Unlocking the potential of *engineering biology:* The time is now

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What is engineering biology?

Engineering biology (also known as synthetic biology) involves the application of principles from biology and engineering, in conjunction with AI and data-driven computational techniques, to create new or redesigned biological systems for valuable purposes. Products, materials, or processes driven by engineering biology are referred to as biosolutions in this report.* In many cases, biosolutions offer significant sustainability advantages over legacy approaches.

Engineering biology has a wide range of applications, including but not limited to the following areas:

- Engineering microbes for industrial production
- Engineering crops for agricultural transformation
- Engineering human cells for therapeutic purposes.

Select examples of engineering biology

Engineering microbes for industrial production

Engineering biology makes it possible to modify microbes such as bacteria and yeast by altering their genetic material, enabling them to produce valuable compounds. These engineered microbes convert feedstocks (typically sugars and starches) into the desired compounds. For example, engineered microbes can transform feedstocks such as corn and sugarcane into drugs, fuels, chemicals, fibers and a wide range of other products. The process, known as precision fermentation, involves precise genetic modifications that allow microbes to perform these specialized production tasks efficiently.

Engineering crops for agricultural transformation

Engineering biology can be applied to plant cells to improve crop traits. For example, crops can be genetically engineered to enhance their nutritional content, develop resistance to disease and pests (reducing the need for chemical crop protection products), and better withstand climatic stresses such as drought, heat, and salinity. Crops can also be engineered to perform nitrogen fixation, reducing reliance on chemical fertilizers, with corresponding sustainability benefits.

Engineering human cells for therapeutic purposes

In the field of medicine, engineering biology is used to alter human cells to create new and advanced treatments for various medical conditions, of which some have been previously untreatable. For example, engineering biology can be applied to modify genes or genetic pathways in an individual's cells to treat genetic disorders. It can also be applied to create artificial tissues and organs by genetically engineering human cells to perform specific functions (such as organizing into specific structures). This has the potential to address organ shortages for transplantation.

**For a more complete definition of engineering biology and an indicative list of biosolutions by industry, please see the Appendix.*

Who should read this report and why?

This report offers an in-depth view of the transformative potential of engineering biology for multiple industries and suggests strategies to unlock this potential. It will help business executives identify valuable applications of engineering biology and accelerate their adoption of biosolutions.

The report is targeted at a broad range of executives, including chief executive officers, chief innovation officers/directors, chief sustainability officers/directors, chief strategy officers/directors, chief science/technology officers, chief digital officers, R&D directors and product managers.

The report also offers insights for leaders of engineering biology startups on accelerating research and scaling up operations, and for government agencies/policymakers/regulators on the perceived role of regulations in supporting the adoption of biosolutions.

Executive summary

Engineering biology (or synthetic biology) is a discipline whose time has come. Advances in DNA synthesis, editing, and sequencing, coupled with breakthroughs in AI, have radically improved the speed and accuracy with which biological systems can be engineered while significantly lowering the time and cost to realize them. A wide range of industries stand to benefit from engineering biology. Use cases of engineering biology exist across industries, extending beyond the healthcare, agriculture, energy, and consumer goods industries to more diverse fields such as fashion, mining, automotive, and aerospace and defense.

To develop this report, we surveyed 1,100 executives from large corporate organizations (also referred to as "organizations" or "corporates" in the report) to gain insights into corporate perspectives and plans related to engineering biology. In addition, we surveyed 500 executives from engineering biology startups to understand their views on the barriers that need to be addressed to accelerate the commercialization of biosolutions.

Our research reveals that organizations view engineering biology as transformative; almost every corporate executive we surveyed agreed that biosolutions will significantly disrupt their industry. Around half of respondents expect to see this within 5 years, and the rest in 5–10 years or more.

The top benefits organizations expect to derive from biosolutions include environmental benefits such as reduced pollution, waste, and emissions; improved product performance and safety; and reduced resource-dependence and exposure to supply chain disruptions.

Organizations are preparing to harness these benefits and navigate the approaching disruption. Most (96%) are already pursuing biosolutions: 40% are at an exploratory stage, with 56% engaging more actively in experimentation, pilots, or scaled deployments. Only 4% say that biosolutions are not a part of their current strategic planning or activities. Corporate investment in biosolutions is expected to steadily increase.

Executive summary

Sustainability is a major driver of corporate interest in biosolutions. Most (72%) corporate executives believe that biosolutions can significantly accelerate progress toward sustainability goals. Surveyed executives identified sustainable materials and packaging and waste management as the environmental applications of engineering biology with the greatest potential impact.

72%

of corporate executives believe that biosolutions can significantly accelerate progress toward sustainability goals.

However, biosolutions may not always be more sustainable than traditional alternatives unless harnessed appropriately. Most corporate executives expect biosolutions to have a positive impact on climate change, and plastic and air pollution. However, they are less certain of a positive impact on deforestation, soil health, and water scarcity. The responsible use of natural resources is a crucial consideration in the development of biosolutions to avoid any negative impacts. Environmental and social impacts of biosolutions need to be assessed across the product lifecycle and supported by strong performance and cost efficiency to drive market adoption.

There are barriers to the accelerated adoption of biosolutions. These include the high cost and long development lead times for biosolutions and challenges with scaling production (due to difficulties in predicting cellular behaviors when production volumes are increased from lab to industrial scale, and the lack of suitable large-scale production infrastructure). Surveyed executives also cite the shortage of talent as a barrier as the domain requires skills in diverse areas, including biological sciences, technology, engineering, and operations.

Executive summary

Regulatory issues, such as the complexity of regulations governing biosolutions, also pose challenges, while a lack of bio-literacy and ethical concerns related to the use of engineering biology hinder market acceptance unless addressed.

Digital and engineering technologies such as AI, digital twins, robotics and advanced sensing are key drivers for reducing costs, optimizing bioprocesses, shortening time-to-market for biosolutions, and helping mitigate environmental and societal risks. AI is seen as the most promising of these – 84% of corporate executives say that AI will play an important role in accelerating the adoption of biosolutions. Further, 70% say that generative AI will significantly increase the efficiency of R&D processes, cutting lead time for the development of biosolutions. Technologies such as robotics and digital twins will also play a pivotal role by enabling more effective scale-up processes and the automation of complex lab workflows, reducing the time and resources needed for experimental validation.

84%

of corporate executives say that AI will play an important role in accelerating the adoption of biosolutions.

To advance the adoption of biosolutions at speed, we recommend:

- **For corporates and engineering biology startups:**
  - Formulate an informed strategy and roadmap to prepare for upcoming disruption. This should include the growth of internal and external expertise and planning for operational changes (e.g., changes in manufacturing, procurement, supply chain, quality, and regulatory processes)

Executive summary

- Support demand generation through industry collaborations that facilitate long-term offtake agreements (long-term commitments to future purchases of biosolutions) to provide financial stability
- Work closely with customers and end-users to understand performance expectations for a biosolutions alternative
- Harness digital and engineering technologies to deliver performance and cost-efficiency that surpass traditional approaches
- Focus on ease of integration and/or minimal disruption to legacy processes, to facilitate adoption
- Conduct robust impact assessments and focus on sustainability and circularity during the design phase
- Build a strong partner ecosystem to access the capabilities required to develop and scale biosolutions
- Raise public awareness on the benefits of biosolutions, address any misconceptions, and ensure transparency in reporting to build public trust.

- **For regulators and government agencies:**
  - Establish a level playing field for biosolutions through policy measures that discourage fossil fuel use and enhance the economic appeal of biosolutions
  - Create clear and progressive regulatory frameworks to drive responsible use of engineering biology and reduce legal uncertainty in the testing and deployment of engineering biology techniques
  - Provide funding to advance engineering biology research and expand biomanufacturing capacity
  - Promote informed public discourse on engineering biology through public education campaigns that dispel misconceptions, and inclusive policy-making processes that involve a diverse group of stakeholders.

Introduction

Sickle cell disease, an inherited blood disorder, affects more than 20 million people worldwide, causing debilitating effects on the lives of those affected. In December 2023, the U.S. Food and Drug Administration (FDA) approved a gene editing treatment that directly alters patients' DNA. The innovative therapy promises to revolutionize the treatment of sickle cell disease. *"It is practically a miracle that this is even possible,"* said Dr. Stephan Grupp, chief of the cellular therapy and transplant section at Children's Hospital of Philadelphia.[1]

This landmark event highlights the transformative power of engineering biology. Engineering biology addresses some of the most pressing challenges facing humanity, from healthcare and climate change to food security and resource scarcity. By transforming biological systems into programmable entities, engineering biology brings limitless opportunities to reimagine products and processes, addressing problems that could not have been addressed with conventional means. Applications of engineering biology touch virtually every industry. These include new drugs, therapies, and vaccines that tackle rare and previously incurable diseases; climate-resilient crops and sustainable agricultural practices that strengthen global food security while protecting soil health; and new materials to reduce reliance on fossil fuels.

