed plastics ended up in landfills or in natural environments, 12 percent were incinerated, and just 9 percent were recycled.⁷⁸ In all of these settings except recycling, plastics contribute significantly to greenhouse gas emis-

sions. Between 1 and 5 percent of all plastics end up in nature, mostly in oceans, with some regional estimates in areas with poor waste management affecting marine life through entanglement and ingestion by animals, upsetting the ecosystem balance and entering the food chain as microplastics.⁷⁹

Bioplastics and plastics recycling, which can be improved through advanced biotechnology, could play a role in reducing this heavy footprint. Plastics recycling through enzymatic degradation presents an important opportunity because it has the potential to reduce the need for incineration of waste, lower GHG emissions, and break down plastic polymers to original monomers for reuse when mechanical recycling is not enough.⁸⁰ However, the presence of specialty grades of plastic, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs), increases the complexity of waste streams, potentially hindering the effectiveness and quality of recycling. These bioplastics can positively affect regions with low recycling rates by diverting waste from landfills. However, they can introduce higher complexity in developed circular-economy models with high recyclability. Separation techniques for PLA and PHAs, such as enzymatic degradation, are technically feasible but require an additional step and investment in the sorting process.⁸¹ Furthermore, PLA and PHA could create challenges in chemical recycling of residual mixed plastics.

Plastics recycling through enzymatic degradation presents an important opportunity because it has the potential to reduce the need for incineration of waste, lower GHG emissions, and break down plastic polymers . . .

75 McKinsey Chemical Insights demand model and Chemical Market Analytics; *The New Plastics Economy: Rethinking the future of plastics*, World Economic Forum, July 2016.

76 "Plastic waste and recycling in the EU: Facts and figures," European Parliament, updated June 25, 2024; *Global plastics outlook: Policy scenarios to 2060*, OECD, June 21, 2022.

77 "GHG emissions from EU's plastics value chain," European Environment Agency, April 18, 2024.

78 "Production, use, and fate," July 2017.

79 Jan-Georg Rosenboom, Robert Langer, and Giovanni Traverso, "Bioplastics for a circular economy," *Nature Reviews Materials*, January 2022, Volume 7.

80 Mohamed Abbas et al., "An investigation of the environmental implications of bioplastics: Recent advancements on the development of environmentally friendly bioplastics solutions," *Environmental Research*, March 2024, Volume 244; James Kennedy, "Enzymatic recycling: Will it revolutionize plastic waste management?" IDTechEx, March 26, 2024; Dong Wang, Na Wei, and Baotong Zhu, "Enzyme discovery and engineering for sustainable plastic recycling," *Trends in Biotechnology*, January 2022, Volume 4, Number 1.

81 "TotalEnergies Corbion and TOMRA Recycling conduct PLA sorting test," PETnology/tecPET, October 18, 2022.

Bioplastics produced through fermentation can support the move away from fossil inputs

Advanced biotechnology applications are one of several pathways that can support and strengthen current solutions to reach global sustainability targets on plastics and offer promising innovations. In some cases, other sustainable alternatives may provide complementary or more feasible solutions depending on specific environmental and economic contexts. Alternative bio-based products could be created through synthesizing biopolymers using precision fermentation to combine with or partially replace conventional plastics. Additionally, modified microorganisms that break down plastics could

Alternative plastics made from bio-based or recycled monomers can serve as an alternative to more quickly reduce emissions in the plastics industry.

improve waste management after product use. However, the likelihood and operational feasibility of this happening at large scale remain uncertain because of challenges in maintaining quality and cost competitiveness, and managing the potential environmental footprint; for example, biopolymers of-

ten necessitate the use of crops, which require substantial freshwater and land resources. Notably, bio-sourced plastics increase the amount of plastic in the world, whereas recycled plastics help maintain the same quantity by transforming waste into new materials, making them a better option in terms of life cycle assessment (LCA).

Production of most plastics is based on fossil monomers; leading platforms include polyolefins, polyesters, polyamides, and resins. Parallel routes toward novel, bio-based plastics—such as polylactic acid, polyhydroxy alkenoates, and succinic acid or furan-based polymers—are in development but face issues in achieving a sizable market share. Alternative plastics made from

bio-based or recycled monomers can serve as an alternative to more quickly reduce emissions in the plastics industry. Several companies have embarked on this journey to drop-in monomers—for example, bio-based 1,4-butanediol and 1,3-propanediol from glucose, and ethylene from bioethanol have been commercialized with success.⁸² The use of renewable monomers can pave the way to novel materials with improved functionalities, which in the long run can bring more revenue.

Plastics that are bio-based, biodegradable, or recycled address the issues of high GHG emissions in different ways, based on their properties. Bio-based plastics are derived from renewable biological sources; biodegradable plastics can decompose naturally through microbial activity under strict conditions regarding temperature, humidity, and light, for example; and recycled plastics are made from reprocessed waste materials. Biodegradability is important when plastics escape recycling processes and end up in the environment, because it means they can break down into nontoxic components, minimizing pollution and contributing to the biological cycle (especially relevant in agronomic and medical applications). Bio-based plastics could capture up to 10 percent of the plastics market by 2050—and about half of this could be produced through advanced biotechnology.⁸³

PHAs, which are among the most commercialized and produced biopolymers, have high potential to replace many conventional plastics such as polyethylene (PE). PHA currently has 20 percent lower emissions than PE, on average, with 1.88 kg CO₂ per kg of plastic, compared with 2.42 kg CO₂ per kg for PE. This difference is primarily because PHA production involves biological processes, such as fermentation, which are inherently less carbon-intensive. Estimates suggest that PHA could further reduce emissions to 0.49 kg CO₂ per kg or lower by storing carbon—that is, by being bio-based or synthesized from CO₂.⁸⁴

82 *Bio-based chemicals: A 2020 update*, Technology Collaboration Programme, February 2020.

83 Michael Carus and Christopher vom Berg, "Scenario for the plastic industry 2050," Renewable Carbon, October 2021.

84 1.88 kg CO₂ per kg of PHA assumes production of PHA with the organic fraction of municipal solid waste, and 0.49 kg CO₂ per kg of PHA assumes production from cellulosic ethanol biorefineries. Additionally, 2.42 kg CO₂ per kg of PE reflects the global average, cradle to gate. See Lilian X. L. Chen and Jian Yu, "The greenhouse gas emissions and fossil energy requirement of bioplastics from cradle to gate of a biomass refinery," *Environmental Science & Technology*, August 2008, Volume 42, Number 18; Luis D. Allegue et al., "Environmental life cycle assessment of polyhydroxyalkanoates production by purple phototrophic bacteria mixed cultures," *Journal of Cleaner Production*, November 2023, Volume 428.

Overall, PHAs have the potential to reduce GHG emissions by up to 80 percent compared with conventional plastics such as PE. PHAs do not turn into microplastics when they degrade, unlike PE, which can break into smaller particles that persist in the environment. PHA is a thermoplastic that is fully biodegradable into non-toxic, bio-available substances such as water, CO₂ (in aerobic conditions), and methane (in anaerobic conditions). In seawater, it degrades into water and CO₂ more than ten times faster than PE and thus significantly contributes to the battle against marine plastic waste pollution.⁸⁵ PHA is also compostable and biodegradable in marine environments, whereas PLA, another biodegradable bioplastic derived from renewable sources, is not.

Bioplastic has clear adoption potential given the various applications and multiple tailwinds including regulatory changes, but it represented only about 1 percent of the polymer market in 2022.⁸⁶ Major consumer brands started to make the transition already several years ago. For instance, the Coca-Cola Company introduced a prototype for a 100 percent plant-based bottle, made from bio-based PET (polyethylene terephthalate) in 2015. Nestlé launched bio-based lids and scoops for its infant nutrition products in 2021, using bio-based PP (polypropylene). L'Oréal announced its first cosmetic bottle pro-

totype in 2021, using PET with Carbios's enzymatic depolymerization process.⁸⁷

In addition to its contributions to reductions in GHG emissions and other sustainability targets, PHA shows promise in terms of technology and cost because its versatility means it can be used for a wide range of applications. Applications include packages for fast-moving consumer goods, electronic products, and automotive and medical products.

PHA is currently more expensive than PE (\$4.0 to \$6.0 per kg versus \$1.5 to \$2.3 per kg), but costs could go down once fermentation costs are optimized at larger scale.⁸⁸ Advances that could help reduce costs include increased equipment size to reap economies of scale, improved yields to reduce the amount of feedstock required (which accounts for about 50 percent of the current production cost), and increased compatibility with waste management infrastructure.⁸⁹ Extracellular production can result in a simplified downstream process or even make it redundant; some promising tests have already been done for this.⁹⁰

However, bioplastics can fall short in high-performance applications such as coatings, paint, and construction.⁹¹ Nevertheless, if the bioplastic can reach the performance demand of the desired application, recycling should be prioritized.

85 Mark E. Hahn et al., "Minimizing the environmental impacts of plastic pollution through ecodesign of products with low environmental persistence," *ACS Sustainable Chemistry & Engineering*, January 2024, Volume 12, Number 3.

86 "Global bio-based plastics production capacity," European Environment Agency, updated December 17, 2024.

87 "Packaging solutions," Coca-Cola Company, accessed December 23, 2024; "Nestlé launches bio-based lids and scoops made from renewable resource," Nestlé, March 15, 2021; "L'Oréal launches the first cosmetic bottle made from recycled plastic with Carbios' enzymatic technology," L'Oréal, June 24, 2021.

88 PHA price range is a 2024 estimation based on IHSM and RecyclingMarkets. PE price range is based on the 2024 Chemical Markets Analytics and OPIS database.

89 Based on McKinsey's cost sizing model.

90 "Bioplastics for a circular economy," January 2022.

91 Ilaria Oberti and Alessia Paciello, "Bioplastic as a substitute for plastic in construction industry," *Encyclopedia*, July 2022, Volume 2, Number 3; Mohd Hanafiah Ahmad et al., "Sustainability of biodegradable plastics: New problem or solution to solve the global plastic pollution?," *Current Research in Green and Sustainable Chemistry*, 2022, Volume 5.

Use case: Nitrogen fertilizer

The global nitrogen fertilizer market, valued at about \$100 billion,⁹² plays a significant role in food production, but it has a large environmental footprint. The nitrogen fertilizer sector, a subsector of our earlier defined market for agriculture, is estimated to cause about 5 percent of worldwide emissions,⁹³ mainly from the release and production of nitrous oxides, each accounting for approximately 50 percent.⁹⁴

Some estimates suggest that fertilizers, mainly nitrogen and phosphorus, cause almost 80 percent of all global marine and freshwater eutrophication, the nutrient enrichment of waterbodies leading to excessive growth of algae, deoxygenation, and biodiversity loss.⁹⁵

Fertilizer production and application could be improved. In production, for example, this could be done by using renewable hydrogen instead of grey hydrogen in ammonia production. In application, for example, this could be achieved by implementing precision fertilization, effective drainage management, and triggered and controlled-release fertilizers on field. These all improve efficiency and reduce runoff.⁹⁶ Such improvements could reduce GHG emissions from fertilizers by as much as 30 to 50 percent.⁹⁷

Biofertilizers could further reduce the sector's ecological footprint

Microbial fertilizers, also known as biofertilizers, are innovative solutions that use living microorganisms to enhance plant growth by improving nutrient availability and uptake. These microorganisms can fixate nitrogen and can be produced (using biomass fermentation) with more than 80 percent less GHG emissions than conventional nitrogen fertilizers.⁹⁸ They complement conventional fertilizers and other biofertilizers by enhancing nutrient uptake, which can reduce the overall amount of fertilizer applied.

These advanced solutions demonstrate how biotechnology fertilizers differ from conventional methods. For example, companies such as Pivot Bio edit microbes' genetic code to enable nitrogen fixation, and Kula Bio supercharges microbes with energy to extend nitrogen release over longer periods.⁹⁹ These examples illustrate the potential of biofertilizers to address environmental challenges and boost agricultural productivity.

Microbial fertilizers are also fully biocompatible, address nitrogen leaching, and can even be used to restore degraded or vulnerable soils such as wetlands without disrupting the ecosystem.

92 *Nitrogen fertilizer global market report*, Business Research Company, October 2024; Hannah Ritchie, "How many people does synthetic fertilizer feed?," Our World in Data, November 7, 2017.

93 Yunhu Gao and André Cabrera Serrenho, "Greenhouse gas emissions from nitrogen fertilizers could be reduced by up to one-fifth of current levels by 2050 with combined interventions," *Nature Food*, February 2023, Volume 4.

94 Frank Brentrup and Christian Pallière, *Energy efficiency and greenhouse gas emissions in European nitrogen production and use*, Fertilizers Europe, 2008.

95 Carole Dalin, Mark A. A. Jwaideh, and Edwin H. Sutanudjaja, "Global impacts of nitrogen and phosphorus fertiliser use for major crops on aquatic biodiversity," *International Journal of Life Cycle Assessment*, August 2022, Volume 27.

96 "Discussion document: Reducing emissions arising from the application of fertilizer in Canada's agriculture sector," Government of Canada, accessed December 23, 2024.

97 Estimated range based on "From green ammonia to lower-carbon foods," McKinsey, December 11, 2023; and "Discussion document," accessed December 23, 2024.

98 "Greenhouse gas emissions from nitrogen fertilizers," February 2023. Nitrogen-fixing bacteria play a crucial role in the nitrogen cycle by converting atmospheric nitrogen (N₂), which is inert and unavailable to most living organisms, into a form that can be used by plants and other organisms: ammonia (NH₃). This already happens in nature today, but advanced biotechnology could use this natural power for crops too.

99 Pivot Bio employs gene-editing techniques to modify nitrogen-fixing microbes, enabling them to provide nitrogen to crops during the growing season ("Harnessing the power of nature," Pivot Bio, accessed December 23, 2024). Kula Bio extends the efficiency of nitrogen-fixing microbes by supplying them with an additional energy source, which prolongs nitrogen release ("Resilience through innovation," Kula Bio, accessed December 23, 2024).

20 PERSONAL-CARE PRODUCTS: COMBINING SUSTAINABILITY AND PERFORMANCE

The personal-care sector has seen strong consumer demand for high-performing products that maximize value, while featuring bio-based “eco-friendly” and “sustainable” ingredients.¹⁰⁰ Consumer demand, however, does not always translate into action. The sector has focused on two primary challenges: how to address the full impact across the life cycle of materials and products, and how to ensure functional performance advantages when replacing existing molecules with a bio-derived solution. Advanced biotechnology has already had a material impact on both areas, laying the ground for accelerated adoption in sectors beyond personal care.