A range of converging factors have brought engineering biology to a pivotal moment. These include technological breakthroughs in DNA synthesis, editing, and sequencing – tools and methods foundational to engineering biology – that have dramatically increased the speed and precision with which biological systems can be engineered while significantly lowering costs. Crucially, breakthroughs in AI have led to dramatic improvements in the understanding and prediction of protein structures. These advances coincide with an increasingly urgent need to address environmental challenges. Frank Chen, Operating Partner at US venture capital firm Andreessen Horowitz: *"I see two frontier technologies. One is synthetic biology. And the other is quantum computing. It is a take on the same idea: if we can harness what nature is doing, we could benefit from it."*[2]

Introduction

There are, however, obstacles to the bioengineering revolution that have made advancement slower than originally planned. This research seeks to outline the opportunities offered by engineering biology and explore how organizations can unlock them. It draws on a survey of large corporates as well as startups. For the survey of large corporates, we gathered responses from 1,100 senior executives from organizations with more than $1 billion in annual revenue. Surveyed executives belonged to organizations headquartered in countries across North America, Europe, Asia-Pacific (APAC), and the Middle East, and operate in 11 industries. For the survey of startups, we gathered responses from senior executives from 500 startups focusing on engineering biology and enabling areas. We complemented the survey with interviews with senior industry executives, engineering biology startups, VCs, and academics. For more details on the survey sample, please refer to the research methodology.

This report covers the following themes:

01 Engineering biology has applications in virtually every industry

02 Organizations view engineering biology as transformative

03 Biosolutions offer significant sustainability benefits, but only if correctly harnessed

04 Barriers to the accelerated adoption of biosolutions

05 Digital and engineering technologies will be instrumental in developing and deploying engineering biology

06 Recommendations

01 Engineering biology has applications in virtually every industry

The art of the possible: Multisectoral applications of engineering biology

While the applications of engineering biology are more commonly associated with the healthcare, food, and agriculture sectors, the potential of engineering biology extends far beyond these industries. As Figure 1 illustrates, applications exist in virtually every industry.

Personal and household care products

Applications	Examples
Sustainable cosmetic ingredients	Squalene, a skincare ingredient, is traditionally derived from shark liver. US-based engineering biology firm **Amyris** produces squalane – a more stable version of squalene – via fermentation of sugarcane using engineered yeast, saving more than 2 million sharks annually.[3] Hyaluronic acid, another skincare ingredient, is traditionally derived from rooster combs, but is now produced through precision fermentation by companies such as **Givaudan**, a Swiss manufacturer of flavors and fragrances.[4]
Palm oil substitutes for personal and household care products	Engineering biology techniques are being applied to develop alternatives to palm oil. US startup **C16 Biosciences** is developing a sustainable alternative using a yeast strain that naturally produces oil. The yeast is engineered to improve the quantity and quality of oil and is grown by fermentation.[5]
Environmentally friendly surfactants	In 2021, **Unilever** partnered with **LanzaTech,** a biotech startup, to pilot the world's first dishwashing liquid and laundry capsule made via gas fermentation. LanzaTech uses engineered microbes to capture and convert industrial carbon emissions to ethanol for surfactant production rather than using fossil-fuel-based feedstocks.[6]
Novel and sustainable fragrances	**Arcaea**, an engineering biology startup, launched a range of fragrances made by sequencing DNA from extinct flowers and using engineered yeast to produce them. Arcaea is backed by Chanel and Givaudan.[7] Givaudan is also collaborating with **LanzaTech**, using their gas fermentation technology to produce fragrance ingredients from recycled carbon emissions.[8]

Fashion

Applications	Examples
Bio-fabricated textiles	**Geno** (US) has developed a plant-based nylon intermediate using engineered microorganisms to replace traditional petroleum-derived nylon. Fermentation converts carbon in plant sugars into a precursor to nylon, which is used to create renewable, plant-based nylon fibers. Geno has partnered with sportswear brand lululemon to launch a range of products using bio-based nylon. Preliminary lifecycle assessments indicate a 50% reduction in carbon emissions compared to conventional fossil-based nylon.[9]
Leather substitutes	Biomaterials startups such as **MycoWorks, Modern Synthesis** and **Modern Meadow** are developing leather substitutes using engineering biology. MycoWorks engineers mycelium (mushroom root) cells to create densely intertwined, three-dimensional structures that serve as a leather alternative, matching the performance of animal leather with a lower environmental footprint.[10]
High-performance materials	**AMSilk**, a German biotech firm, has partnered with **21st.BIO**, a Danish bioproduction startup, to produce spider silk proteins at scale using precision fermented microbes. Spider silk offers exceptional strength, elasticity, and lightness, making it ideal for high-performance textile applications such as sportswear, outdoor wear, and protective clothing.[11]
Sustainable dyes	**Octarine Bio**, a Danish engineering biology startup, designs custom microbes to produce microbially fermented textile dyes. Octarine Bio's colors bind directly to textiles without the use of toxic chemical additives and with significantly less water and energy use than conventional processes.[12] **Colorifix**, another biotech startup, engineers microorganisms to produce color pigments found in nature (produced by animals, plants, insects, or microbes) with 80% less chemicals, 77% less water and 31% fewer carbon dioxide emissions than conventional dyeing processes.[13]

Energy

Applications	Examples
Biofuels	The US's **National Renewable Energy Laboratory (NREL), LanzaTech, Northwestern University**, and **Yale University** are collaborating on a project funded by the US Department of Energy to make more sustainable biofuels via engineering biology. They aim to engineer carbon-consuming bacteria using genome engineering and machine learning tools to convert carbon emissions into biofuels at industrial scale.[14]

Mining

Applications	Examples
Biomining	Australian mining company BHP is partnering with **Allonnia** – a US-based biotech startup – to test Allonnia's microbial technology to purify iron ore. Allonnia identified microbes in BHP's iron ore that can consume phosphorus and release alumina, both of which are key impurities in iron ore. Applied at scale, this could produce cleaner iron ore suitable for hydrogen-powered steel mills, potentially paving the way for carbon-free steelmaking.[15]

Aerospace and defense

Applications	Examples
Sustainable aviation fuel	**LanzaJet** – a spinoff from LanzaTech – has signed offtake agreements with Japanese trading and investment company Mitsui, Canadian oil and gas producer Suncor, and Japanese airline All Nippon Airways to produce sustainable aviation fuel (SAF) using LanzaTech's gas fermentation technology. This uses microbial fermentation to convert carbon emissions captured from power plants and other industrial sites to ethanol.[16]
Space exploration	**NASA**'s Space Synthetic Biology (SynBio) project is developing technologies that allow space station crews to use microbes to biomanufacture essential products such as food and medicines during long space missions. As part of this project, NASA is conducting an experiment called BioNutrients that allows astronauts aboard the International Space Station to use genetically engineered yeast to produce beta carotene and zeaxanthin, that are essential to support their nutritional needs on multi-year missions.[17]

Water utilities

Applications	Examples
▪ **Bioremediation/ water treatment**	**Allonnia** (US) has developed a water treatment solution using engineered bacteria that can degrade 99% of 1,4-Dioxane – a toxic chemical that contaminates groundwater – rendering it harmless.[18] **Puraffinity**, a UK-based startup, addresses the problem of PFAS (per- and polyfluoroalkyl substances) contamination in water systems. PFAS or "forever chemicals" are a group of 15,000 synthetic chemicals that do not degrade easily, persist in the environment, and cause adverse health effects.[19] Puraffinity is developing an adsorbent material with a surface tailored with molecular groups that trap PFAS compounds and remove them from water.[20]

Automotive

Applications	Examples
▪ **Bio-based paints and coatings**	**Lygos**, a US-based biotech startup, engineers microbes to produce malonic acid, a variant of which (malonate) has applications in the automotive industry. The traditional process of hardening or setting paints and coatings involves temperatures of up to 450 degrees Fahrenheit, while malonate enables low-temperature painting. Lygos's process enables the sustainable production of malonic acid, which otherwise requires toxic chemicals that pose environmental and health risks.[21]
▪ **Bio-based materials for interiors**	**Spiber** (Japan) has partnered with Toyota. The car manufacturer is using Spiber's bioengineered fibers, produced via microbial fermentation, for the interiors of a concept model of the Land Cruiser Prado.[22]
▪ **EV battery recycling**	Researchers at the **University of Edinburgh** are exploring the use of engineered bacteria to extract valuable metals such as cobalt, manganese, nickel, and lithium from used lithium-ion EV batteries.[23]

Chemicals and materials

Applications	Examples
Sustainable chemicals	**BASF** is using engineered microorganisms to produce sustainable alternatives for a range of chemicals and products including biopolymers, food ingredients, crop protection products, flavors and fragrances, and enzymes for detergents and cosmetics.[24] **Solugen**, a US-based startup, is using engineering biology to develop enzymes that convert corn sugar into chemical intermediates. Solugen's process offers greater efficiency and a lower carbon footprint compared to traditional petrochemical-based chemical production processes.[25]
Bioplastics	Bioengineers at **Kobe University**, Japan, partnered with polymer manufacturer **Kaneka Corporation** to use engineered bacteria to produce LAHB – a bioplastic. Combined with PLA (a brittle and non-biodegradable plastic derived from plant biomass) this produces plastics that are biodegradable and more fracture resistant.[26]
Biosynthetic rubber	**Laastix**, a startup based in Europe, is using engineered microorganisms to produce rubber as an alternative to both traditionally cultivated rubber, which causes significant deforestation, and synthetic rubber, which uses fossil fuels. Laastix engineers E. coli bacteria following biochemical pathways found in the Hevea rubber tree to produce the proteins required to make rubber.[27]