The case for advanced biotechnology's role

Already, several top global consumer product companies, including some in personal care, have committed to 100 percent sustainable sourcing of specific ingredients from oleaginous crops by 2025.¹⁰¹ The Personal Care Product Council underscores that sustainable sourcing is integral to procurement and supply chain strategies of its member companies.¹⁰² Some companies have already met this sourcing commitment and are now setting similar targets for their broader portfolios. Some personal-care brands are taking a comprehensive approach by adopt-

ing a full life cycle perspective and aiming for complete transparency in tracing ingredient derivatives across the value chain.¹⁰³ Brands such as Unilever, LVMH, Shiseido, L'Oréal, Beiersdorf, and Kao Corporation have been actively working on using ingredients that do not contribute to deforestation but that minimize waste and have less environmental impact.¹⁰⁴ Moreover, a rising group of new ventures is focused on alternative solutions, while ensuring functional performance. For instance, in 2014, dsm-firmenich introduced Clearwood, an alternative patchouli perfumery ingredient that can be developed using microbial fermentation with sugar and commercialized at scale. While not a one-to-one replacement for patchouli oil, the end product belongs to the same olfactive family, can serve as a building block for new olfactive creations, and has a carbon footprint only 20 to 45 percent of that of botanical patchouli oil.¹⁰⁵ Another example is the joint venture of Geno, Kao, L'Oréal, and Unilever, which seeks to scale and commercialize sustainable surfactant alternatives to fossil fuel-derived products—proving that ingredients produced by biotechnology with bio-based sources can deliver both high performance and sustainability, at scale.¹⁰⁶

100 “Sustainable personal care ingredients: Riding the wave of evolving consumer demands,” Shell, accessed December 23, 2024; *Bio-based cosmetics and personal care ingredients market size, share and forecast to 2032*, Straits Research, updated July 25, 2024; Emily Hood and Kayla Villena, “Top trends shaping the beauty and personal care industry in 2024,” Euromonitor International, July 9, 2024; “85% of consumers would pay more for beauty products with proven benefits,” Euromonitor International, November 23, 2023; Guneet Kaur, Makary Nasser, and Malvika Sharma, “Advances in the production of biosurfactants as green ingredients in home and personal care products,” *Frontier in Chemistry*, March 2024, Volume 12.

101 Sustainable sourcing involves using products that are 100 percent RSPO-certified and can be traced back to their originating plantations. See Steffany Bermúdez et al., *Global market report: Palm oil prices and sustainability*, IISD, July 2023.

102 “Responsible sourcing,” Personal Care Products Council, accessed December 23, 2024.

103 “Palm oil,” Ferrero, accessed December 23, 2024; “Approvisionnement durable de l’huile de palme: L’Oréal accélère ses efforts” (“Sustainable sourcing of palm oil: L’Oréal accelerates its efforts”), L’Oréal, accessed December 23, 2024.

104 “Does Lush use palm oil?” Lush, accessed December 23, 2024; “Aveda supply chain,” Aveda, accessed December 23, 2024; “Does The Body Shop use sustainable palm oil?” Body Shop, accessed December 23, 2024.

105 Estimation for patchouli essential oil based on secondary data models built on Xavier Bengoa et al., *Methodological guidelines for the life cycle inventory of agricultural products*, World Food LCA Database, July 2014; E.V.S. Prakasa Rao, “Patchouli cultivation guide - How to grow patchouli commercially for oil,” Wikifarmer, accessed December 23, 2024; and N. Arpi, Cut Erika, and Dewi Ermaya, “Survey and study on yield and quality of patchouli oil in Aceh Barat Daya District, Indonesia based on original area of raw materials, methods and length of distillation,” *Proceedings of the Annual International Conference Syiah Kuala University*, 2011, Volume 1, Number 1. Clearwood data from an internal model. Both LCA models use Ecoinvent 3.10 and WFLDB 3.5 as background LCA databases.

106 “Unilever, Geno launch \$120M venture to scale alternative to palm oil-, fossil fuel-based cleansers,” Sustainable Brands, June 16, 2022; “Future Origins launches from joint venture to develop sustainable ingredients in personal care and cleaning products, announces completion of pilot scale activities,” PR Newswire, January 31, 2024.

These ingredients, plant-based by design, have the potential to enhance supply-chain resilience and improve product functionality. For instance, biosurfactants, which we describe in the case study below, contain natural fatty acids and sugars. This allows for better integration with skin proteins and lower skin irritation than petroleum-derived surfactants. Other examples using fermentation include natural-origin retinol, patchouli oil, and high-purity squalane made from sugarcane as well as butylene glycol made from renewable plant sugars.

Personal care, with its forward-looking sustainability targets across the product life cycle, has been a significant driver of advanced biotechnology. Advanced biotechnology may develop faster in this sector, as operations are licensed to sustainability developments and end products typically bear additional functional performances that can be vaporized on the market, compared with food or chemicals.

Use case: Surfactants

Surface active agents (surfactants) are crucial for daily life and health because they enable people to clean their hands, bodies, clothes, dishes, and households. It is a market of approximately \$40 billion globally, with a market volume of 18 Mt and an average annual growth rate of 3 percent.¹⁰⁷ The surfactant sector accounts for an estimated 54 million to 108 Mt of CO₂ emissions annually.¹⁰⁸ Many traditional surfactants are derived chemically from fossil resources or based on tropical oil derivatives—resources that are under increasing pressure because of their impacts on climate (fossil resources) and agriculture practices and climate change (tropical oil derivatives). Fossil-derived molecules, for example, emit net carbon emissions during their degradation (at their end of life), when the carbon coming from the fossil feedstock is released.

The surfactant market has already been changing in response to shifting consumer demand toward more-sustainable products, while maintaining performance. Partially bio-based surfactants already account for a large part of the global surfactant market: about half of surfactants in Europe had at least one constituent originating from a renewable feedstock from oleaginous crops, such as coconut or palm kernel oil.¹⁰⁹ These surfactants emit lower absolute CO₂ emissions throughout their life cycle.¹¹⁰

Personal care, with its forward-looking sustainability targets across the product life cycle, has been a significant driver of advanced biotechnology.

Advanced biotechnology can play an important role in improving the sustainable supply of surfactants and reduce their environmental footprint by employing low-emission processes as well as non-fossil carbon feedstocks. Some fully bio-based surfactants are already available, but they still have a smaller overall market share relative to partially bio-based surfactants. Their limited adoption to date is primarily due to their relatively higher production costs, the difficulty of sourcing the right bio-based feedstock, and the time and effort required to develop new formulations.¹¹¹ Performance also needs to be at least on par with conventional surfactants, and ideally, fully bio-based surfactants need to provide additional performance benefits to justify their higher price per kilogram, reach parity in cost in use, or both.

107 *Surfactants market size (2024 - 2029)*, Mordor Intelligence, accessed December 23, 2024; Jacob J. Mueller and Hans H. Wenk, "Biosurfactants – Nature's solution for today's cleaning challenges," *Renewable Feedstock and Biomass Valorization*, September 2021, Volume 75, Number 9.

108 The estimate is based on an annual volume of about 18 Mt of surfactants with an average emission of 3 to 6 kg CO₂e per kg. "SURFs UP," Circular Bio-based Europe Joint Undertaking, accessed December 23, 2024; M. K. Patel, A. Theiß, and E. Worrell, "Surfactant production and use in Germany: Resource requirements and CO₂ emissions," *Resources, Conservation and Recycling*, January 1999, Volume 25, Number 1.

109 "Surfactants and sustainability," CESIO, accessed December 23, 2024.

110 Oleochemical surfactants could enable a reduction of about 34 percent when replacing petrochemical surfactants. "Surfactant production and use," January 1999.

111 "Bio-based surfactants," SOFW, accessed December 23, 2024.

How advanced biotechnology can accelerate the shift to sustainable surfactants

Biosurfactants are a class of surfactants that are naturally produced by microorganisms such as bacteria, yeast, and fungi. They are fully bio-based as well as fully biodegradable, making them a more environmentally friendly alternative to traditional surfactants.¹¹²

Biosurfactants can be produced with a low carbon footprint, and they offer potential for further reductions to zero emissions in the case of green energy across the whole production value chain.¹¹³ Fossil-derived surfactants emit about 3.0 to 6.0 metric tons of CO₂ per metric ton of product on average,¹¹⁴ while biosurfactants are estimated to produce at least 1.5 metric tons of CO₂ less per metric ton of product.¹¹⁵ Shifting from petrochemical to biosurfactants would cut the market's emissions by more than one-third.¹¹⁶

Types of biosurfactants include glycolipids, lipopeptides, phospholipids, and fatty acids. In the personal-care and cleaning industries, glycolipids such as sophorolipids and rhamnolipids are the most widely researched and commercialized types of biosurfactants. Rhamnolipids are produced from corn-derived sugar that is fermented by bacteria. Sophorolipids are produced from sugar beet-derived sugar and rapeseed oil through synthesis with a yeast called *Candida bombicola*. Sophorolipids are manufactured by a variety of companies, but to date, there is only

one example of large-scale rhamnolipids production.¹¹⁷ The performance profiles of various biosurfactants differ—for example, in foaming behavior—allowing brands to respond to different needs from their consumers.

For consumers of personal-care products, biosurfactants can outperform conventional surfactants.¹¹⁸ Biosurfactants stand out because of their mildness to the skin as well as their antimicrobial properties and low aquatic toxicity, combined with their high performance in terms of solubilizing oils. This reduces the burden on the environment related to the use of skin care products while simultaneously improving consumer well-being in the long run. For instance, it has been shown that rhamnolipids protect the integrity of the human skin barrier.¹¹⁹ They may even be used to treat skin conditions and reportedly support wound healing efficacy.¹²⁰

Biosurfactants have a wide range of applications beyond the cosmetic industry, including in the food and pharmaceutical sectors. Rhamnolipids in feed can improve the health and performance of birds and swine, and they may even be used to prevent fungal infections in agriculture. They can be used as emulsifiers or foaming agents, and in contrast to traditional surfactants, which usually taste bitter, rhamnolipids even have a sweet taste.¹²¹ Additionally, they have been shown to be effective at cleaning contaminated soil and water. Other potential uses include, for example, agents for pigment wetting.¹²²

112 Mohammed Latif Khan et al., "Microbial biosurfactants: Green alternatives and sustainable solution for augmenting pesticide remediation and management of organic waste," *Current Research in Microbial Sciences*, 2024, Volume 7.

113 Oleochemical surfactants could enable a reduction of about 34 percent when replacing petrochemical surfactants. "Surfactant production and use," January 1999.

114 Ibid.

115 "Switching to sustainable surfactants," *Chemical & Engineering News*, May 1, 2022.

116 Estimate reflects the theoretical maximum potential for the substitution of traditional biosurfactants; based on 24 percent market size increase of the European Union between 2008 (880 kilotons) and 2010 (1,100 kilotons). Martin Patel, "Surfactants based on renewable raw materials," *Journal of Industrial Ecology*, July 2003, Volume 7, Number 3–4.

117 "Evonik manufactures first product from world's first industrial-scale rhamnolipid biosurfactant plant," Evonik, January 18, 2024.

118 Andrew M. Bodratti et al., "Biosurfactants, natural alternatives to synthetic surfactants: Physicochemical properties and applications," *Advances in Colloid and Interface Science*, January 2020, Volume 275.

119 E.B. Marangoni et al., "Rhamnolipid: An eco- and skin-friendly alternative to synthetic surfactant," *SOFW Journal*, 2021, Volume 12.

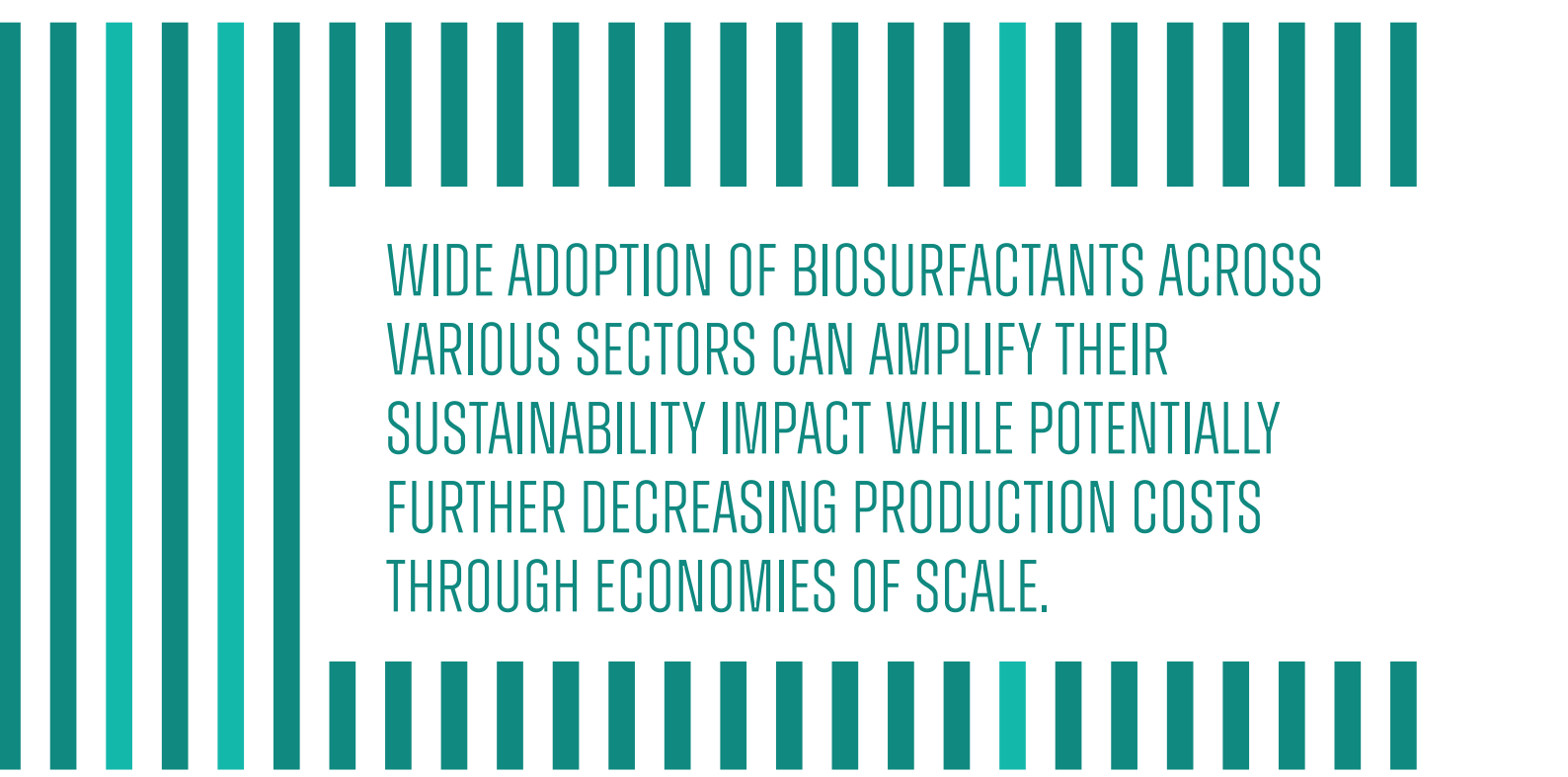
120 Abdel Rahman Mohammad Said Al-Tawaha et al., "Microbial biosurfactant as an alternate to chemical surfactants for application in cosmetics industries in personal and skin care products: A critical review," *Biomed Research International*, April 2023.

121 "We go beyond with sustainable: Rhamnolipids," Evonik, accessed December 23, 2024.

122 Ibid.

In conclusion, biosurfactants could offer enhanced performance and notable sustainability benefits. Their lower CO₂ emissions, biodegradability, and reduced ecotoxicity make them a viable option for industries seeking to minimize environmental impact. At the same time, their mildness to the skin and protective qualities, combined with biological activities and exem-

plary cleaning performance, could improve the performance of personal-care products formulated with biosurfactants. Wide adoption of biosurfactants across various sectors can amplify their sustainability impact while potentially further decreasing production costs through economies of scale.



WIDE ADOPTION OF BIOSURFACTANTS ACROSS
VARIOUS SECTORS CAN AMPLIFY THEIR
SUSTAINABILITY IMPACT WHILE POTENTIALLY
FURTHER DECREASING PRODUCTION COSTS
THROUGH ECONOMIES OF SCALE.

20 TRANSPORTATION FUELS: USING ALCOHOL-TO-JET

Transportation fuels represent as much as 20 percent of total GHG emissions¹²³ and are primarily fossil-based. Providing an alternative to fossil fuels through electrification and renewable fuels has the potential to significantly curtail the increase of total GHGs.

The transportation sector has already started moving away from fossil fuels. The global fleet of passenger vehicles, for example, is increasingly shifting to electric alternatives. However, the road ahead is still a long one for all forms of transportation. Some liquid fuels remain necessary due to their high volumetric energy content compared with electric propulsion, which is important for long-distance and heavy-duty transportation and aviation. Electrification is not as advanced for heavy trucks as for passenger cars. For shipping, direct electrification may be possible for small ships but not larger shipping vessels, which will need alternative fuels such as methanol, ammonia, hydrogen, or biodiesel.¹²⁴ And even with passenger cars, there is a long tail of internal combustion engines that will remain on the roads for decades.¹²⁵

The most likely pathways for land and water transportation to move away from fossil fuels lie in electrification or alternative fuels for which advanced biotechnology can play a complementary role, including through ethanol production. Ethanol in car engines is expected to complement a transition toward hybrid and electric cars. The story is different for air transportation. Within the aviation sector, the only net-zero fuel applicable to all aircraft is renewable fuel, which

includes bio-based SAF and electric sustainable aviation fuel (eSAF). Advanced biotechnology can potentially play a role in SAF production.

While we expect biofuels to take a relatively large market share in aviation in the near term, there is more uncertainty for other transportation sectors; today, fossil-based jet fuel is at least three times cheaper than all SAF production pathways except for hydroprocessed esters and fatty acids (HEFA),¹²⁶ even when emission benefits are taken into account. More generally, liquid fuels are hard to replace with more-sustainable alternatives because of their inherent complexity, including the stringent safety and performance standards they must meet.¹²⁷

Use case: Aviation fuel

Global energy demand in aviation today is almost entirely met by fossil kerosene. Successfully navigating away from fossil fuels will require a holistic approach that leverages a range of proven and emerging technologies, rather than relying on a single solution. Advanced biofuels in the form of SAF could represent one of these technologies and could meet some of that demand in the future. Global demand for SAF is expected to grow by 17 percent annually to 2050.¹²⁸ Thereafter, the share of fossil kerosene in the mix could drop to between 40 and 55 percent by 2050, according to various scenarios.¹²⁹

Advanced biofuels are a category of renewable fuels derived from nonfood biomass sources, such as agricultural and forestry residues, woody

123 "Driving the difference: Cars, trucks, and the road to net zero," McKinsey, November 21, 2021.

124 "Global Energy Perspective 2023: Sustainable fuels outlook," McKinsey, January 10, 2024.

125 *The future of mobility: Transforming to be ahead of the opportunity*, McKinsey, September 1, 2022.

126 Axel Esqué and Daniel Riefer with Geert Mulder, "How the aviation industry could help scale sustainable fuel production," McKinsey, July 22, 2024.

127 Wide-body planes with range of 2,000 km or more, which constitute about 30 percent of the global fleet, consume about 75 percent of the jet fuel. The uptake of new powertrains is limited, particularly for medium- and long-range planes, given the physical limits of battery and hydrogen options. The adoption rate for alternative powertrains will also be limited because they are primarily suitable for smaller aircraft such as turboprops, gas turbine-powered propulsion planes, and regional planes. For electric powertrains, the weight of the batteries required to power the motor is too heavy. See "Global Energy Perspective 2023: Sustainable fuels outlook," McKinsey, January 10, 2024.

128 "Global Energy Perspective 2023: Sustainable fuels outlook," McKinsey, January 10, 2024.

129 The scenarios are the Current Trajectory, Further Acceleration, and Achieved Commitments scenarios from *Global Energy Perspective 2023*, McKinsey, October 18, 2023. In this report, we focus on the Further Acceleration scenario, which assumes an accelerated transition driven by country-specific commitments.

crops, algae, or waste materials. This can reduce competition for biomass (or the land it is grown on) that could otherwise be fully used to support the food system. This distinguishes them from first-generation biofuels such as ethanol and biodiesel, which are made from feedstock that can also be used for food or fodder purposes, such as edible oils, corn, or sugarcane. There are several production pathways for advanced biofuels. Advanced biotechnology could significantly improve the pathway that uses fermentation. In this process, microorganisms turn carbon sources into alcohols such as ethanol and butanol.¹³⁰

On the regulatory front, the aviation sector is seeing new regulation that supports decarbonization, including specific mandates for alternative fuels.¹³¹ Moreover, industries including airlines have started to announce targets and commit to offtake volumes, in part because of demand for change from emission-conscious customers. To meet global demand will require a sharp ramp-up of biofuels supply, which in turn will require improved processes to lower the cost of biofuel production. By 2040, demand for SAF could rise to about 100 million metric tons, of which about 10 percent would be made using advanced biotechnology, according to McKinsey research.¹³² Notably, this scenario reflects an accelerated transition driven by country-specific commitments and substantial global policy shifts, following the currently proposed regulations in Europe and the United States.¹³³

Advanced biotechnology can help decarbonize the aviation industry with low-emission jet fuel made from ethanol

One of the promising advanced biotechnology technologies to date for creating SAF is the production of jet fuel from ethanol. This precision fermentation process, known as alcohol-to-jet

(AtJ), involves fermenting sugar feedstocks (that is, first-generation feedstock) into second-generation ethanol and refining it into jet fuel. The economic feasibility of producing AtJ largely depends on the type of feedstock used. First-generation feedstocks, such as sugar, are more cost competitive than second-generation feedstocks, such as wood, when compared with other low-carbon alternatives. Biotechnology is not necessarily the winning solution and to transition away from fossil kerosene, there are various alternative production pathways to consider, including HEFA, gasification, and power-to-liquid (PtL).

However, SAF could provide an attractive and large market with demand potential in countries that make a strong decarbonization push, potentially accounting for about one-third of the global aviation fuel market, which is assumed to be about 330 million metric tons per annum (Mtpa).¹³⁴ In the SAF market (100 Mtpa), AtJ could represent about nine Mtpa in the aviation industry and be produced through advanced technologies. Under one potential scenario for 2040 that sees AtJ accounting for about 3 percent of global aviation fuel, the sustainability impact would be considerable.

The use case of jet fuels shows a reduction potential of about 20 MtCO₂e, which translates to a carbon abatement potential of 2 percent of global aviation fuel emissions. For the transportation sector as a whole, the total emissions reduction could be up to 0.4 GtCO₂e.¹³⁵

In terms of sustainability, SAF has an environ-

The use case of jet fuels shows a reduction potential of about 20 MtCO₂e.

130 Jay Keasling et al., "Microbial production of advanced biofuels," *Nature Reviews Microbiology*, June 2021, Volume 19, Number 11.

131 "ReFuelEU Aviation," European Commission, accessed December 23, 2024; "Sustainable aviation fuel policy in the United States," Climate Catalyst, December 2024.

132 "Global Energy Perspective 2023: Sustainable fuels outlook," McKinsey, January 10, 2024.

133 SAF demand is currently largely driven by the European Union and the United States due to their proposed mandates and financial incentives. For example, the EU mandate is 2 percent SAF blends by 2025 and 6 percent by 2030, and the US mandate is a minimum of three billion gallons of SAF production in 2030. "European Union Aerospace and Defense Sustainable Aviation Fuel Regulation," International Trade Administration, February 8, 2024; "Fact Sheet: EU and US policy approaches to advance SAF production," IATA, accessed December 23, 2024.

134 "Global Energy Perspective 2023: Sustainable fuels outlook," McKinsey, January 10, 2024.

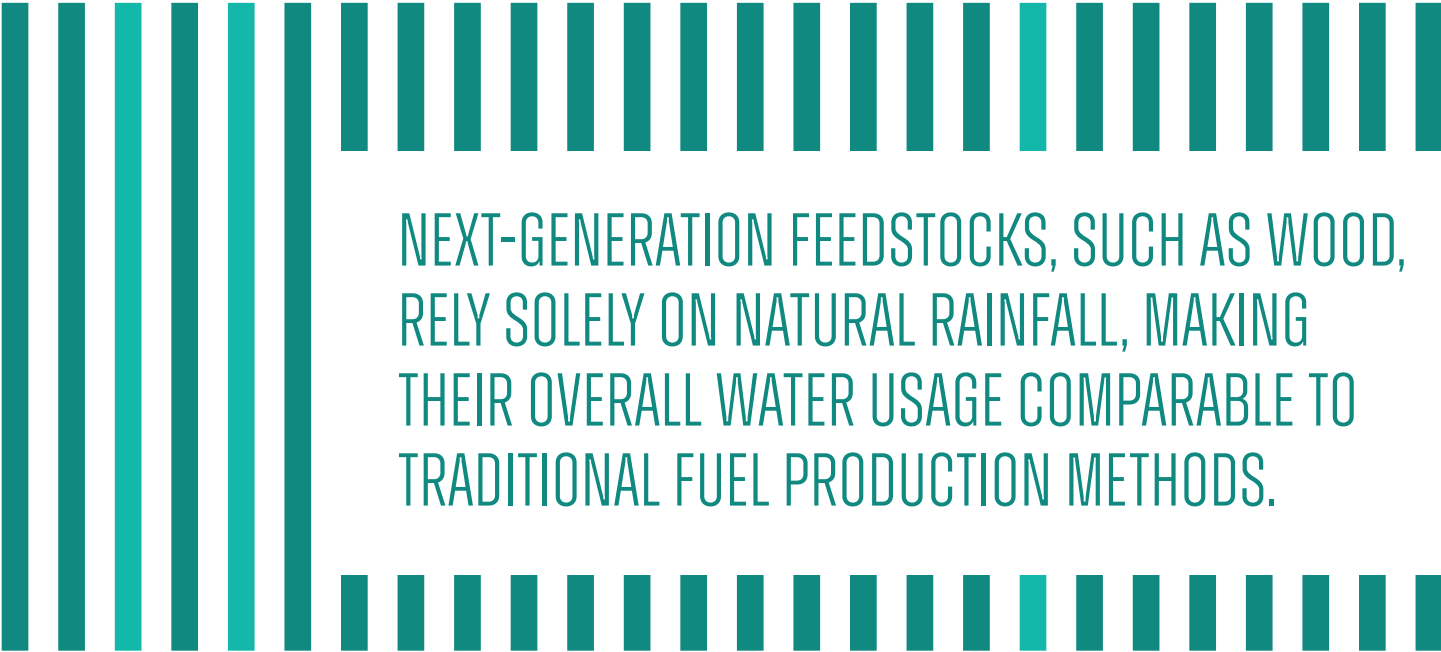
135 See the technical appendix for detailed methodology. *ICAO Carbon Emissions Calculator Methodology: Version 13.1*, ICAO, August 2024; Aaron Smith and Andrew Swanson, "Alternative land-use impacts of the sustainable aviation fuel grand challenge: Corn ethanol vs. soybean oil pathways," American Enterprise Institute, April 2, 2024.

mental footprint of its own, both from land use and water use, depending on the type of feedstock used (for example, first generation or second generation). With conventional fuels, land is mostly used for extraction and refineries. However, some biofuels based on plant oils require crops as feedstock. For SAF produced through advanced biotechnology, this could lead to increased land use of about 0.1 million square kilometers, based on an increase up to 400-fold of current land-use efficiency for global aviation fuels, from an average of 0.005 hectares per metric ton to about 2.0 hectares per metric ton.

Water usage for SAF is expected to increase by up to 0.1 billion cubic meters, an increase of up to 5 percent compared with the current water usage of about two billion cubic meters for conventional global aviation fuel production.¹³⁶ Conventional fuels, including kerosene, require relatively low amounts of water. In contrast, first-generation oil plant feedstock used for AtJ production can have high water with-

drawals because of the need for crop irrigation and fermentation. However, next-generation feedstocks, such as wood, rely solely on natural rainfall, making their overall water usage comparable to traditional fuel production methods. If it becomes possible to produce AtJ with CO₂ and renewable energy, the pressure of AtJ on land and water would also be significantly reduced. One company, LanzaTech, has already fueled a transatlantic flight with jet fuel produced from waste gases via a fermentation process.¹³⁷ It is important to note that these processes demand a substantial amount of (renewable) energy, necessitating significant potential changes to the current power mix and related energy system.