Healthcare

Applications	Examples
Drug development	**Merck** has applied engineering biology to develop enzymes to produce sitagliptin, a diabetes drug marketed as Januvia, more efficiently and sustainably. This approach has increased yield, eliminated the use of toxic metals, and reduced waste to around one-hundredth of original levels. Merck has also applied this approach to develop islatravir, an antiretroviral drug for the treatment of HIV.[28] **Antheia** (US) biosynthetically manufactures prescription drug ingredients to combat drug shortages, offering a faster and more reliable alternative to using agricultural inputs. For example, Thebaine, an essential pharmaceutical ingredient typically produced from poppy plants over two years, can be produced in just two weeks using engineered yeast.[29] Engineering biology is also being applied to develop new drugs such as GLP-1 agonists – a class of anti-diabetes drugs that mimic a natural hormone that helps regulate blood sugar levels. Pharma companies such as **Novo Nordisk** and **Eli Lilly** are developing these drugs.[30]
Vaccine development	The use of engineering biology to produce synthetic RNA molecules for RNA-based vaccines gained prominence during the pandemic. It is also being applied to develop personalized cancer vaccines. **Merck** and **Moderna's** experimental RNA cancer vaccine has shown promising results in clinical trials, reducing the risk of death or recurrence of skin cancer by nearly half.[31]
Diagnostics	**Sherlock Biosciences** (US) develops molecular diagnostic products to make diagnostic tests faster, more accurate, and affordable. It uses the CRISPR gene editing tool to detect specific genetic sequences in a given sample without the use of complex lab instruments. Potential applications of the company's diagnostic products cover infectious diseases, early detection of cancer, and personalized medicine, among others.[32]
Cell and gene therapy	**Elevate Bio** (US) uses a CRISPR-based gene editing platform to address genetic disorders. It is collaborating with pharma firm **Novo Nordisk** to develop therapies for rare and cardiometabolic diseases. It has also demonstrated promising results in addressing Huntington's disease.[33]

Food

Applications	Examples
Animal-free dairy	**Perfect Day** (US) precision ferments animal-free dairy proteins. Precision-fermented whey has up to 97% lower greenhouse-gas emissions, 60% lower energy demand, and uses 99% less water than traditional dairy.[34]
Animal-free eggs	**The EVERY Company** (US) inserts chicken-egg protein DNA into yeast, which it converts to protein via fermentation. Preliminary analysis indicates that this process uses significantly less water, land, and energy, and produces fewer emissions, than animal-derived egg protein.[35]
Cultivated meat	**Mosa Meat** (Netherlands) grows cow-cell samples into beef and claims that one sample can produce 80,000 burgers. Cultivating beef can lower climate impact by 92%, air pollution by 94%, land use by 95%, and water consumption by 78%, and no animal is harmed.[36]
Cultivated seafood/ cellular aquaculture	**BlueNalu** (US) uses fish-cell cultures to produce an alternative to natural seafood. BlueNalu's products avoid issues with contaminated seafood, overfishing, and supply issues.[37]
Optimizing food production	Engineering biology is used to produce enzymes, such as those from **Novonesis** (formerly Novozymes), that can increase the efficiency of food production processes (such as beer brewing) and reduce operating costs while ensuring quality.[38]
Bio-based food additives	**DSM** and **Cargill** are partnering to produce stevia (a sweetener traditionally derived from the stevia plant) using engineered yeast and fermentation. This method offers a more sustainable and scalable approach to producing stevia, with a 49% lower carbon footprint according to LCA studies.[39]

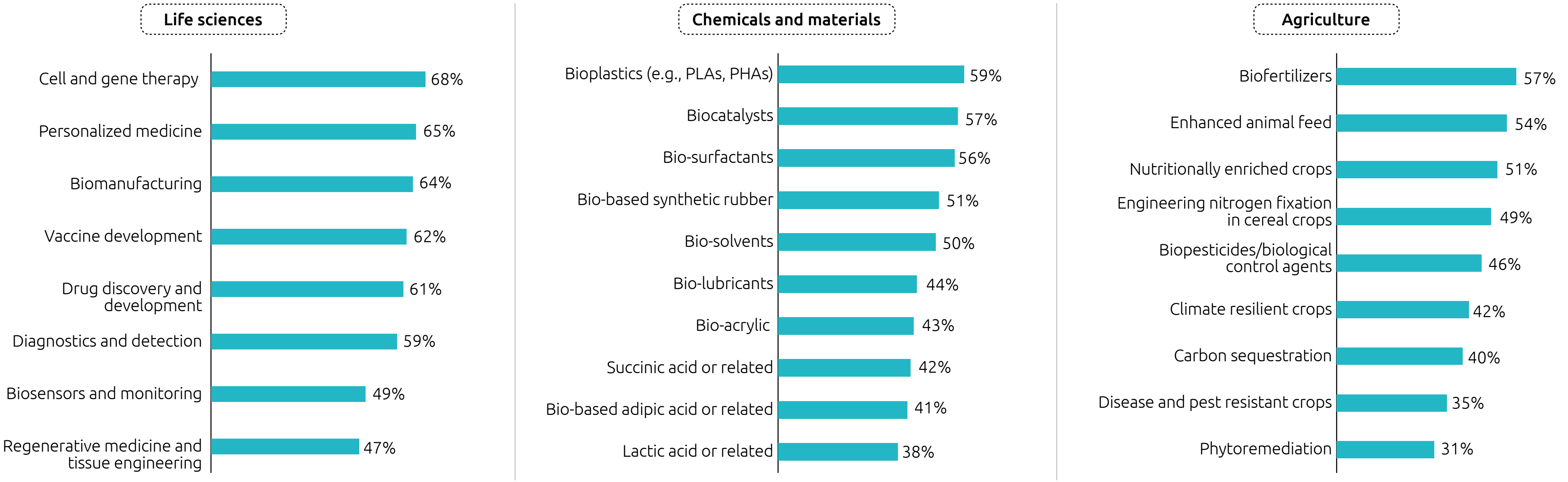
Agriculture

Applications	Examples
Biofertilizers	**Bayer** has partnered with **Ginkgo Bioworks**, a bioengineering firm, to engineer nitrogen-fixing bacteria, aiming to provide a sustainable alternative to synthetic fertilizers.[40] Similarly, **Pivot Bio** (US) engineers microbes that can deliver nitrogen directly to plant roots. Its products can meet up to 25% of crops' nitrogen requirement with 2% of the emissions of synthetic fertilizer and using 1,000 times less water.[41]
Crop protection products	An estimated 20-40% of crops worldwide are lost to disease each year.[42] **GreenLight Biosciences** (US) develops RNA-based biopesticides that target pests without harming other insects. The product degrades rapidly, leaving behind no harmful residues, unlike conventional pesticides. To combat the Colorado potato beetle, it has secured US EPA approval.[43]
Climate resilient crops	Swedish agritech **OlsAro** designs salt-tolerant wheat that delivers significantly higher yields than traditional crops on otherwise unfarmable land. The organization is also working on heat-tolerant and nitrogen-efficient crops. OlsAro has a contract in Bangladesh and is looking to expand to Nepal, Pakistan, Oman, Kenya, Australia, and India.[44]
Animal health and nutrition	**Novonesis** produces engineered enzymes and microbe-based solutions that improve animal health and feed efficiency.[45]

Figure 1.

Applications of engineering biology exist in virtually every industry

Share of executives that rate each use case as having a high impact on their industry (based on the value the use case can generate for the industry)



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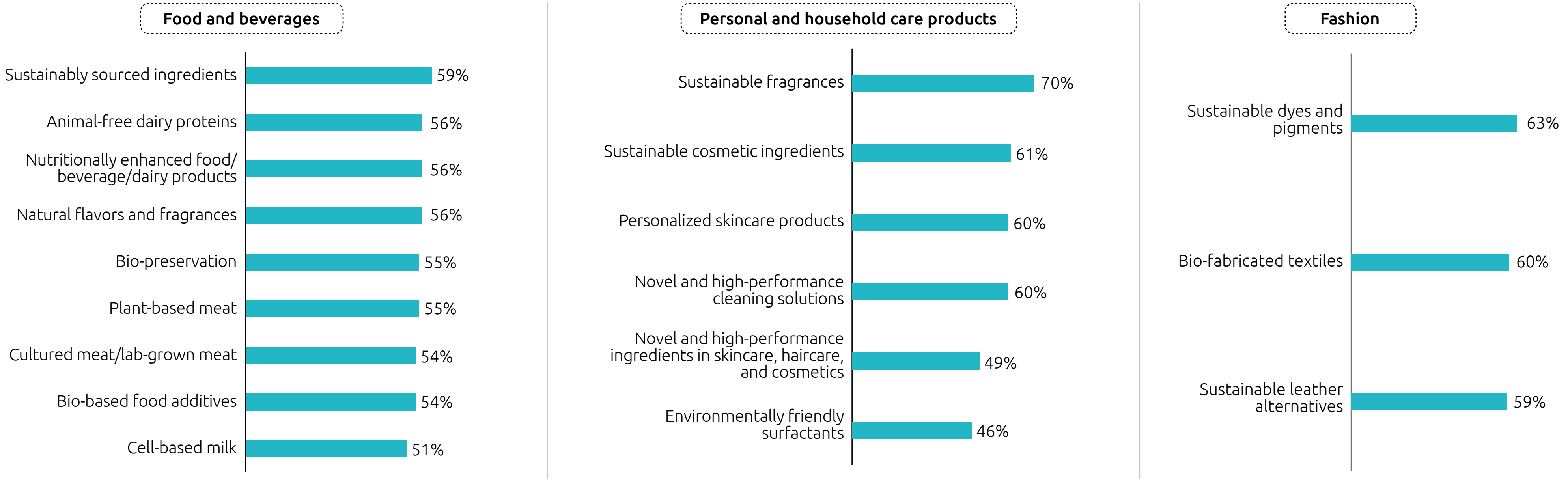
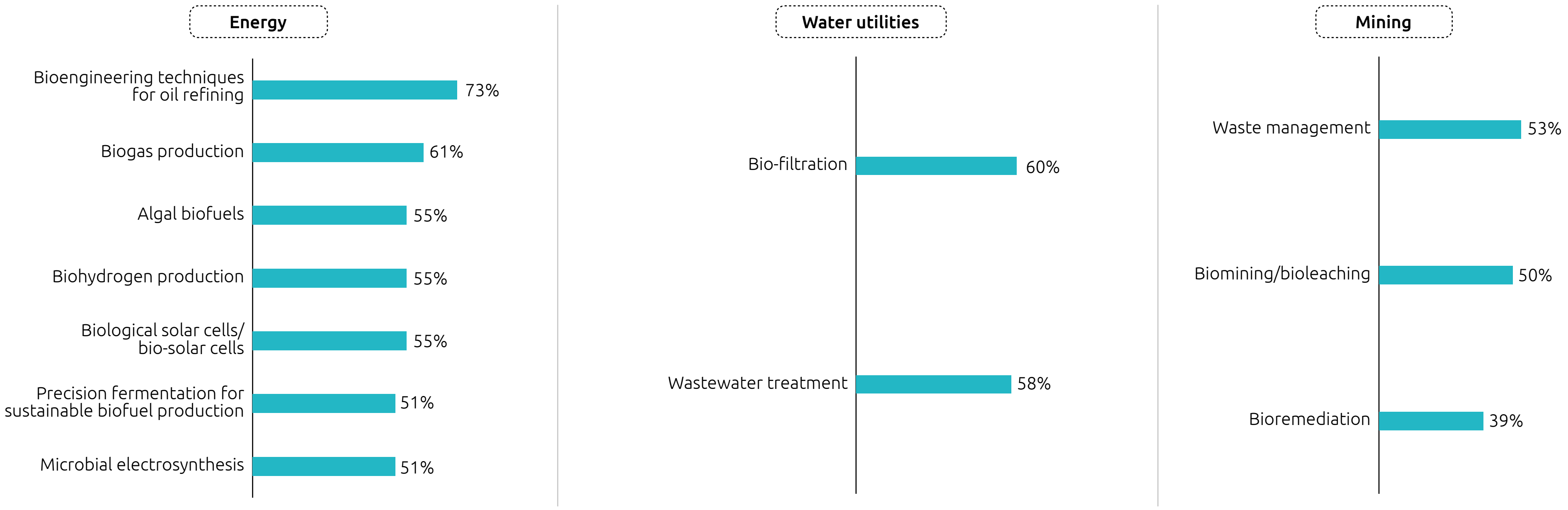

Food and beverages
Sustainably sourced ingredients 59%
Animal-free dairy proteins 56%
Nutritionally enhanced food/ beverage/dairy products 56%
Natural flavors and fragrances 56%
Bio-preservation 55%
Plant-based meat 55%
Cultured meat/lab-grown meat 54%
Bio-based food additives 54%
Cell-based milk 51%
Personal and household care products
Sustainable fragrances 70%
Sustainable cosmetic ingredients 61%
Personalized skincare products 60%
Novel and high-performance cleaning solutions 60%
Novel and high-performance ingredients in skincare, haircare, and cosmetics 49%
Environmentally friendly surfactants 46%
Fashion
Sustainable dyes and pigments 63%
Bio-fabricated textiles 60%
Sustainable leather alternatives 59%

Continue...


Energy
Bioengineering techniques for oil refining
73%
Biogas production
61%
Algal biofuels
55%
Biohydrogen production
55%
Biological solar cells/ bio-solar cells
55%
Precision fermentation for sustainable biofuel production
51%
Microbial electrosynthesis
51%
Water utilities
Bio-filtration
60%
Wastewater treatment
58%
Mining
Waste management
53%
Biomining/bioleaching
50%
Bioremediation
39%

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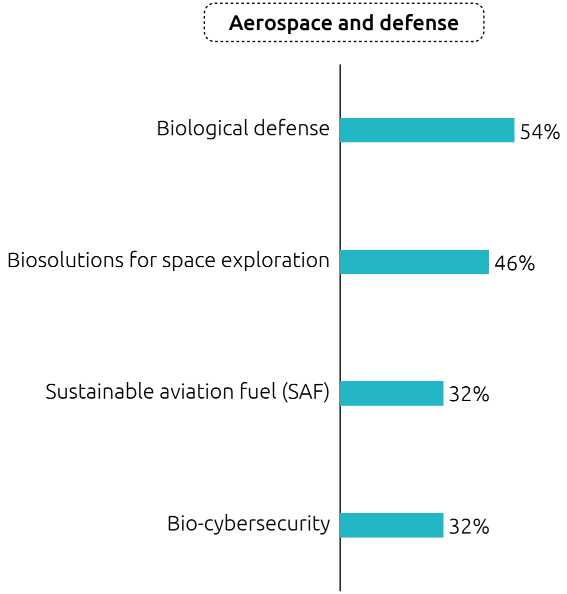
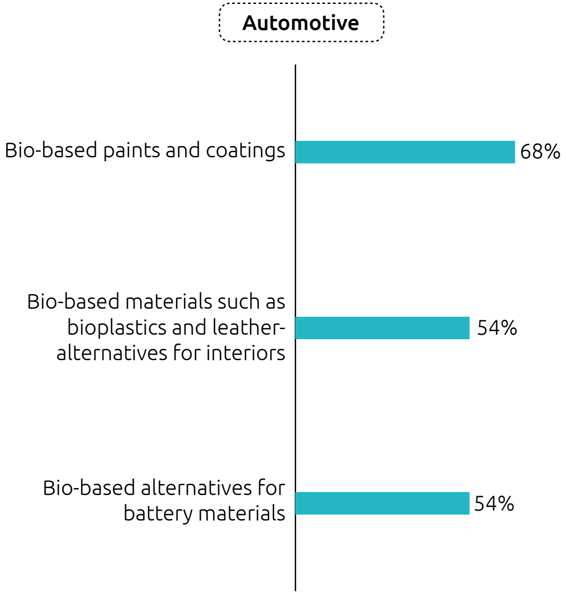
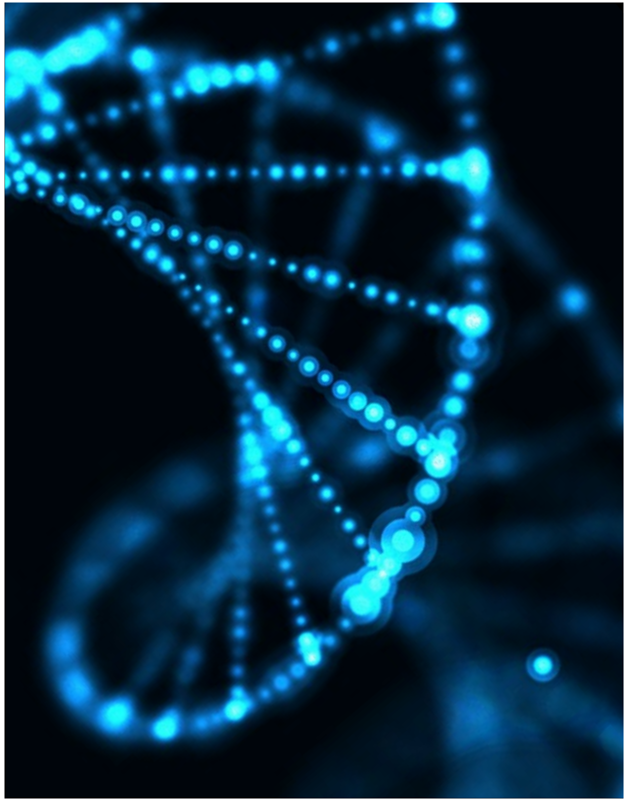