Overall, the analysis indicates that advanced biotechnology can reduce the environmental footprint of these four sectors by three to four GtCO₂e, decrease land use by two million to four million square kilometers, and save 250 billion to 500 billion cubic meters of water.



NEXT-GENERATION FEEDSTOCKS, SUCH AS WOOD, RELY SOLELY ON NATURAL RAINFALL, MAKING THEIR OVERALL WATER USAGE COMPARABLE TO TRADITIONAL FUEL PRODUCTION METHODS.

¹³⁶ See the technical appendix for detailed methodology. Steven R. H. Barrett et al., "Water consumption footprint and land requirements of large-scale alternative diesel and jet fuel production," *Environmental Science & Technology*, 2013, Volume 47, Number 2.

¹³⁷ Richard Branson, "Virgin Atlantic flies the first ever commercial flight using LanzaTech's sustainable jet fuel," Virgin, October 2, 2018.



03 CAPTURING ADVANCED BIOTECHNOLOGY'S FULL POTENTIAL

KEY TAKEAWAYS

- To achieve its full potential, the advanced biotechnology industry would benefit from adopting a market-backed approach, focusing on commercially viable products and markets with a supportive regulatory environment.
- Value creation for advanced biotechnology requires industrial scale. The investment required far exceeds that needed for lab-scale solutions, with value ultimately realized at the end of the product development pipeline.
- To achieve industrial scale, companies would need to optimize plant operations, adopt flexible capital investment strategies, and invest in technological breakthroughs to improve process efficiency—for example, by leveraging AI for operational enhancements, reusing existing capacities, and pursuing innovative feedstocks and production methods.
- New thinking on risk and value sharing is needed to accelerate commercialization. Players need to be brought together across the value chain for joint projects, with risk and value shared.
- Greater industrialization of advanced biotechnology is predicated upon three concepts: the reduction of variables; standardization across process, tools, and technology; and shift to “low-tech” deployment.

If advanced biotechnology is to achieve the full market and sustainability potential we have outlined in this report, the overall approach will need a fundamental rethink. No single solution provides all the answers. Rather, advanced biotechnology will need some new approaches and a supporting ecosystem.

In this concluding chapter, we focus on three priorities for change, each of which positively reinforces the others (Exhibit 7):

- prioritizing bio-solutions based on market demand
- derisking the scaling process
- ensuring cost-effectiveness at scale

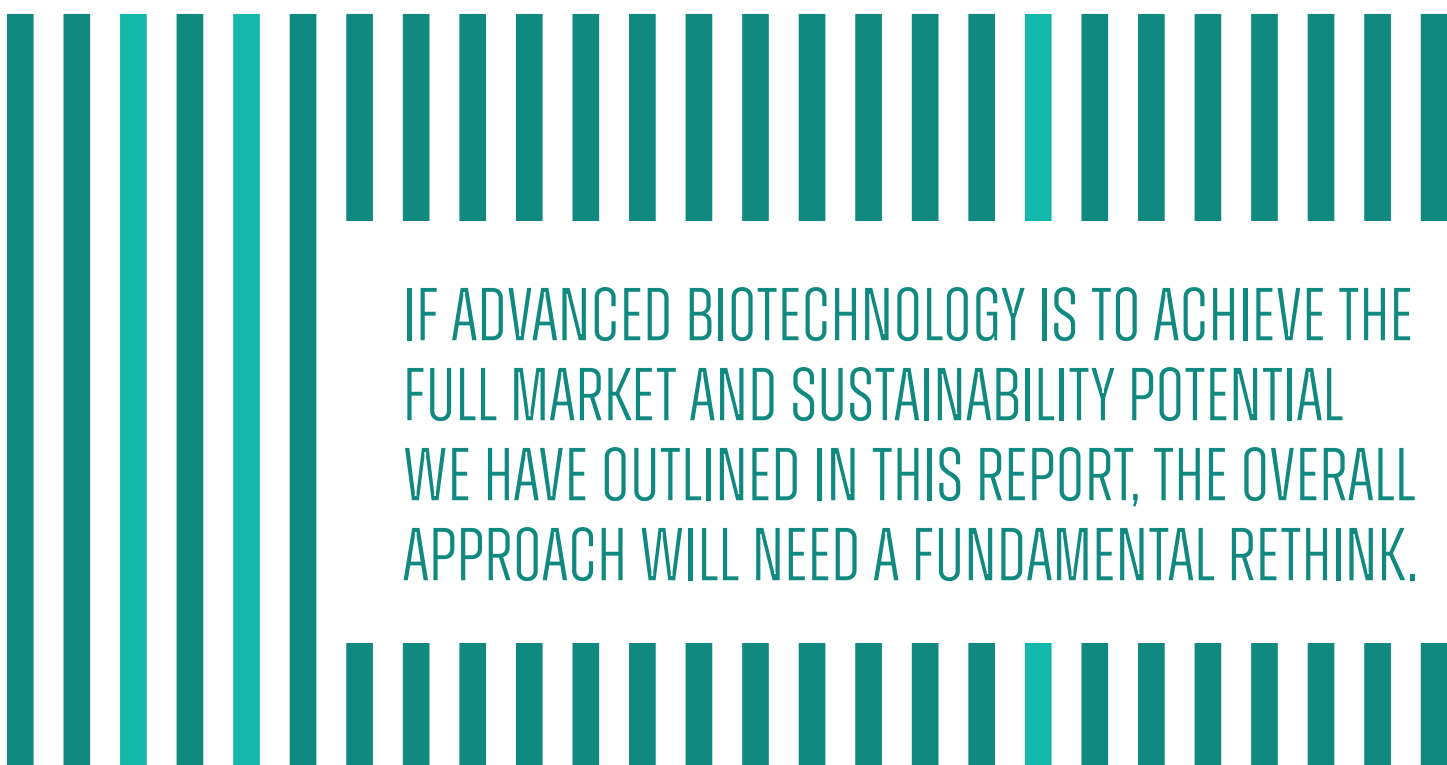
Across the three priorities, our findings suggest that industrialization of advanced biotechnology at renewed pace and scale will rely on three enabling concepts:

- **Reduction of variables.** Minimize the variety of the overall approaches across business and technology to focus resources efficiently. Numerous advanced biotechnology pathways are in development, fighting for

the same resources, but few reach maturity because they are competing for resources. This leads to a dilution of effort and focus. Concentrating on fewer, more promising technologies will ensure adequate attention and resources.

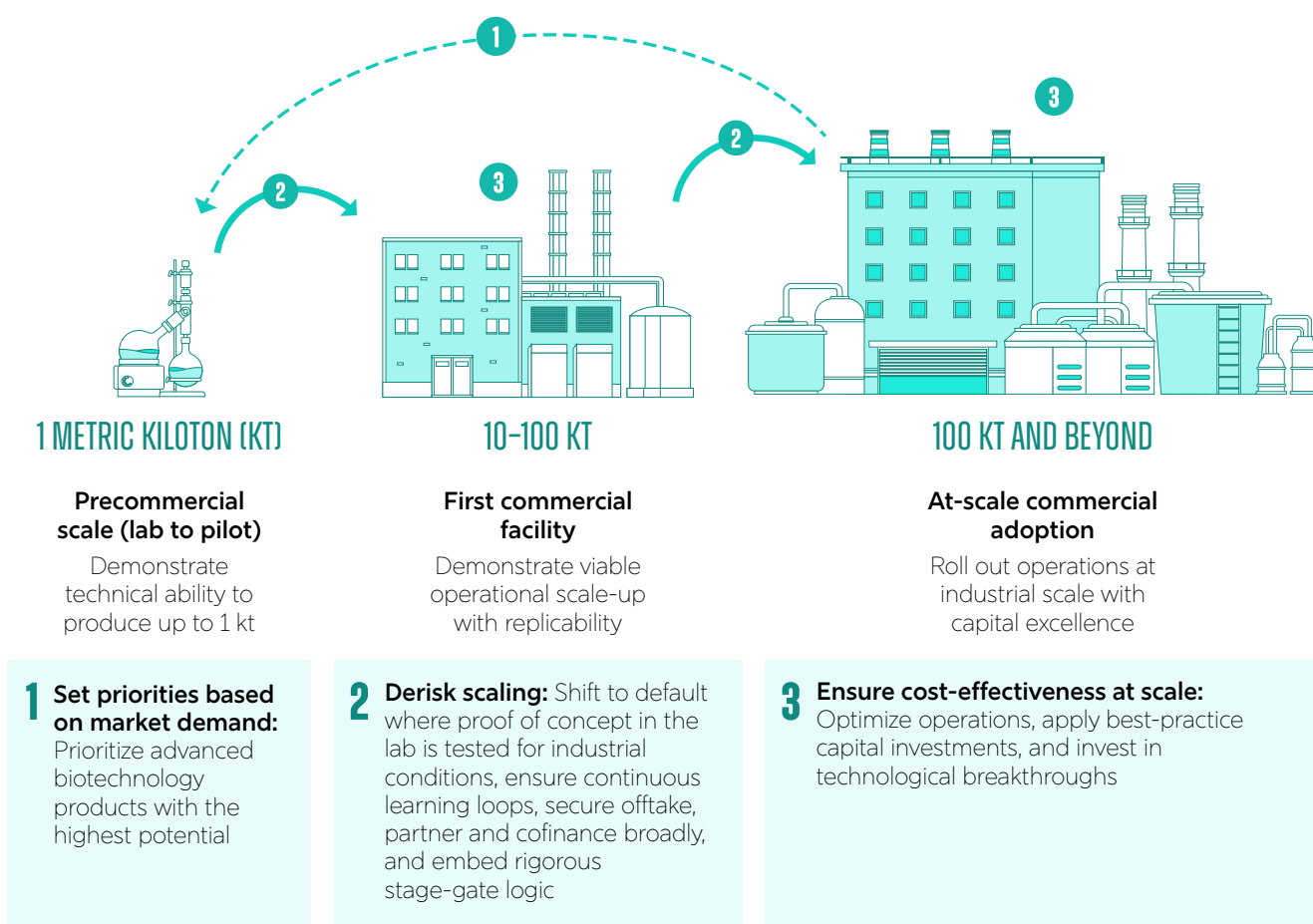
- **Standardization.** Create uniformity across processes, tools, roles, and technology to streamline operations, development, and scaling—such as standardizing terminology, process tools, and methods; establishing uniform analytical techniques and process designs; and standardizing test and measurement approaches. This standardization will play an important role in aligning investors, normalizing to standard processes, and accelerating lead times and could, for instance, guide the holistic assessment of maturity level of projects and start-ups.

- **Shift to 'low-tech' deployment.** Transition advanced biotechnology from high-tech development to cost-effective, repeatable deployment of mature technology with mature and predictable supply chains while focusing on solutions that are easily replicable.



IF ADVANCED BIOTECHNOLOGY IS TO ACHIEVE THE
FULL MARKET AND SUSTAINABILITY POTENTIAL
WE HAVE OUTLINED IN THIS REPORT, THE OVERALL
APPROACH WILL NEED A FUNDAMENTAL RETHINK.

THREE PRIORITIES FOR CHANGE CAN HELP ADVANCED BIOTECHNOLOGY ACHIEVE ITS POTENTIAL.



1. SETTING PRIORITIES BASED ON MARKET POTENTIAL

The advanced biotechnology industry has historically not achieved its full potential partly because it has not successfully focused on most commercially viable products and markets. Hence, going forward, advanced biotechnology will need to adopt a market-driven strategy, focusing efforts on products with scalable demand and clear commercialization pathways. It is key to not only assess the markets in which biotechnology products can be successful and the potential demand for specific products at the expected future price points (assuming production at scale), but also to integrate lessons from past successes in scaling. For example, strong regulatory incentives are now enabling SAF to deploy largely at scale, while succinic acid faces a lack of similar incentives and a high level of complexity in demonstrating the value of new,

higher-cost molecules in the applications. Furthermore, PLA took decades to transition from lab research to industrial reality, highlighting the need to align production with market readiness. Thus, improved performance of bio-solutions and favorable market conditions—such as clear end-use demand, cost outperformance, or regulatory support—must be considered. Such analysis can guide resource allocation and prioritization of bio-solutions, ensuring that efforts are directed toward areas with the greatest potential for high-impact, scalable adoption.

High demand. Bio-solutions can meet substantial market needs, ensuring that new large-scale production can be sold effectively. This involves targeting sectors with robust growth potential and unmet needs (in terms of sustainability or future availability, for instance) and where advanced biotechnology has a cost edge. That would guarantee that the bio-solutions devel-

oped will have a ready market capable of absorbing new, large-scale production.

Viable path to commercialization through cost competitiveness and technical feasibility at scale. Bio-solutions need to be economically feasible for large-scale production so that they can compete with fossil-based alternatives, which remain the benchmark for cost and scalability. Sustainable solutions are not widely valued in the market, making cost performance, regulatory incentives, or additional functionality essential for adoption.¹³⁸ Solutions need to be able to meet industry standards and requirements without significant technical barriers. When setting priorities based on market demand, the following factors need to be assessed: the maturity of the technology, scalability of processes, and availability of necessary infrastructure. The long-term sustainability and attractiveness of these solutions in the market will depend on how cost competitive they are. This can be improved through technological advances to optimize production efficiencies and leverage economies of scale.

Regulatory environment for market entry.

Regulatory and policy frameworks play an important role in prioritizing markets for scaling and commercialization of bio-solutions—especially because new technologies (particularly in the fields of AI and biotechnology) are being developed at a rate that makes it challenging for companies and governments to shape norms regarding civil liberties, privacy, and ethics. When entering markets, companies will need to consider existing regulatory incentives for sustainable products and identify regulated markets with potential for large-scale deployment; for example, the regulation promoting biofuels usage in Europe is making the market more attractive for biofuels¹³⁹).

Companies will therefore need to consider the regulatory environment as well as the regulatory approval process before entering a market: does the market have a functioning legal framework for advanced biotechnology applications? What is the time to approval? Are tax and investment incentives available? And what are the restrictions on advanced biotechnology products?