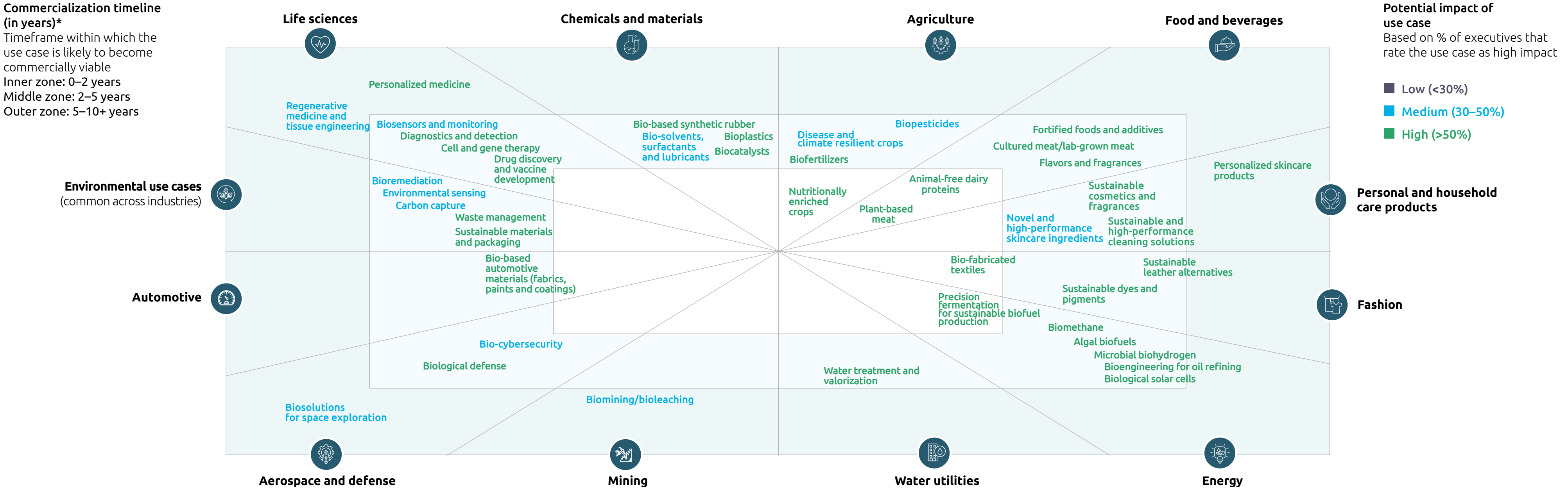




Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=1,100 corporate organizations with N=110 organizations from the life sciences industry, N=210 organizations from the chemicals industry, N=100 organizations from the agriculture sector, N=140 organizations from the food and beverages industry, N=80 organizations from the personal and household care products industry, N=120 organizations from the fashion industry, N=120 organizations from the energy industry, N=50 organizations from the water utilities industry, N=70 organizations from the mining industry, N=50 organizations from the aerospace and defense industry, and N=50 organizations from the automotive industry.

Figure 2.

Impact and commercialization timelines for engineering biology use cases by industry



*Commercialization timelines are based on the assessment of surveyed executives and Capgemini experts.
For descriptions of the use cases and industry-specific figures, please refer to the Appendix. For simplification purposes, not all use cases in Figure 1 are represented here.
Source: Capgemini Research Institute analysis.

02 Organizations view engineering biology as transformative

Engineering biology is a disruptive option that could redefine or entirely replace existing development and production approaches. Its major impacts include:

- Changing the way we produce, either by replacing existing unsustainable materials, processes, or supply chains (e.g., those requiring fossil-based feedstocks) with cleaner, biotech-based processes or by creating innovative, greener materials and ingredients;
- Creating entirely new, more sustainable products.

The impact of this disruption is already visible, as the examples below illustrate:

- **Chemicals:** 1,4-Butanediol (BDO), a key raw material in the bulk manufacturing of plastics, elastic fibers, and films, is used in industries including textiles, automotive, packaging, and consumer goods. It is traditionally made using fossil-based feedstocks. Engineering biology offers a greener manufacturing process that is cost-competitive and offers an end product of comparable quality. US startup **Genomatica** (known as Geno) has successfully scaled production of bio-BDO[46] with global food corporation Cargill as a major licensee. Cargill expects to cut emissions by over 90% compared with traditional production methods.[47]

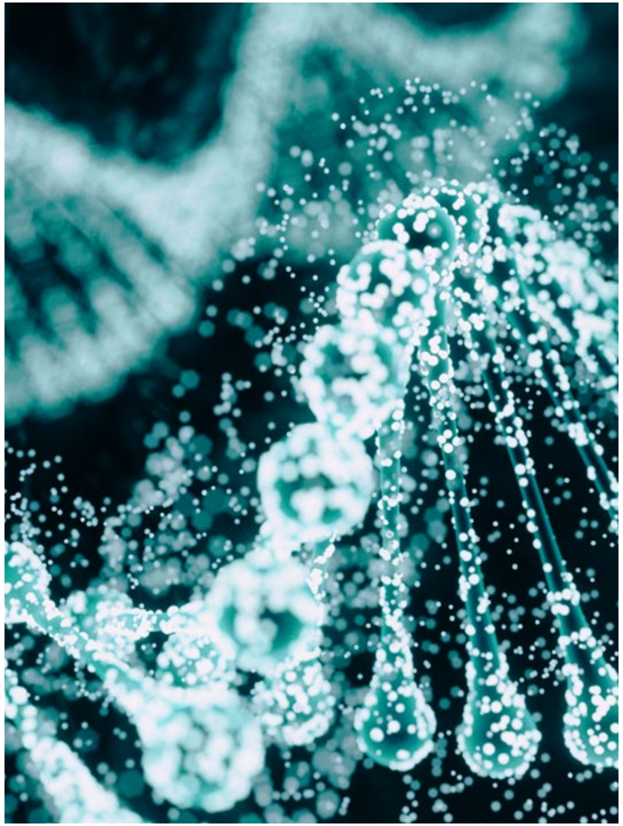
  Jill Zullo, Vice President, Biointermediates/Bioindustrial at Cargill: *"Sustainable chemicals are quickly becoming table stakes for our customers and our investments will enable the chemicals industry to embrace new markets with the materials consumers are demanding from companies they trust."*[48]

- **Cellular agriculture:** Threats to food security and the role of animal agriculture in greenhouse gas (GHG) emissions[49] have made sourcing of viable alternatives that use non-harmful production methods essential. **Cultivated meat** (also known as lab-grown meat) refers to meat grown from animal stem cells under controlled conditions. Following the unveiling of the world's first cultivated meat burger in 2013, the number of companies developing cultivated meat has risen to 174.[50] Production costs have reduced dramatically, and while scale and capacity are still a challenge, cultivated meat products are emerging as a realistic alternative to traditional meat. In 2023, the sale of cultivated meat was approved by the US. Additionally, cultivated meat products are approved for sale in Singapore (the first country to approve them) and Israel.[51]

- **Dairy:** As with meat production, dairy farming leaves a significant environmental footprint[52] and consumes a vast amount of resources in terms of land and water use. **Animal-free precision-fermented dairy proteins** are nutritionally identical to those produced by animals, but the process is much less resource-intensive and more environmentally friendly.[53] Since the 1990s, engineered microbes have been used to produce rennet, an enzyme traditionally harvested from calves. Today, most US cheese is made using rennet produced via microbial fermentation.[54]

US-based startup Perfect Day has successfully commercialized precision-fermented dairy protein in 2020 and today it is used in ice-creams, cream cheese, baked goods, and sports nutrition products across the US, Hong Kong, and Singapore. Perfect Day has attracted investment from ADM, a multinational nutrition corporation, and has entered a long-term partnership with French dairy giant Bel, as well as holding talks with the likes of PepsiCo (US).[55]

Agnieszka Tokarek-Nowicka, a senior executive from the dairy industry: *"Precision fermentation could be the most significant disruptor the dairy industry has seen in decades. By enabling milk production without cows, it decouples milk supply from local conditions. Regions like Asia, which face challenges with milk supply, can establish their own production sources. This technology will revolutionize dairy supply chains by allowing large-scale milk production from non-cow sources and addressing the industry's major environmental concern – carbon emissions."*



- **Crop nutrition**. Engineering biology can significantly impact the agricultural sector by offering sustainable alternatives to synthetic nitrogen fertilizers. Pivot Bio's microbial nitrogen products have grown in usage from 3.5 million acres in 2022 to 4.7 million acres in 2023, leading to a reduction in synthetic nitrogen fertilizer use by 80,700 metric tons. This reduction in fertilizer use resulted in preventing emissions totaling 932,500 metric tons and conserving 334 million gallons of water.[56]

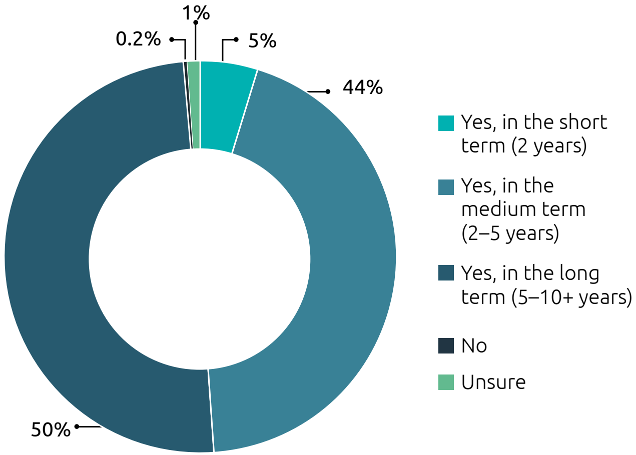
Executives widely agree that engineering biology will disrupt their industries

Our research highlights a strong consensus among executives that biosolutions will disrupt their industry (see Figure 3). There is a roughly even split between those who expect this to happen in 2–5 years and those who see it as a longer-term prospect (5–10 years or more). This is influenced by the industry and application, and the breakthroughs required to unlock the potential of biosolutions.

Figure 3.

Biosolutions are widely expected to disrupt industries, but opinion is divided on timing

In your opinion, will biosolutions create a major disruption in your industry?



Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=1,100 corporate organizations.

"Precision fermentation could be the most significant disruptor the dairy industry has seen in decades. By enabling milk production without cows, it decouples milk supply from local conditions. Regions like Asia, which face challenges with milk supply, can establish their own production sources. This technology will revolutionize dairy supply chains by allowing large-scale milk production from non-cow sources and addressing the industry's major environmental concern – carbon emissions."

Agnieszka Tokarek-Nowicka
A senior executive from the dairy industry

Agnieszka Tokarek-Nowicka says: *"The pace of change will be influenced by the intricacy of the applications. Straightforward solutions, such as the creation of single ingredients like protein and sugar, are likely to materialize in the near future. However, more intricate applications will require a longer timeframe. The schedule will also hinge on the existence of conducive regulatory policies and the ability to expand production capabilities."*

Organizations recognize the merits of biosolutions

Organizations consider the top benefits of biosolutions to be:

- **Reduced environmental impact** due to lower levels of pollution, waste, and emissions
- **Improved product performance and safety levels** owing to biosolutions with improved features such as temperature tolerance or greater efficacy, or bioprocesses that use fewer/no hazardous substances[57]
- **Reduced resource dependence and increased resilience to supply chain disruption** as scarce resources can be replaced with bioengineered alternatives that can be manufactured locally or in more resilient supply chains (see Figure 4).

Further, as we examine later in the report, while the high cost of biosolutions is a challenge for organizations currently whilst the domain matures, a significant proportion (42%) of organizations believe that biosolutions have the potential to deliver cost efficiencies.

The historical reluctance to change to a new disruptive solution unless its performance and/or cost significantly outweighs the traditional solutions (often referred to as the "10x effect"), means that these benefits – and in particular product performance – are important to the rate of adoption. Our research shows that 23% of corporates have already secured performance increases using biosolutions.

Pili, a biotech startup that develops bioengineered dyes, aims to replace petroleum-based indigo with a bio-based alternative produced using engineered microorganisms. Pili's bioengineered dyes deliver significant environmental improvements (50% reduction in emissions and 20% less water consumption compared to producing petrochemical dyes). At the same time, the company states that the quantity of dye produced using microorganisms is the same as conventional approaches, while growing at room temperature.[58]

Ana Dutra, senior corporate executive and global board director with expertise in biotech: *"Biosolutions are a game changer in terms of environmental protection and the ability to reproduce organic compounds synthetically while maintaining purity and quality control. They also transform supply chains by removing geographic constraints on production. Synthetic reproduction of organic compounds allows for production facilities to be established anywhere, reshaping supply chains significantly."*

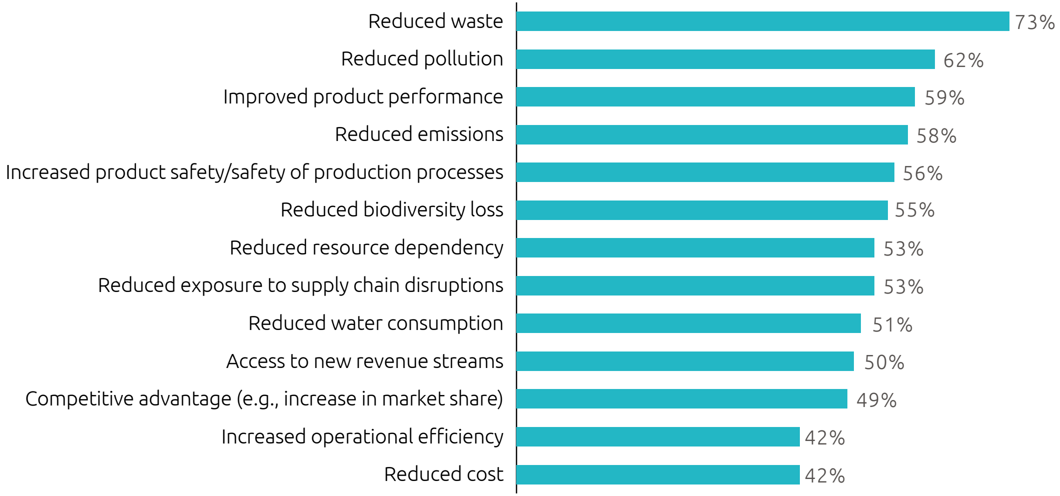
"Biosolutions are a game changer in terms of environmental protection and the ability to reproduce organic compounds synthetically while maintaining purity and quality control. They also transform supply chains by removing geographic constraints on production. Synthetic reproduction of organic compounds allows for production facilities to be established anywhere, reshaping supply chains significantly."

Ana Dutra
Senior corporate executive and global board director with expertise in biotech

Figure 4.

Organizations expect to derive environmental and product performance benefits from biosolutions while increasing supply chain resilience

In your opinion, to what extent do biosolutions have the potential to deliver the following benefits for your organization?
% of executives who rate the following benefits as high potential



Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=1,100 corporate organizations.

Organizations are preparing for disruption

Most organizations are already exploring biosolutions. While 40% are at the exploratory stage, 56% are engaging more actively in experimentation, pilots or scaled deployments. Only 4% say that biosolutions are not a part of their current planning or activities (see Figure 5) – reasons cited include lack of expertise (58%), lack of understanding of the technology within their organization (43%), and the high cost of biosolutions (40%).

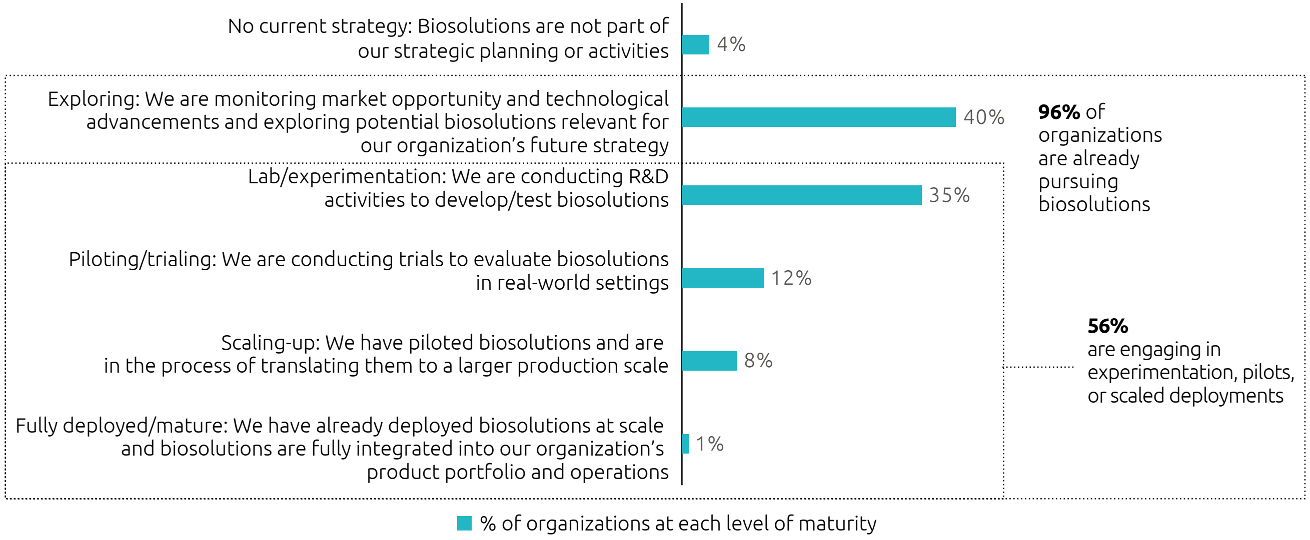
96%

of organizations are already pursuing biosolutions.

Figure 5.

96% of organizations are already pursuing biosolutions, with 56% engaging more actively in experimentation, pilots, or scaled deployments

Which of the following best describes your organization's level of maturity towards biosolutions?



Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=1,100 corporate organizations.

Corporate investment in biosolutions is expected to steadily increase

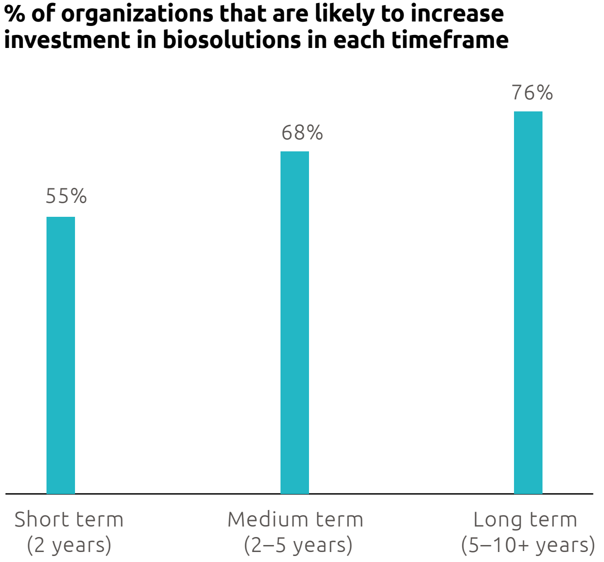
As Figure 6 shows, 55% of surveyed executives say their organization plans to increase investment in biosolutions in the short term (2 years), rising to 68% for the medium term (2–5 years) and 76% for the long term (5–10 years or more). This confirms positive market sentiment towards and confidence in the scientific and commercial potential of biosolutions.

68%

of corporate executives say their organization plans to increase investment in biosolutions in the next 2–5 years.

Figure 6.

Nearly seven in ten (68%) corporates plan to increase investment in biosolutions in the next 2–5 years



Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=1,100 corporate organizations.