Regulatory approvals are essential for compliance because bio-solutions must navigate regulatory frameworks that require proof of meeting or exceeding performance and safety standards of fossil-based alternatives. For example, in the United States, the FDA regulates plant and animal biotechnology products in coordination with the Department of Agriculture and the Environmental Protection Agency. Compliance with regulatory approvals can minimize delays, accelerate market entry, reduce legal risks and operational uncertainties, and strengthen market position, demonstrating viability of the bio-solution. Some countries that focus on growing tech, including China and the United States, already have regulations tailored to encourage innovation and to attract biotechnology investments.¹⁴⁰

Beyond regulations, governments create strategies and publish policies to steer demand and market players toward agreed goals. These can include developing clear taxonomies and industry standards, setting up public-private partnerships to derisk commercial investments, establishing demand incentives such as subsidies, and streamlining the allocation of feedstocks and biomass. For example, ReFuelEU Aviation, a mandate to gradually increase the use of SAF in aviation, is expected to increase demand, investment, and infrastructure for SAF.¹⁴¹

138 “Sustainable feedstocks: Accelerating recarbonization in chemicals,” McKinsey, October 26, 2023.

139 ReFuelEU Aviation will boost innovation and investments in SAF across the whole supply chain and across all regions of the European Union. See “ReFuelEU,” accessed December 23, 2024.

140 The United States regulates novel food through the FDA without involvement of federal and state governments. Individual states can prohibit sales of specific food products. In the European Union, novel food requires approval from the European Commission, based on the risk assessment of the European Food Safety Authorization, and 55 percent of member states, representing 65 percent of the EU population, can block approval (qualified majority). “Novel food: Authorisations,” European Commission, accessed December 23, 2024; “Qualified majority,” European Council, updated June 28, 2024. See also “Government policies driving innovation in China’s biotech industry,” *Life Sciences Review*, September 6, 2024; “Executive order on advancing biotechnology and biomanufacturing innovation for a sustainable, safe, and secure American bioeconomy,” White House, September 12, 2022.

141 “ReFuelEU,” accessed December 23, 2024.

Companies aiming to enter the advanced biotechnology sector need a comprehensive understanding of global regulations and policies to ensure their market introduction is compliant, safe, and efficient. For instance, in the case of fermented and cultivated food products, key considerations include the following:

- understanding the regulatory science-based approval process centered on food safety and risk assessment
- understanding the submission process for approvals, such as level of detail in guidance, process to review draft submissions, and opportunity to contact staff during the process
- understanding the regulations on advanced breeding products, especially if they are product- rather than process-oriented; product-oriented regulations often have clearer guidance on application of genetic modification and can support adoption rates of advanced biotechnology solutions

Once the most promising bioproducts are identified for production based on demand outlook, technical feasibility, and regulatory environment, industry players can act upon them. Public-private collaborations might play an early role in guiding resources toward priority products. Such endeavors could take the shape of a joint undertaking with governments, policy makers, funding agents, and companies, including those representing the entire value chain from feedstock providers (ensuring sourcing) to consumer goods companies (providing advance market commitments). One existing example is the Circular Bio-based Europe Joint Undertaking, a partnership between the European Commission and the Bio-based Industries Consortium.¹⁴²

We expect that a variety of companies will seek to produce high-priority products simultaneously, but shared learnings will be important for the industry's future growth. As proof points emerge, perceived risk goes down along with the cost of capital, because evidence of future

commercialization can make a business more appealing to investors.

2. DERISKING SCALING

Venture capital (VC) for advanced biotechnology has seen a significant decline in funding, falling 62 percent by 2023 from its peak at the end of 2021. This decline can be attributed to factors related to the macroenvironment, including rising interest rates, a shift in focus from growth to cash flow generation, and investors' skepticism driven by broader uncertainty in the VC landscape. These dynamics have shifted the focus from intellectual property to commercial traction and price competitiveness.

Consequently, investors are wary of the extended time horizons toward profitability typically seen in biotechnology and have shifted their focus from broader hype-driven solutions to specialized or enabling technologies (for example, B2B ingredient companies and enabling technologies that focus on specific aspects to improve taste or texture).¹⁴³

Valuations have declined substantially, leaving many investors with losses. For example, the valuations of publicly traded agriculture technology (agtech) companies dropped by about 60 percent between peak valuations in early 2021 and 2023, in many cases declining to levels below their initial funding amounts.¹⁴⁴

Nonetheless, several advanced biotechnology scale-ups have been able to attract capital in 2024, including Perfect Day (\$90 million), Mosa Meat (\$85 million), Samsara Eco (\$65 million), Formo (\$60 million), Onego Bio (\$55 million), Again (\$43 million), and Galy (\$33 million).¹⁴⁵ They are active in precision-fermented dairy proteins, cultivated meat, enzymatic plastic recycling, animal-free cheese, animal-free eggs, chemicals based on CO₂, and precision-fermented

Public-private collaborations might play an early role in guiding resources toward priority products.

¹⁴² For more, see "About," Bio-based Industries Consortium, accessed January 27, 2025.

¹⁴³ The number of biotechnology VC deals peaked at 473 in 2021 and decreased to 178 during the first three quarters of 2023. "What early-stage investing reveals about biotech innovation," McKinsey, December 12, 2023; Megan Tatum, "Investment in European food tech set to worsen in 2024," Food Navigator, updated August 2, 2024; Gwendolyn Wu, "Early-stage biotech funding on pace to drop 40% in 2023, HSBC report shows," Biopharma Dive, July 28, 2023.

¹⁴⁴ "Seizing opportunities amid the agtech capital drought," McKinsey, March 19, 2024.

¹⁴⁵ Data from PitchBook.

cotton, respectively. Notably, these companies demonstrate a pathway to commercialization and cost competitiveness, and have initial commercial partnerships. For example, Onego Bio has developed a method for cost-effectively biomanufacturing a protein found in egg whites in partnership with Perfect Day,¹⁴⁶ and Samsara Eco has established partnerships with various leading apparel brands.¹⁴⁷

This market context and the lack of widely recognized success stories (as is common for any nascent market and technology) suggest that derisking will be needed to promote scaling. Such derisking can be an important factor in reinstating investors' appetite for the sector and drive its full potential.

Biotechnology is often associated with biopharma, a low-volume, high-value industry in which most value is created in the lab. However, value creation for many non-pharma applications requires industrial scale, with a required investment far exceeding that needed for lab-scale solutions, and value ultimately realized at the end of the product development pipeline.

Derisking scaling to demonstrate viable operational scale-up and replicability can be amplified by addressing four dimensions: technical, commercial, financing, and capabilities. This requires efforts across the whole ecosystem, and a supportive and enabling ecosystem that will be conducive to the scaling of advanced biotechnology needs to be in place.

Technical: Derisking manufacturing by replicating industrial conditions

Derisking the technical aspect of scaling requires a fundamental shift: rather than trying to bring lab conditions to industrial scale, industrial conditions must be integrated into the lab starting at the R&D phase to minimize trial and error and costly work and rework. Several overarching concepts are important when addressing the reduction of both capital expenditure and operational expenditure during scaling, as we note below. These include the reduction of variables in manufacturing by reusing established industrial capacity and processes, the standardization

of equipment, and the modularization of production. Additionally, shifting the approach from high-tech development to low-tech deployment would enable the use of existing cost-effective and repeatable technologies to kick-start the market.

Up-front scrutiny on design choices can ensure the use of host organisms and feedstocks that have been proved at scale, and an economic analysis can underscore the market fit and positive business case. Research and industry collaboration can help map "lower risk" molecules and technologies that have been proved to work, as well as identifying markets in which consumers would be ready to pay a premium linked to the additional performance. Both the food sector and cosmetics could be candidates here. For food, inspiration can be drawn from several examples that have already been proved to work (at least in demonstration scale), including alternative proteins, sweeteners (steviol glycosides), milk proteins, omega-3 fatty acids, human milk oligosaccharides, iron-binding molecules (heme), and texturizers (hydrocolloids). Cosmetics could include hyaluronic acid, biosurfactants, and ceramides. These examples provide reference cases regarding the uptake of new biomolecules and their business case. As a follow-up, the industry and investors would need to map the next-priority molecules to direct investments.

Following a similar industrial approach to data use would derisk the scaling path; the lack of thorough and comprehensive data currently poses a serious obstacle for scaling. Gaps such as lack of access, noise in the available data, high cost of data points, and the lack of advanced real-time sensing capabilities prevent the digitization of industrial processes and use of AI and omics (studies of large-scale biological data, such as genomics) in scaling. A new approach to data generation and sensing can help integrate industrial conditions in the lab and provide much better understanding and control of the processes at scale. Doing so can transform the current view of scaling as a one-way process into a continuous learning loop.

¹⁴⁶ "Perfect Day and Onego Bio announce partnership," Onego Bio, September 20, 2022.

¹⁴⁷ "Samsara Eco scales up infinite recycling for plastic waste," Clean Energy Finance Corporation, updated July 2024.

Finally, replicating derisking methods from other industries is essential for the technical dimension of scaling potential. The pharmaceutical R&D process contains rigorous mechanisms (also known as stage gates) that help players understand when the chance of failure has grown too large for the required investments.¹⁴⁸ Translating this process to the advanced biotechnology sector could increase success rates and help companies mitigate risks faster. Such processes are already established in some of the domains where advanced biotechnology can make a difference but could be strengthened in others. A robust and standardized phased-review framework can distinguish and communicate the level of technical risk for industrial applications to enhance the chances of commercial success. Also, contingency plans—with next-in-line bio-solutions in case first efforts fail—could enable a more-reliable scaling approach.

Commercial: Ensuring offtake and customer acceptance

Like many capital-intensive industries, advanced biotechnology faces a growth dilemma: offtake agreements are not being signed because proof of commercial-scale production and proven applications for the novel output are lacking. At the same time, offtake agreements are widely regarded as a key unlock for investments in commercial-scale plants. Conversely, investments for commercial-scale plants are not being made because offtake agreements are not in place.

Historically, companies have battled to overcome this growth dilemma. Going forward, new business models for risk and value sharing could accelerate the commercial scaling path of advanced biotechnology. This would mean gath-

ering players across the value chain to engage in joint projects to share the risk and value more broadly, thus reducing variables in the commercial scaling path. Some value chain consortiums already exist; for example, Danone, DMC, Michelin, and Crédit Agricole joined forces to set up a biotechnology center (also supported by several public and private institutions)—signaling collective coordination, expertise, and risk sharing.¹⁴⁹ In another example, a collaboration among Abolis, Evonik, and L'Oréal, demonstrates how existing industrial infrastructure and market access are being articulated to streamline scale-up efforts. Other emerging industries, such as the sustainable-fuels sector, have also shown the potential of broad industry consortiums; Project SkyPower exemplifies stakeholder organization by uniting a diverse consortium of airlines, fuel providers, airports, and financial institutions to collaboratively advance the production of eSAF.¹⁵⁰ Such partnerships reduce operational uncertainties, align stakeholders across the value chain, and enhance the commercial viability of new bio-solutions.¹⁵¹ Partnerships can be especially valuable if they lead to joint investment in open-access facilities and guaranteed offtake agreements with end-market players: incumbents' investments, shared fermentation capacities, and expertise could help start-ups and scale-ups reach commercialization faster.

A coordinated ramp-up of production with the other steps in the value chain is also needed,

New business models for risk and value sharing could accelerate the commercial scaling path of advanced biotechnology.

148 This process involves a series of checkpoints or “gates” at critical stages of development, from discovery through clinical trials and, ultimately, market approval. At each gate, the project undergoes thorough evaluation based on predefined criteria, including scientific feasibility, safety, efficacy, and commercial potential. This structured approach allows companies to systematically assess the risk and viability of a project, ensuring that resources are allocated efficiently and effectively.

149 “Danone, DMC, Michelin, and Crédit Agricole Centre France join forces to create a cutting-edge biotechnology platform,” Danone, June 12, 2024.

150 For more, see the Project SkyPower website.

151 “L'Oréal Groupe partners with Abolis and Evonik to scale development of next-generation bio-based ingredients,” L'Oréal, September 12, 2024.

so that the market can absorb the incoming new production. Various stakeholders, including upstream, downstream, and consumers, need to work closely together as a team to ensure that different value chain perspectives (such as feedstock volumes and cost or price from both the supplier and producer side) and consumer perspectives are incorporated into the design phase.

To reinvigorate investment in advanced biotechnology, the industry will need to highlight derisked investment opportunities and attract investors beyond venture capital and equity financing.

The industry will thus need to raise customer and consumer awareness of advanced biotechnology to build trust and market acceptance. A joint narrative highlighting the benefits of advanced biotechnology solutions and products for nature, health, and climate could be an effective tool to achieve this.

The emphasis in communication may differ depending on whether applications are B2B or B2C. For B2B applications, such as chemicals, the market is mainly driven by a cost-competitive price and proof of environmental impact. In B2C applications, similar performance (taste, texture) and (perceived) acceptance of the product play a larger role. For the latter, public awareness campaigns could highlight environmental benefits and confirm product safety.

Financing: Establishing an investment framework

Bioproduction is capital-intensive and, especially in the B2C sector, faces high commercialization costs because of the high cost of building the brand and consumer acceptance. A new investment framework will be needed to scale beyond the demonstration plant stage. For fermentation

alone, we estimate that total investments for reaching full potential in 2040 would amount to about \$500 billion, counting both capital spending on the build-out and start-up financing (for details of this estimate, see the technical appendix). That is equivalent to yearly investments of \$25 billion to \$40 billion. About 85 percent of these investments would go to building out the required fermentation capacity, which may need to increase 50-fold, from about 50 megaliters (ML)¹⁵² in 2020 to 2,000 to 3,000 ML in 2040, according to a range of forecasts by various sources. The remaining 15 percent of total required investment would be for R&D.¹⁵³

Current investment in fermentation for alternative proteins, for example, has moved in the opposite direction over the past two years, falling to about \$850 million to \$900 million per year on average from 2020 to 2023.¹⁵⁴ Investment in biotechnology more broadly has followed a similar trend: while investment tripled in the past decade and grew strongly during the pandemic, capital market activity has dropped in the past two years.¹⁵⁵

The full biotechnology sector, which can be seen as a proxy for the advanced biotechnology sector, has raised an average of about \$40 billion in funding per year between 2019 and 2023. However, an estimated 60 to 70 percent of this is for health and medical companies, which are out of this report's scope. Almost 65 percent of this has been invested in the United States, followed by China and then the European Union, showing the need for more investments outside the United States. More than 50 percent has been invested in companies active in Series A and Series B financing, quickly declining in further rounds: total capital raised in Series D financing is almost a third lower than in Series A or Series B. This suggests a need for biotechnology companies to have more late-round, low-risk financing options from institutional investors, among

152 Capacity for precision fermentation and biomass fermentation for chemicals and food (excludes capacity required for other technologies, such as cultivated meats, and other sectors, such as fuels).