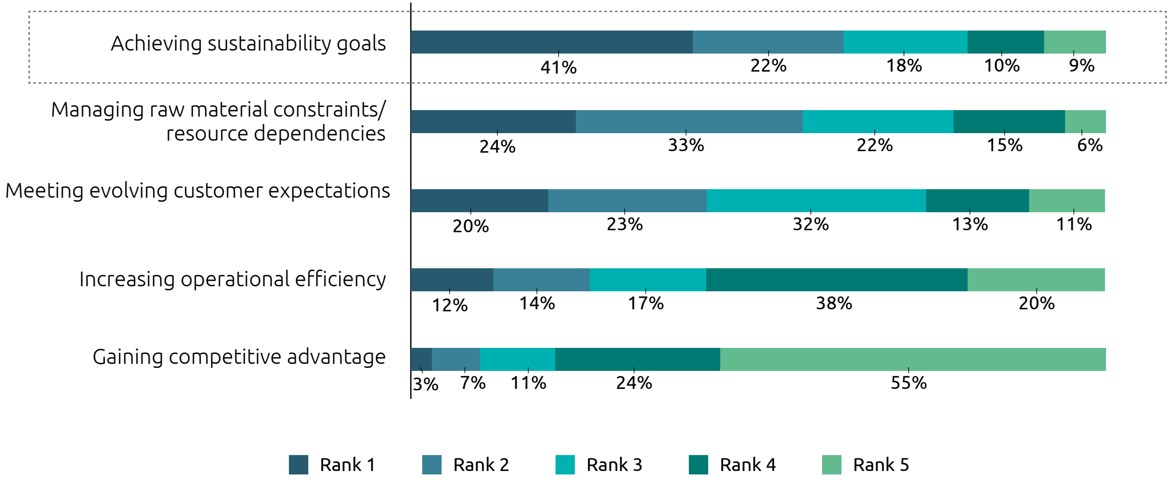
03 Biosolutions offer significant sustainability benefits, but only if correctly harnessed

Corporate interest in biosolutions is driven significantly by the need to adopt more sustainable practices. Sustainability was the top driver of adoption of biosolutions for 41% of surveyed executives (see Figure 7). However, biosolutions are not always more sustainable. Unlocking their true potential for sustainability requires deliberate action, such as measuring the environmental and social impacts across the product lifecycle, and designing the lifecycle to avoid any unintended consequences. In addition to being sustainable, biosolutions need to be able to compete effectively on performance and cost with conventional alternatives to spur market adoption.

Figure 7.

Sustainability is the top driver of corporate interest in biosolutions

What is driving your organization's interest in pursuing biosolutions?



Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=1,060 corporate organizations that are pursuing biosolutions.

Executives believe biosolutions can significantly accelerate progress toward sustainability goals

Most (55%) surveyed executives believe that disruptive approaches are required to reach net zero. The majority believe biosolutions can help organizations address sustainability challenges; 72% believe they have the potential to significantly accelerate progress toward sustainability goals.

Dr. Thomas Satzinger, Vice President Strategy at Evonik Care Solutions, a leading supplier of ingredients for the cosmetics industry: *"The cosmetics industry is under significant pressure to be sustainable, especially in ensuring that products biodegrade and do not accumulate in nature. The technology with the greatest potential to drive sustainability in the cosmetics industry is biotechnology. Over the next decade, traditional, non-biodegradable chemical technologies are likely to be replaced by sustainable alternatives."*

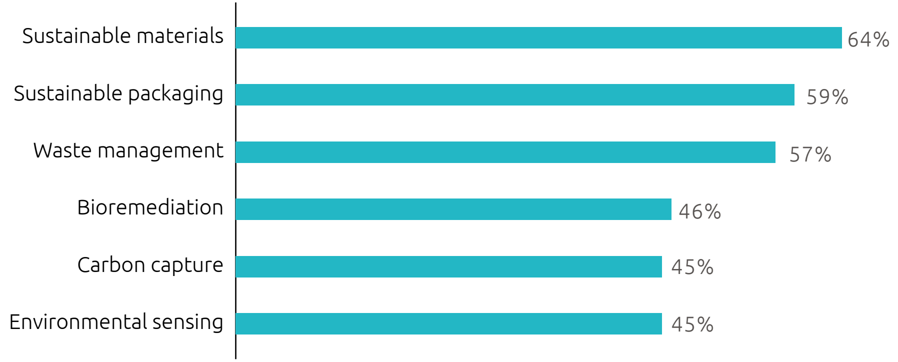
Sustainable materials, packaging, and waste management are among the top environmental use cases of engineering biology

Engineering biology offers various environmental use cases, including the development of sustainable materials and packaging, improved waste management, bioremediation, carbon capture, and environmental sensing (see Figure 8).

Figure 8.

Close to two-thirds (64%) of surveyed executives believe that sustainable materials developed using engineering biology can have a high positive impact on their industry

% of executives who rate the following environmental use cases of engineering biology as high impact based on the value that the use case can create for their industry



Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=1,100 corporate organizations..

The examples below illustrate the applications of engineering biology that can help organizations reduce their environmental impacts:

- **Sustainable materials:** US-based biomaterials startup Modern Meadow makes sustainable leather substitutes, engineering yeast to produce animal proteins. In partnership with Italian textile and materials supplier Limonta, they created the Bio-Tex™ range, which reduces greenhouse gas emissions by 91% and water consumption by 83% compared to traditional chrome-tanned leather. Fashion brands, including Tory Burch, Senreve, and Everlane, have taken up their products.[59]

- **Sustainable packaging and waste management:** Mango Materials, a US-based startup, harnesses microbes to convert methane from waste sources such as landfills, wastewater treatment plants and agricultural facilities into biodegradable packaging materials.[60] Ourobio (US) uses engineered microorganisms to upcycle industrial waste byproducts into new biodegradable materials. The company has developed a proof of concept to turn waste from the dairy industry into biodegradable plastics.[61] BRAIN, a German biotech startup, identifies and optimizes microbes to recover metals from waste streams (e.g., extracting gold from e-waste). The company has built an archive of 50,000 microbes to identify the most efficient organisms for extracting various metals and rare earth elements.[62]

- **Carbon capture:** LanzaTech (US) specializes in converting industrial-waste carbon emissions (e.g., from steel plants) into compounds such as ethanol to make products such as plastics and sustainable aviation fuel. According to LanzaTech, the technology can help steel plants cut emissions by 30%, and sustainable aviation fuel thus made can reduce emissions by 85% compared to conventional jet fuel.[63]

- **Environmental sensing and bioremediation:** BluumBio, a US-based biotech startup, harnesses microbes that produce specialized enzymes to break down and remove toxic chemicals such as petroleum hydrocarbons, carcinogenic dyes, heavy metals, arsenic, and microplastics from the environment. BluumBio engineers the microbes to enhance this ability.[64]

64%

of corporate executives believe that sustainable materials developed using engineering biology can have a high positive impact on their industry.

57%

of corporate executives believe that waste management solutions developed using engineering biology can have a high positive impact on their industry.

However, biosolutions are not always more sustainable than traditional alternatives

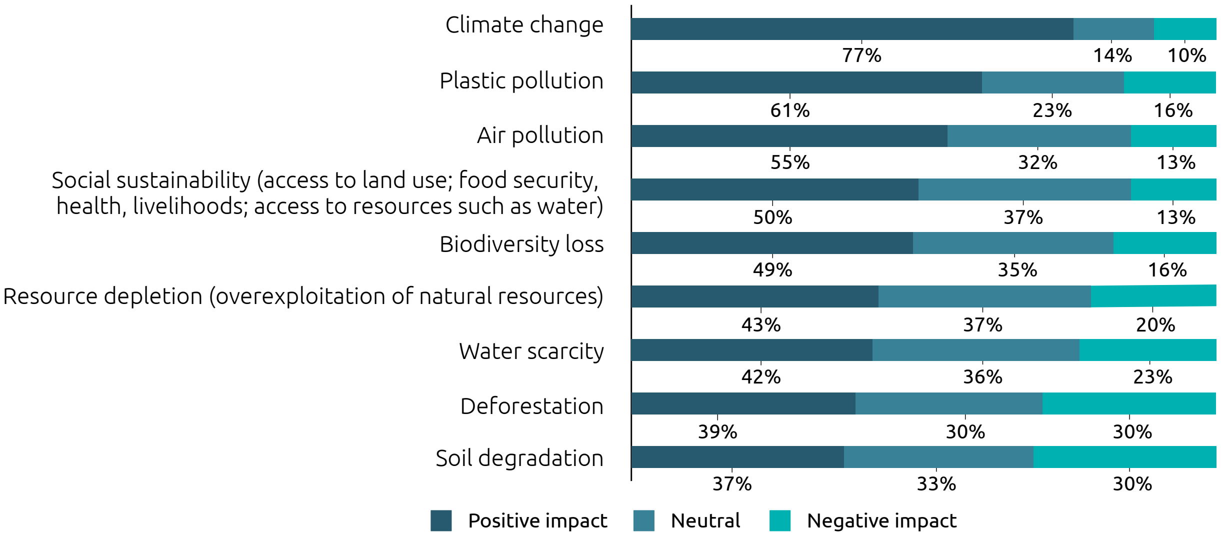
As Figure 9 shows, most executives expect biosolutions to have a positive impact on climate change, and plastic and air pollution.[65] However, executives are less certain of a positive impact on:

- Deforestation – clearing of land to meet the demand for agricultural feedstocks (e.g., corn and sugarcane) for fermentation could contribute to deforestation.
- Soil degradation – growing feedstocks could intensify the use of synthetic fertilizers, leading to reduced soil fertility.
- Water scarcity – colocating biomanufacturing facilities near feedstock sources could exacerbate water scarcity if these facilities are established in regions with limited water resources.

To minimize the risk of potential negative impacts and ensure the responsible use of natural resources, it is crucial to predict the environmental impact of biosolutions through comprehensive lifecycle assessments, adopt transparent reporting, and harness emerging technologies such as cell-free sensing[66] and eDNA testing[67] to monitor ongoing impact. Assessing social impacts, such as those on food security, access to resources such as land and water, and population health are also paramount.