153 See the technical appendix for detail.

154 *Fermentation: Meat, eggs, and dairy*, Good Food Institute, April 2021; "Executive summary: Fermentation: Meat, seafood, eggs, and dairy," Good Food Institute, April 2022; *Fermentation: Meat, seafood, eggs, and dairy*, Good Food Institute, January 2023; *Fermentation: Meat, seafood, eggs, and dairy*, Good Food Institute, April 2024.

155 Analysis of company financial statements for animal industry stats. For alternative protein stats, analysis of Good Food Institute state of industry reports and AgFunder. Good Food Institute analysis of PitchBook data. Invested capital includes accelerator and incubator funding, angel funding, seed funding, equity and product crowdfunding, early-stage venture capital, late-stage venture capital, private equity growth and expansion, capitalization, corporate venture, joint venture, convertible debt, and general debt completed deals.

other investors. To reinvigorate investment in advanced biotechnology, the industry will need to highlight derisked investment opportunities and attract investors beyond venture capital and equity financing, including those with a broader range of performance metrics—for example, environment, social, and governance (ESG) metrics.

As previously noted, today's new advanced-biotechnology start-ups are largely financed by VC, with the financing primarily oriented toward precommercial-scale developments. While developing a cost-effective engineered strain (wiring) at pilot scale is an area for which VC money is adequate, scaling bioproduction facilities requires substantial capital. Given the cost of large-scale fermentation and downstream-processing assets, the capital needed goes beyond typical investable capital of VC firms and will require a broader set of investors. Moreover, it takes several years to develop a bioprocessing site at scale, challenging the attractiveness of the typical private equity holding period. The risk profile of scaling bio-solutions is currently not conducive to large-scale and "patient" investors such as pension funds and other institutional investors that can provide debt financing.

The key to successful financing is thus to attract a wide range of investors, encouraging the combination of large-enough tickets, longer holding periods, and comfort with bioproduction's associated risk levels. Cofinancing, asset sharing, public-private partnerships, and special-purpose vehicles all have roles to play here. Potential ways to establish such financing include the following:

- **Attract funding for pilot scale by stimulating joint investments from multiple VC and private equity firms and taking an incremental approach to scaling.** This will allow players to pool larger sums of venture capital and growth equity. It will also reduce risk and investable-capital requirements.
- **Accelerate the pathway to flagship production by creating consortiums of value chain players to jointly request financing, establish asset sharing models, and**

collaborate in cofinancing. Requesting financing as a group of technology providers, manufacturers, consumer goods companies, and financiers can signal credibility regarding supply and offtake as well as allow for better risk assessment and risk sharing. A first step could involve mapping the value chain with where the investment needs to sit (typically within the innovative technology providers or start-ups) and where the risk-carrying ability sits (typically with large corporations). To correct this imbalance, consortiums could add substantial value when spreading the risk and investment burden.

- **Ensure an ecosystem for hyperscaling by creating risk-capped formats of bioprocess scaling.** This could be done through standardized transferable assets, multiple contingency plans, and project financing using special-purpose vehicles. Companies could also consider creating infrastructure-specific asset classes for infrastructure investors and highlighting the local social benefits such as food security, nature preservation and jobs, to appeal to public capital including sovereign wealth funds.
- **Use blended financing mechanisms of debt investors—both public and private, dilutive and non-dilutive—to help de-risk investments.** For example, non-dilutive capital can be ensured through bank debt and government grants and loans. Additionally, players need to derisk the technical and commercial path to appeal to investors overall (see "Derisking scaling" in chapter 3 for more about the steps to derisking).

Finally, requests for financing would need to be calibrated to investor profiles, ranging from raising tens of millions of dollars for incremental developments from VCs to raising hundreds of millions for industrial-scale bioprocessing infrastructure from large investors. Solugen's "bioforge" in the United States is an example of successful financing of large facilities building on (local) government and alternative financing sources for the capital outlay.¹⁵⁶

156 Lora Kolodny, "Solugen scores \$214 million loan from DOE to make chemicals from corn sugar not petroleum," CNBC, June 23, 2024.

Supporting operational capabilities: Removing potential scaling bottlenecks

Beyond technical, commercial, and financing dimensions, players need to remove the operational bottlenecks of advanced biotechnology to derisk scaling. Bottlenecks can focus on topics such as skills input (bridging talent gaps), knowledge inputs (facilitating precompetitive knowledge and intellectual property [IP] sharing between biotechnology players), and feedstock input. Sufficient renewable energy and feedstock is also required to facilitate the transition toward sustainable production at scale.

Bridging the talent gap. Advanced biotechnology requires specific talent and knowledge with in-depth understanding of bioengineering and biomanufacturing, in combination with commercial skills to develop the relevant technologies and to scale. The industry typically faces strong competition for talent from pharma, which can offer higher salaries, industry maturity and stability, and job attractiveness. There are also geographical differences in talent availability: Europe, already tapping into a smaller talent pool than the United States, is also facing the problem of talent leaving for the larger and more heavily funded US market.¹⁵⁷

Several actions can support the development of more biotechnology talent, including the following:

- Educate and excite people about this career path. Position advanced biotechnology as an opportunity to drive societal impact, sustainability impact, or both through campaigns or events such as the iGEM Competition, a global annual event that gives students a chance to explore synthetic biology.
- Broaden curriculums in higher education beyond biotechnology-related theory to align with industry needs. Include topics such as economic analysis, regulation, project management, and industry-scale experience with fermentation and cultivation.

Overall, develop stronger collaborative ties between academia and industry.

- Upskill the existing biotechnology workforce or pull nontechnical talent into the advanced biotechnology space by offering part-time education options such as single modules, trainings, and courses. Facilitate the application of knowledge through workshops, seminars, and internships.

Organizations are already taking steps to bridge the talent gap within the broader community. For example, the Novo Nordisk Foundation awarded a grant of approximately \$1 million to support a university's bioentrepreneurship program, which includes advanced biotechnology courses.¹⁵⁸ This initiative exemplifies how targeted efforts can drive talent development in biotechnology. Scaling up such efforts by engaging a broader community of stakeholders, including other foundations, industry players, and academic institutions, can create a more robust and integrated ecosystem for nurturing biotechnology talent globally.

Facilitating precompetitive knowledge and IP sharing between biotechnology players, academia, or governments. This can accelerate tech transfer to commercialization.

Strategic partnerships can help among advanced biotechnology players learn from one another's knowledge and infrastructure by sharing IP or using facilities that allow for experimentation and production on a larger scale. Several such partnerships have emerged or are being set up. For example:

- The US-based BioMADE Pilot Plant Network (PPN) established several bioproduction sites to foster innovation by derisking new technologies and products with innovative start-ups, small companies, and large industries.
- The Cultured Hub in Switzerland provides facilities to help start-ups scale their cultivated-meat operations more efficiently.

¹⁵⁷ "Finance, culture, talent: Why Europe struggles to commercialise its biotech expertise," *Financial Times*, March 20, 2022; Vincent Bérubé, Dana Maor, Marino Mugayar-Baldocchi, and Angelika Reich, "European talent is ready to walk out the door. How should companies respond?" *McKinsey Quarterly*, December 12, 2022.

¹⁵⁸ "CBS-BIO – Master's programme in bioentrepreneurship," Novo Nordisk Foundation, accessed December 23, 2024.

- Cluster Industrial Biotech (CLIB) in Düsseldorf facilitates projects to stimulate collaboration on innovation across its network of biotechnology players, academia, and governments.
- And Toulouse White Biotechnology (TWB) offers a public-private partnership model supporting start-ups by providing lab and scale-up facilities, as well as access to academic expertise and capabilities.¹⁵⁹

Strategic partnering with universities can help companies access targeted research funding and foster collaboration with other institutions to expand networks and growth potential. Strategic partnerships between governments and advanced biotechnology players can create a road map to achieve national sustainability commitments.

3. ENSURE COST-EFFECTIVENESS FOR AT-SCALE ROLLOUT

After prioritizing markets based on demand and derisking the scaling path, three routes can help advanced biotechnology to scale up cost competitively to its full potential beyond demonstration scale.

First is the need to optimize plant operations to minimize running costs. While it can take decades to achieve full optimization for industrial plants, advanced biotechnology players need to find a way to accelerate the timeline to cost competitiveness at scale by leveraging data, sharing insights, and using advanced modeling to reduce variability, enhance strains, and maximize yields. Integrating biological and chemical processes, supported by AI, can further streamline operations and maximize outputs.

Second is to apply best practice capital investment methods to develop and commission additional capacity as quickly as possible and with the lowest risk. This includes using flexible,

modular, less-specialized designs and shared capacities to adapt to varying production needs. Also, by standardizing equipment and reusing existing bioproduction capacities, rather than commissioning new processes for each product, companies can save on capital expenditures and reduce time to market. Taking this low-tech deployment approach instead of high-tech development could derisk the scaling path, as mentioned in the previous section.

Third, advanced biotechnology companies will need to invest in technological breakthroughs to improve process efficiency and reduce the capital intensity of scaling—especially through driving disruptive innovation into processes that are already known to work well and at low cost. That will involve switching to lower-cost feedstocks such as platform molecules or CO₂, decreasing process costs by turning microorganisms thermophilic or anaerobic (as described below), or altering and valorizing waste streams.

We modeled the cost reduction potential with existing technologies for precision fermentation as an example for dairy proteins in the specialty-foods sector. Our analysis suggests that using precision fermentation could lead to a unit cost of \$8 to \$13 per kg of dairy protein molecule (Exhibit 8). That is about 50 to 75 percent cheaper than the current unit cost (about \$30 per kg), and can make the advanced biotechnology product cost competitive with its conventional alternative. Similar cost reductions can likely be reached for other novel fermentation molecules, because the levers are applicable in the same fashion.

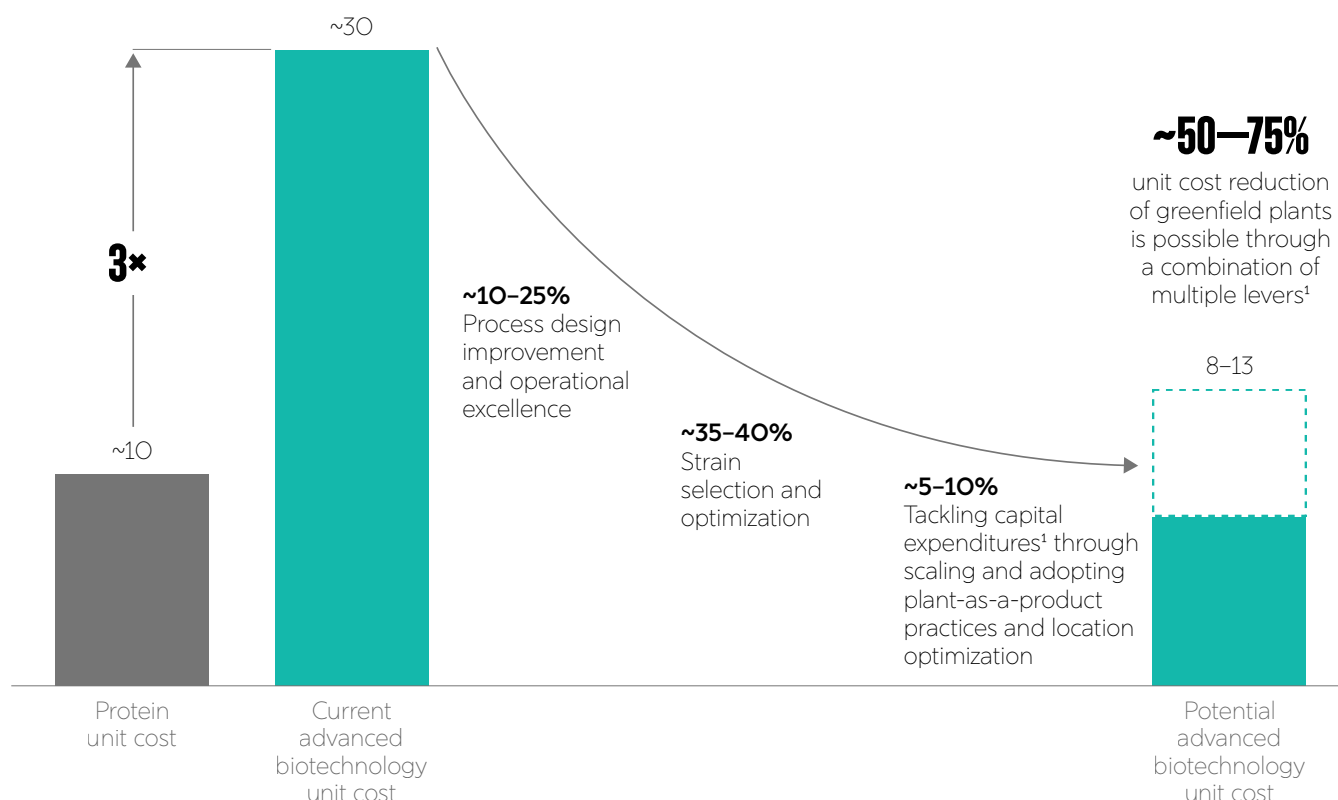
Advanced biotechnology players need to find a way to accelerate the timeline to cost competitiveness at scale by leveraging data, sharing insights, and using advanced modeling to reduce variability, enhance strains, and maximize yields.

159 "Addressing infrastructure gaps to build the biomanufacturing industry," BioMADE, accessed December 23, 2024; see the Cultured Hub website; see the Cluster Industrial Biotech website; "R & D projects," Toulouse White Biotechnology, accessed December 23, 2024.

EXHIBIT 8

THE COST OF PRECISION FERMENTATION PRODUCTION TODAY IS MORE THAN THREE TIMES HIGHER THAN CURRENT UNIT COSTS, BUT SEVERAL LEVERS CAN HELP REACH COST PARITY.

Cost reduction potential of proteins from precision fermentation, \$/kg



Note: Allocation of impact by lever depends on the computing order. Computing order in this example is operational excellence, process design, location, strain selection and optimization, capital expenditure reduction, and scaling. The individual reduction potentials shown are based on their respective contributions when applying them together. When applied individually, the effects of levers may differ. Exhibit assumes a plant with 6×200 m³ fermenter capacity producing ~80 batches per year with a productivity of 0.55 grams per liter per hour (g/L/h), 4.2 metric kilotons per year from 1.2 ML installed capacity, and \$300 million per plant capital expenditures (15-year lifetime and 10% cost of capital).

¹Assumes already diluted capital expenditures through process improvements.

Bioscience already has precedents for this combination of rapid innovation and cost reduction. For example, economies of scale and technical and financial innovations led to a substantial decrease in the costs of ethanol production in the 1990s.¹⁶⁰ In the ten years between construction of the world's first large ethanol production plants in the early 1990s and the early 2000s, capital costs of the facilities went down by about 70 percent. One study found that operating costs also fell between the early 1990s and the early 2000s, with energy and water inputs declining by 30 percent and 70 percent, respec-

tively. These improvements were due not to revolutionary new inventions but rather to learning curves and economies of scale.¹⁶¹

Another use case highlights how AI and high-throughput screening can significantly speed up innovation and improve R&D predictability and effectiveness. Biotechnology R&D is an iterative development process of strain engineering (for example, for specific enzyme production) and optimizing growing environments to optimize productivity, yield, and media requirements. Rapid advances in AI and protein

160 S.C. Dekker et al., "Understanding the reductions in US corn ethanol production costs: An experience curve approach," *Energy Policy*, January 2009, Volume 37, Number 1.

161 *Chemical Economics Handbook: Ethanol*, SRI Consulting, 2023.

design have been underscored by the Nobel Prize awarded to David Baker—a biochemistry professor at the University of Washington who has developed protein design software and uses it to create molecules that solve challenges in medicine, technology, and sustainability—and the team behind the AlphaFold protein structure database, developed by Google DeepMind, which provides open access to more than 200 million AI-generated protein structure predictions.¹⁶² Such innovations put more pressure on derisking the scaling process, because the next step is expressing and industrially producing these proteins and enzymes to be able to translate the computational predictions and designs into real-world applications.

Finally, downstream processing (for example, extracting and drying product from fermentation broth via several steps) can help ensure a cost-effective at-scale rollout. Downstream processing is responsible for 30 to 40 percent of operating costs and heavily affects capital spending, but it is often neglected in the early phases of the product design. There is often a lag between the time when downstream-processing costs are determined (in the design of the organism and of the process) and the time when the cost is incurred (at the end of the fermentation process), possibly because it is far from the lab in which it has been determined. Thus, a holistic view of product design is needed: designing size to match output from the upstream processing units to minimize bottlenecks across the process flow, and maximizing for successful runs through minimizing process fluctuations and variations as well as contamination. Optimizing yield through, for example, analytics-driven “profit per hour” optimization of equipment and process conditions would be beneficial.

Innovating for the medium to long term

Looking ahead, overcoming current production limitations—for example, in microbial strain performance, fermentation productivity, and process inefficiencies—would be a critical breakthrough. This would allow for increased production efficiency including higher-concentration target product.

Investing in transformative technologies can radically improve efficiency, ranging from strain design to downstream processes, and allow companies to achieve sustainable commercial success more rapidly. For example, this could involve shifting to CO₂ or abundant platform molecules (such as industry side streams) as fermentation feedstocks or exploring bioproduction with thermophilic or anaerobic organisms—which have lower energy or input oxygen costs—if thermodynamics allow. Another opportunity would be to deploy process intensification solutions, leading to higher yields and better feedstock utilization, and radically redesigning the process to minimize carbon, energy, water, and pH spills and ensure consistent, efficient, and rapid conversion.¹⁶³

Current production processes are mostly batch or fed-batch, and advances that allow for continuous production methods could improve production efficiency by 10 to 20 percent by reducing turnaround cycles (emptying, cleaning in place, sterilizing, inoculating, and starting up again).¹⁶⁴

Overall, to make bio-based solutions competitive with their conventional counterparts and to achieve significant cost reductions, both near-term and longer-term innovation levers need to be deployed.

162 For more, see “AlphaFold Protein Structure Database,” EMBL, accessed January 8, 2025.

163 See the methodology description in chapter 1 and the technical appendix for details of these calculations.

164 Ibid.

4. OVERVIEW OF SCALING BOTTLENECKS, POTENTIAL SOLUTIONS, AND TOPICS FOR FURTHER RESEARCH

In Box 3, we summarize some of the most important bottlenecks that could hold back progress in advanced biotechnology's scale-up journey and offer some solutions that can help accelerate scaling.

Potential topics for further research

Advanced biotechnology has massive potential to support sustainability transitions and create economic value. At the same time, this potential requires focused and strategic efforts across sectors from both advanced biotechnology players and supporting industries around it.

BOX 3: KEY QUESTIONS ON SCALING BOTTLENECKS AND POTENTIAL SOLUTIONS

Why has biotechnology not already achieved its full potential?

- **Cost disadvantage.** In their early stages, solutions are less cost competitive than conventional alternatives because of their smaller scale and higher R&D costs.
- **Funding gap.** There is a significant gap in securing funds between early-stage and full-scale production, customer trials, and cost optimization, often spanning five to ten years.
- **Scale-up risks.** Challenges in technological feasibility, regulatory hurdles, and securing commercial offtake agreements deter large investments.
- **Societal ecosystem role.** There is a lack of unified industrial policies, gaps in education and talent development, and low customer awareness and acceptance of biotechnological solutions.

What would be required for advanced biotechnology to achieve its full potential?

- **Prioritize resource allocation to high-potential products.** Focus on products with high demand, cost competitiveness, and regulatory approval to build industry proof points.
- **Derisk scaling biotechnology production.** This can be done via the following:
 - › **Technology:** Test production processes in industrial conditions, standardize and modularize processes, and ensure continuous learning through data generation.
 - › **Commercial:** Bring together players across the value chain for projects with joint risk and value sharing, secure offtake agreements, and raise customer awareness through fact-based insights.
 - › **Financing:** Quantify financial opportunities, enable lower-risk financing through standardized assets and special purpose vehicles, attract diverse investors, and form consortiums for joint financing requests.
 - › **Supporting capabilities:** Promote knowledge sharing through intellectual property sharing, upskill the workforce, and collaborate with academia.
- **Ensure cost-effectiveness at scale.** Optimize plant operations, apply best practice capital investment methods, and invest in technological breakthroughs.

As we look ahead, several high-impact knowledge topics would benefit from close collaboration. These topics can further inform the industry's scaling approach and formulate strategies of unlocking the potential of advanced biotechnology.

1. A road map for industry scaling. Based on cost fundamentals, in which markets can biomolecules be adopted early, and how can cost learnings be captured to secure a right to play in subsequent markets?

- Which advanced biotechnology products have the potential to be adopted at scale (more than 10 percent of market supply) by 2030?
- What is the supply and demand curve? When, where, and how would advanced biotechnology solutions fit in this competitive landscape (for example, in terms of unit costs)?
- Which actions can which stakeholders take to accelerate time to market—for example, to get to a scale of 10 kilotons (kt) and finally to 100 kt or million metric tons (Mt) by 2030 and beyond?
- What are the prerequisites outside the ecosystem to allow the scale (for example, access to sustainable energy, sufficient supply of feedstock)?

2. Feedstock pathway for advanced biotechnology.

- Which alternative feedstocks can be delivered at scale for biotechnology applications (in the short, medium, and long term)?
- What is the economic and environmental viability of these different feedstock routes to ensure sustainable and cost-effective production?
- What are the technological advances needed to unlock the feedstocks, such as those for small molecules and $\text{CO}_2 + \text{H}_2\text{(O)}$ routes?
- What is needed to scale the supply of alternative feedstocks (for example, local resources and conditions, collaboration between suppliers and supply chains)?

3. Flagship bioproduction partnerships. What types of production collaborations can be set up to move from idea to action?

- What will make a flagship biotechnology production partnership attractive to key stakeholders in advanced biotechnology value chains (for example, offtakers, producers, technology providers, and investors)?
- How can such flagship collaboration take shape? What learnings can be distilled from similar initiatives? And how can we move to action (for example, getting to a final investment decision on a flagship facility)?

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4. Regional opportunities. How can different regions unlock advanced biotechnology at scale?

- Different regions and countries have made biotechnology a strategic priority. What does it take to be successful in developing the industry?
- What are the strengths of each specific region's biotechnology sector (for example, R&D advantage), and how can the region better monetize the opportunities (for example, in light of economic competitiveness)?
- What supportive ecosystem is required to channel investments and skills to identified areas in the specific region (including finance, regulatory oversight, talent, and consumer awareness)?
- In which industries and steps in the value chain is the specific region best placed to compete for both the domestic and global market? What is the associated potential in terms of GDP growth, sustainability, and employment?

5. Supportive policy. How can biotechnology frameworks be evolved to advance and create positive impact?

- What are the key geographic differences of policy and regulatory frameworks from a stakeholder perspective (including both industry and society) and their implications for enabling advanced biotechnology adoption?
- What are the policies and regulations shaping the advanced biotechnology markets, and which modifications can considerably accelerate biotechnology for sustainability?



Advanced biotechnology holds immense promise as a force for sustainable products and processes covering a wide range of sectors, as well as a creator of economic value. As we have outlined in this report, many hurdles will still need to be overcome. Some are external to the industry and hard to predict or influence, including consumer acceptance and awareness. But many are fully in the hands of the industry—in particular, prioritizing products with highest market demand, derisking the scale-up process, and reducing costs at scale. The challenges are significant, yet the rewards for successfully addressing them are paramount.

GLOSSARY



Advanced biotechnology leverages breakthroughs in natural and engineering sciences (such as tailored genetic engineering of cells or microorganisms) as well as advances in computing, automation, data analytics, and artificial intelligence to improve the efficiency of organisms or cells for specific applications. We identify four types of advanced biotechnologies: precision fermentation, biomass fermentation, organism-as-a-product, and tissue-as-a-product (see definitions below). Advanced biotechnology differs from classical biotechnology, a multidisciplinary field that uses microorganisms or parts of them for products and services. Classical biotechnology has existed for millennia and is essential in our lives through fermentation, food conservation, medicines, and more.

Advanced breeding refers to a set of techniques used to enhance the genetic traits of plants and animals by speeding up or altering the natural breeding process. These techniques include genetic modification, artificial insemination, IVF, marker-assisted breeding selection, and in-vitro cultivation, among others. These methods aim to improve desirable characteristics, such as yield, disease resistance, and environmental resilience.

APGs, or alkyl polyglycosides, are biodegradable, plant-derived surfactants used in personal care.

AtJ, or alcohol-to-jet, refers to a process that converts alcohols, such as ethanol or butanol, into jet fuel. This technology is part of the broader effort to produce sustainable aviation fuels from renewable sources.

Biocatalytic refers to the use of natural catalysts, such as enzymes or whole cells, to perform chemical transformations. Biocatalytic processes can be more environmentally friendly and efficient than traditional chemical methods, and they are widely used in the production of pharmaceuticals, bio-fuels such as ethanol, and fine chemicals and food ingredients, including amino acids and organic acids.

Biomass fermentation is a process in which microorganisms such as bacteria, fungi, or yeasts are used as a product themselves. The best-known examples include production of baker's yeast or lactic ferments that are then used to produce bread and yogurt.

Bioremediation is the process of using microorganisms, plants, or enzymes to remove or degrade contaminants from polluted environments, such as water, soil, or air. This method is often used to clean up oil spills, heavy metals, pesticides, and other pollutants.

Bio-solutions are derived from biological processes or organisms to which advanced biotechnology levers have been applied to address various challenges, often in agriculture, healthcare, environmental management, and industrial processes (such as biofertilizers, biopesticides, and microbial treatments).

CNG, or compressed natural gas, is a natural gas that is compressed to less than 1 percent of its volume at standard atmospheric pressure. It is used as a fuel for vehicles and in other applications for which it can be used as a cleaner alternative to gasoline and diesel because of its lower emissions.

Full-potential analysis is a methodology to help assess the full potential of a technology by assuming a realistic best-case scenario where all nonphysical roadblocks to technology adoption are removed and all other things are equal. This implies making various assumptions about technology (that expected technological improvements are realized, and that no other unforeseen technology development materializes that would radically change the relative attractiveness of technology), financing (that sufficient investment is directed toward this technology), supply-side scaling (that industrial-scale rollout happens), regulation (that regulations do not hinder or promote adoption of these technologies), consumer preferences (that consumers are willing to try and adopt these technologies), and overall economic dynamics (that competition for feedstock, energy, or other inputs does not become a significant roadblock).

GMMs, or genetically modified microorganisms, are a form of strain selection in which microorganisms are genetically modified to improve fermentation processes—for example, by increasing fermentation efficiency, enabling use of a different feedstock, or changing the output. Whether a microorganism from a specific strain selection process formally qualifies as GMM depends on local regulations.

GMOs, or genetically modified organisms, are organisms whose genetic material has been altered using transgenic genetic engineering techniques, meaning foreign strings of DNA have been inserted in the existing cell's DNA. Examples include genetically modified maize that is more drought-resistant than conventional crops, or genetically modified mosquitos whose offspring do not survive in nature and are used to prevent mosquito-mediated diseases, such as dengue or Zika.

GE, or gene editing, is a technique to create stable changes to the native genome, either through cisgenic engineering, with a transfer of material already existing within the genome, or precise editing, made possible through recently developed techniques such as CRISPR-Cas9. Because no foreign DNA is used in GE, regulators and consumers often view the technique more favorably than transgenic genetic engineering.

High-throughput screening is a method used in drug discovery, microbial strain development, and other fields to rapidly test and analyze large numbers of samples for biological activity and functionality. This process involves automated equipment and large data sets to identify active compounds, antibodies, or genes that modulate a particular biomolecular pathway.

LNG, or liquefied natural gas, is a natural gas that has been cooled to a liquid state at about -162°C (-260°F) for storage and transportation purposes. This process reduces its volume, making it easier and more economical to transport over long distances.

Microorganisms are living organisms, including bacteria, fungi, protozoa, and microalgae, that typically range in size from about 0.1 to 100 micrometers. They are found everywhere in nature and are important for processes such as breaking down nutrients, and they have various applications in biotechnology and advanced biotechnology.

Organism-as-a-product refers to advanced breeding of macroorganisms (livestock, crops) to perform novel functions; the living organism itself is the product.

Plastics are materials made from a wide range of polymers (such as polyethylene, PVC, and nylon) that can be molded into shape while soft and then set into a rigid or slightly elastic form. Categories of plastics include the following:

- **PE (polyethylene)**, a versatile and widely used thermoplastic polymer, is characterized by its light weight, durability, and chemical resistance. It is commonly used in a variety of applications, including packaging materials such as plastic bags and films, containers, bottles, and piping. PE is known for being easy to process and recyclable, making it a popular choice in both industrial and consumer products.
- **PHA (polyhydroxyalkanoates)** are a group of biodegradable polyesters that are synthesized by numerous microorganisms. They are used in applications ranging from packaging and textiles to medical devices and agricultural films because of their eco-friendly properties and versatility.
- **PHB** (polyhydroxybutyrate) is a type of biopolymer from the polyhydroxyalkanoates (PHA) family, produced naturally by a variety of microorganisms as a form of energy storage.
- **PLA** (polylactic acid) is a thermoplastic monomer derived from renewable organic sources such as corn starch or sugarcane. Using biomass resources makes PLA production different from most plastics, which are produced using fossil fuels through the distillation and polymerization of petroleum.

Platform molecules are a class of compounds that serve as intermediates in the production of various products. They are typically derived from biomass and can act as versatile building blocks for various applications, including in biofuels (ethanol or biodiesel) or chemicals (solvents, lubricants, and plastics).

Precision fermentation combines the process of traditional fermentation with the latest advances in biotechnology to efficiently produce a compound of interest. It uses engineered microbial hosts as “cell factories” to manufacture organic molecules, which are then purified. These include ingredients such as sweeteners, food additives or proteins, monomers for plastics, and fuels such as ethanol and butanol.

Renewable natural gas, also known as biogas or biomethane, is produced from organic materials such as agricultural waste, landfills, and wastewater treatment plants. It is processed to meet pipeline quality standards and can be used as a sustainable alternative to conventional natural gas.

Sustainability is defined as follows by the United Nations Brundtland Commission: “Sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future.”¹⁶⁵ This concept encompasses a balance among environmental stewardship, social equity, and economic viability, ensuring that human activities do not deplete natural resources or harm ecosystems while promoting fairness and opportunity for all.

Technology-push refers to cases in which new technologies drive the development of products or solutions. Technologies and products are introduced, and then efforts are made to find applications or markets. This contrasts with “market pull,” in which consumer demand and market needs drive product development. In this latter approach, companies identify gaps in the market or specific customer needs and then develop technologies or products to fulfill those needs.

Tissue-as-a-product refers to biological tissues grown in an artificial environment; the tissue (that is, a structured, multicellular product) itself is the product. An example is cultivated meat, which is meat produced directly from mammalian cells: the process of cultivating meat uses the basic elements needed to build muscle and fat and enables a biological process similar to what happens inside an animal.

¹⁶⁵ Report of the World Commission on Environment and Development: *Our common future*, World Commission on Environment and Development, August 1987.



TECHNICAL APPENDIX

This appendix provides details about the methodologies used in this report. It is divided into the following sections:

1. Methodology for sustainability potential sizing
2. Market sizing methodology
3. Investment sizing methodology
4. Cost reduction methodology

All of our estimates assume that there are no global regulatory bans on advanced biotechnologies, that R&D continues, and that consumers, at a minimum, do not shift their preferences away from advanced biotechnologies. The sizing of the potential of advanced biotechnology has been conducted with a technology-forward view, and as such is particularly sensitive to assumptions about adoption rates, which capture the extent of which current roadblocks (such as feedstock availability, funding, and public perception) can be removed. Last, these estimations were conducted “all other things equal” and do not include the impact from, for example, future competition for feedstock (and associated price changes) or changes in energy sources (and associated prices and emission factors).

1. METHODOLOGY FOR SUSTAINABILITY POTENTIAL SIZING

We size the potential of advanced biotechnology on three sustainability metrics (greenhouse gas [GHG] emissions, land use, and water use) for four sectors within the report's scope: animal farming, plant farming, chemicals, and transportation fuels. We follow a three-step approach: (a) within each sector, we select a subsector (use case) that is representative for the sector and has a large environmental footprint; (b) we size the advanced biotechnology potential for each subsector on the three sustainability metrics; and (c) we extrapolate to the rest of the sector. This section describes the methodology for each of these steps, using the practical example of beef cows.

For GHG emissions, we sometimes express the baseline emissions or abatement potential as a share of global 2022 emissions to give a sense of their magnitude. Data on global GHG emissions are taken from the EDGAR database.¹

(a) Subsector (use case) selection

Within each sector, we identified a long list of subsectors (use cases) and selected those that were representative of the sector in terms of proven potential for advanced biotechnology solutions, based on expert input, and in terms of environmental footprint, based on publicly available data.

- **Animal farming.** We computed the sustainability potential of advanced biotechnology in animal farming leveraging two use cases: beef cows and dairy cows. Together, these use cases represent about 60 percent of the sector's GHG emissions, approximately 70 percent of land use, and around 25 percent of water use.
- **Plant farming.** We computed the sustainability potential of advanced biotechnology in plant farming based on rice production. Rice production accounts for about 30 percent of the sector's GHG emissions, about 7 percent of land use, and approximately 15 percent of water use.

- **Chemicals.** We compute the sustainability potential of advanced biotechnology in chemicals using bioplastics as a use case. Bioplastics account for about 35 percent of the sector's GHG emissions, about 13 percent of land use, and about 6 percent of water use.
- **Transportation fuel.** We compute the sustainability potential of advanced biotechnology in transport fuels using alcohol-to-jet (one type of sustainable aviation fuel [SAF]) as a use case. Aviation fuel currently accounts for about 13 percent of transport fuel's GHG emissions, about 8 percent of land use, and about 7 percent of water use.

(b) Sizing advanced biotechnology potential on sustainability metrics in the identified subsectors

We size the potential of advanced biotechnology in the identified subsectors in four steps:

- **Estimate the baseline.** We first estimate the baseline for each subsector in terms of GHG emissions, land use, and water use. This is typically done by multiplying the relevant production quantity (for example, metric tons of protein from beef cows) by an emission or usage factor (such as kilograms of CO₂ equivalent (CO₂e) per kilogram of proteins for GHG emissions, square meters per kilogram of protein for land usage, and liter per kilogram of protein for water usage). We use the latest year for which we can find data—2022 or 2023 for most cases. We use a mix of publicly available data (for example, Our World in Data, Statista, and scientific publications), complemented and triangulated with expert input where relevant (for instance, emission or use factor). As these emission or usage factors are industry averages, this methodology implies that we compare the potential of advanced biotechnology with the “average” process currently used, not with one specific technology.

¹ “GHG emissions of all world countries,” European Commission, accessed September 12, 2024.

- **Estimate the relative importance of the ‘conventional production pathway’ and the ‘advanced biotechnology alternative pathway.’** In each use case, we estimate the improvement potential of advanced biotechnology from two different angles. In the “conventional production pathway,” we estimate the extent to which advanced biotechnology can improve the environmental footprint of current products (for example, through nitrogen-fixating biologics, feed additives that reduce enteric methane, and large-scale anaerobic digestives). In the “advanced biotechnology alternative pathway,” we estimate the extent to which advanced biotechnology can lead to new products with a different environmental footprint (for example, cultivated beef). In some use cases, advanced biotechnology has no impact on one specific pathway: we estimate that GHG emissions from conventional rice could be reduced by 40 percent, but we did not identify any advanced biotechnology levers that could lead to such a reduction. Consequently, we did not take this estimate into account in the overall calculation. To estimate the relative importance of each pathway, we estimate “full potential” (volume) market share of each pathway in 2040 using a mix of publicly available data, where available, and proprietary models (such as McKinsey’s ACRE alternative-protein model). From this, we derive the total volume from each pathway by multiplying market share by the baseline volume.
- **Derive the net benefit from advanced biotechnology.** We derive the net benefit from advanced biotechnology by subtracting the environmental footprint of the two pathways from the baseline scenario. Therefore, our estimates quantify the net benefit from advanced biotechnology.
- **For each pathway, estimate the sustainability potential of advanced biotechnology.** We do so by multiplying the volume from each pathway with the improved emission or usage factor leveraging advanced biotechnology. These improved emission or usage factors are based on expert assessment (for example, academic publications where available, the Good Food Institute for alternative proteins, and McKinsey’s Value Chain Twin models). In all cases, we assume a lower and higher bound on the improvement potential to arrive at an estimated range. From this, we can derive the environmental footprint for both pathways.

(c) Extrapolating to the rest of the sector

We extrapolate advanced biotechnology sustainability potential to the rest of the sector by multiplying the size of the remaining sector by a typical improvement factor (in percent) for each sustainability metric.

The size of the remaining sector is the difference between the sector’s GHG emissions, land or water use, and the subsector baseline metric. Sector-level sustainability metrics are primarily taken from academic publications, publicly available data (such as Our World in Data), and public institutions (for example, FAO).

Improvement factors are based on expert inputs and consider the advanced biotechnology applicability to the rest of the sector through (i) technological feasibility of the solutions to products in other segments; (ii) differences in adoption rates due to non-advanced biotechnology alternatives, regulations, or consumer preferences and awareness; (iii) differences in baseline emissions that can affect relative improvement potential.

We have deliberately taken a conservative approach in the improvement potential. As a result, estimated percentage improvements in the rest of the sector are systematically lower than what has been estimated for more detailed subsector analysis. For instance, while we estimate that advanced biotechnology has a potential to reduce GHG emissions by about 35 percent in beef and dairy cows, we estimate that it can lead to only a 1 to 8 percent (net) reduction in GHG emissions in the rest of the animal farming sector, assuming lower advanced biotechnology impact because of a lack of methane emissions for nonruminants.

For GHG emissions in particular, we estimate an improvement factor for each subsector, which we weight by the subsector's overall emissions. For instance, for animal farming, the subsegments (excluding beef and dairy cows) are poultry, pig, sheep, and other animals.

In all cases, we assume a lower and higher bound on the improvement factor to arrive at an estimated range.

2. MARKET SIZING METHODOLOGY

We assessed the potential market size of advanced biotechnology in five sectors: agriculture (including improvements to yield and productivity of crops and animals), food (including alternative proteins such as fermented proteins and cultivated meat), chemical intermediates for industrial applications (such as biopolymers and bulk and specialty chemicals), personal care (such as bio-based skin and facial care, fragrances, hair care, and oral care), and transportation fuels (including liquid and gas biofuels such as fermented alcohols or aromatic compounds that can be further processed or directly blended with fuels, and biogas or biomethane). We adopted different methodologies for these sectors, as detailed below.

The full potential of the report assumes that modern gene editing techniques will be prevalent by 2040 and beyond. While it excludes transgenic modification of multicellular organisms, such as crops, the full potential includes modern genetic engineering techniques such as (nontransgenic) gene editing of crops and considers genetic modification (including transgenic modification) of microorganisms, such as bacteria, yeast, or fungi used for manufacturing of biotechnology products in a confined environment.

Overall, these estimated market sizes are built upon a similar methodology as those published by the McKinsey Global Institute in a recent report that included biotechnology as a transformational area of business that could reshape the global economy.²

(a) Agriculture and personal care

For these sectors, we leveraged McKinsey's *Bio Revolution* report and its library of about 400 identified use cases.³ We adapted the estimates to the advanced biotechnology market as follows:

- **We restricted ourselves to the impact of biomolecules and biosystems.** We also discarded the impact of biomachines and biocomputing interfaces. Biomolecules and biosystems together cover our definition of advanced biotechnology.
- **We translated the direct economic potential into a market size.** McKinsey's *Bio Revolution* report estimates direct economic impact, which covers not only cost productivity potential but also improvement in product quality, health, and environmental improvements. To translate into market size, we assumed that advanced biotechnology players in these industries could capture about 15 percent of the economic value they create, based on the industry's competitive dynamics.
- **We adjusted the market size to the 2040 economy.** McKinsey's *Bio Revolution* report estimates direct economic impact for the future relative to the 2020 economy. We scaled the impact potential of advanced biotechnology for these sectors to 2040, adjusting for the expected market growth for these sectors based on data from the International Monetary Fund.

(b) Alternative proteins

We estimated the advanced biotechnology potential in the food sector by estimating the projected market size of cultivated and precision-fermentation-based food, based on McKinsey's proprietary ACRE alternative-protein model. The model accounts for a wide variety of parameters, including current costs and production volumes, technological learning rate and R&D investments, consumer response to price changes, dietary transition, and climate transition drivers (such as GHG pricing). We further ran scenario analysis to arrive at an estimated market size range.

² "The next big arenas of competition," McKinsey Global Institute, October 23, 2024.

³ *The Bio Revolution: Innovations transforming economies, societies, and our lives*, McKinsey, May 13, 2020.

(c) Chemical intermediates

We estimate the advanced biotechnology potential in chemical intermediates leveraging primarily McKinsey's proprietary Chemistry and Agriculture Model. The model delivers addressable market size for products that have biotechnology as a production route. We further reduce the scope to only products that have advanced biotechnology as a production route. For each end sector, we assume that advanced biotechnology can capture a share of the addressable market, based on expert interviews. We further run scenario analysis to arrive at an estimated market size range.

(d) Transportation fuels

We estimate the advanced biotechnology potential in chemical intermediates leveraging McKinsey's proprietary Energy Solutions Model. Advanced biotechnology potential is estimated by identifying the addressable market for anaerobic digestion to biogas or methane, SAF made from ethanol, and first- and second-generation ethanol outside of SAF, because these are the main advanced biotechnology use cases in this sector.

3. INVESTMENT SIZING METHODOLOGY

To arrive at the likely size of investment required by 2040 (\$500 billion for fermentation only), we separately sized capital expenditure and R&D investments.

- **Capital expenditure investments.** Our estimate is based on potential demand in 2040 for bioproducts in kilotons per annum (kt/pa), based on our market sizing exercise, capacity per plant (kt/pa), and capital expenditure costs per plant, in dollars, based on expert input. We also factored in learning rates—that is, expected efficiency improvement in capital expenditure investment as

technologies mature and scale, based on analogous mature technologies.

- **R&D investments.** These are assumed to be a constant fraction of industry revenue (about 5 percent), consistent with what we observe today in publicly available data, even as the market grows.

4. COST REDUCTION METHODOLOGY

To estimate the cost reduction potential of advanced biotechnology, we looked at current production costs and the impact of a range of cost reduction levers.

For the current cost of production, we used a base case scenario for a precision-fermentation plant operating at a production rate of 3.5 kt per megaliter per year. We modeled the cleansheet cost of the entire process based on average technical specifications across capital expenditures, labor, energy, feedstock, and other materials.

We focused on five cost reduction categories. Each of these categories consists of several drivers to reduce overall unit production costs, for a total of about 20 drivers. The levers are the following:

1. operational excellence and efficiency
2. process design
3. strain optimization
4. location
5. capital down and scaling

For each driver, a range of estimated improvement factors have been identified by industry experts and then applied to the current production cost to arrive at a cost reduction potential.



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