Figure 9.
Close to eight in ten executives believe that biosolutions will help address climate change

In your opinion, what is the impact that biosolutions can have on the following areas?



Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=1,100 corporate organizations.

Sustainability needs to be backed by performance and cost efficiency that exceeds traditional solutions, for wider adoption of biosolutions

While sustainability is an important driver of corporate investment in biosolutions, the switch to biosolutions hinges on their ability to compete effectively on cost and performance. Christophe Schilling, Chief Executive Officer and founder of Geno, a US-based biotech startup: *"Across our portfolio, we review each technology before it goes to market to ensure that the carbon profile offers significant sustainability benefits, while also being cost-competitive and of similar or better performance as the incumbent source it's replacing."*[68]

Potential sustainability benefits need to be demonstrated at scale and supported by strong performance and cost efficiency to drive market adoption. Jim Ajioka, Chief Scientific Officer of Colorifix: *"Sustainability isn't just about having a great idea. It's also whether you can scale it and make it into something that will be acceptable to the current market."*[69]

Pivot Bio's nitrogen-fixing microbes are aimed at reducing the environmental harm caused by nitrogen fertilizers due to greenhouse gas emissions and water pollution. However, adoption of the product has been enabled by its financial appeal. Unlike nitrogen fertilizers, Pivot Bio's products do not wash away in the rain, helping lower cost and risk for growers.[70]

77%

of corporate executives believe that biosolutions will help address climate change.

04 Barriers to the accelerated adoption of biosolutions

The adoption of biosolutions is being held back by a range of challenges. In many cases, these challenges are reinforced through a lack of familiarity and understanding of engineering biology given that it is a new area of science and engineering. We examine these challenges below, as they affect corporates as well as engineering biology startups.

Market awareness and acceptance

Almost two-thirds (65%) of engineering biology startups surveyed cited a lack of bio-literacy in their customer base as a barrier to the development and scale-up of biosolutions. A senior executive at a US-based agribusiness firm: *"What the public thinks about genetically modified crops can potentially be a barrier to growth. Because of the huge potential of that technology, I think the public will start to embrace it, but the industry has to educate the public on what a genetically modified crop is and how it can benefit society."*

Hamid Rismani Yazdi, Senior Project Director at Novonesis, a Denmark-based global biotech firm: *"While we see a positive trend toward increasing awareness of engineering biology, we also see concerns and skepticism from the public. Companies need to help the public understand the impact of the adoption of biosolutions."*

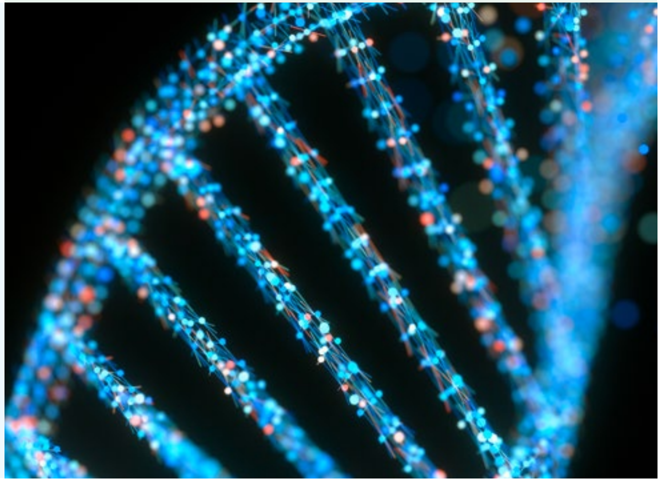
Public concerns can stem from ethical concerns posed by the deliberate misuse or accidental consequences (e.g., bad actors, or unforeseen environmental impacts resulting from the introduction of engineered organisms into ecosystems) of engineering biology. Our survey found that 69% of engineering biology startups cite deliberate misuse of engineering biology as a barrier. These concerns highlight the need for responsible guardrails to be developed for the development of biosolutions, as well as a need for education, where the concerns may be unfounded.

69%

of engineering biology startups cite deliberate misuse of engineering biology as a barrier.

65%

of engineering biology startups cite a lack of bio-literacy in their customer base as a barrier to the development and scale-up of biosolutions.



Business viability

The cost of developing and scaling biosolutions also poses a challenge. More than six in ten (62%) engineering biology startups and close to half (52%) of corporate executives cite the high cost of biosolutions as a barrier, which is linked with the long lead time required to develop these solutions (cited as a key issue by 58% of engineering biology startups). Additionally, the construction of business cases can sometimes be difficult for organizations that lack the data and models for this new area of innovation.

A senior executive at an engineering biology startup focused on carbon transformation: *"Time and resources are the main challenges to scaling biosolutions. Building the business case remains a challenge. Biosolutions often cost higher than the corresponding fossil-based solutions."*

Simon Trancart, Head of Adaptive Laboratory Evolution at Ginkgo Bioworks: *"The lower the unit cost of a given molecule or product, the more challenging to produce it profitably, because it will have to compete with the incumbent solution."*

For engineering biology startups, financing concerns remain significant – 63% say they face challenges in obtaining financing due to the risks or uncertainties associated with biosolutions. Simon Trancart from Ginkgo Bioworks: *"Without a commitment from the industry to buy these solutions, and without a structured financing system, it's very hard for industrial biotechnology startups to get funding because of the long lifecycle for scaling bioprocesses and path to commercialization."*

52%

of corporate executives cite the high cost of biosolutions as a barrier, which is linked with the long lead time required to develop these solutions.

63%

of engineering biology startups say they face challenges in obtaining financing.

"The lower the unit cost of a given molecule or product, the more challenging to produce it profitably, because it will have to compete with the incumbent solution."

Simon Trancart
Head of Adaptive Laboratory Evolution at Ginkgo Bioworks

Science and technology

Scientific and technological barriers pose challenges to the development and scale-up of biosolutions. Fundamentally, scientific understanding of DNA and its role in biological processes remains limited. The ability to write long and accurate sequences of DNA and successfully transferring them to an organism is an ongoing focus of research. AI and foundational large language models have an important role to play in predicting the behavior of biological systems.

However, 57% of corporates cite the lack of foundational data available for training AI models as a challenge.

Further, almost two-thirds (64%) of engineering biology startups cite complexities in optimizing bioprocesses (e.g., optimizing media for the growth of microorganisms or process conditions) as a challenge. Unlike traditional processes, where interactions between mechanical or chemical components are better defined, biological systems are inherently complex and cellular behaviors harder to predict. These factors pose challenges to scaling production.

More than half (52%) of startups say they face challenges arising from complexities in scaling bench-scale engineering biology research through to high volume production.

In addition, engineering biology startups require supplementary technical solutions such as lab automation and data analytics tools to fully develop or commercialize core science into market-ready solutions. Our research shows that engineering biology startups face challenges accessing supplementary technical solutions (60% cited this as a challenge).

64%

of engineering biology startups cite complexities in optimizing bioprocesses (e.g., optimizing media for the growth of microorganisms or process conditions) as a challenge.

Infrastructure and supply chain

The lack of suitable large-scale infrastructure (i.e., bioreactors and control systems) emerged as a top barrier cited by corporates (57%) and startups (64%). While biosolutions offer the advantage of increasing supply chain resilience by reducing raw material constraints or biomanufacturing products locally, they also require adaption of existing supply chains or the building of new ones. Of the engineering startups we surveyed, 62% cited the need to establish new supply chains or adapt existing ones as a challenge in gaining adoption of their biosolution. This highlights the importance of treating the transition to biosolutions as an organizational and operational transformation exercise beyond the technical and engineering aspects. Further, the development of biosolutions often depends on reliable and sustainable sourcing of feedstocks for fermentation processes. Shortage of feedstocks or issues related to sustainable sourcing of feedstock was cited as a challenge by 56% of startups.

Talent and ecosystem

The lack of skilled professionals with expertise in engineering biology/biosolutions emerged as a key barrier (cited by 65% of startups and 62% of corporates). This is particularly relevant as the domain requires an unusual combination of skills to be brought together in diverse areas, including biological sciences, technology, engineering, and operations.

Our research also shows that 62% of startups struggle to access broad interdisciplinary capabilities. While a strong partner ecosystem is crucial to helping startups access these capabilities, 63% of startups say this is currently lacking.

62%

of engineering biology startups cited the need to establish new supply chains or adapt existing ones as a challenge in gaining adoption of their biosolution.

“Engineering biology will require new skills. There will be increasing demand for synthetic biologists, bioprocess engineers, data scientists and analytics experts, alongside regulatory specialists, bioethicists, and lawyers specialised in intellectual property for synthetic biology-enabled products. In addition to the emergence of new job roles, existing roles will evolve, necessitating retraining, particularly in quality control.”

Hamid Rismani Yazdi
Senior Project Director
at Novonesis

Regulation

As Figure 10 shows, 60% of engineering biology startups cite regulatory complexity as a challenge. A similar share (59%) say that lack of geographical uniformity in regulations is an issue. Further, more than half (53%) of engineering biology startups believe that regulations that are not fit for purpose (i.e., outdated or restrictive) pose a challenge to the development and scale-up of biosolutions. Ester Baiget, Chief Executive Officer of Novonesis, on the challenges posed by current regulations that classify biosolutions as chemicals: *"By forcing biosolutions through the chemical path, we create unnecessary barriers that add no value to consumers. They hinder the speed of the penetration of the solutions of the future."* [71]

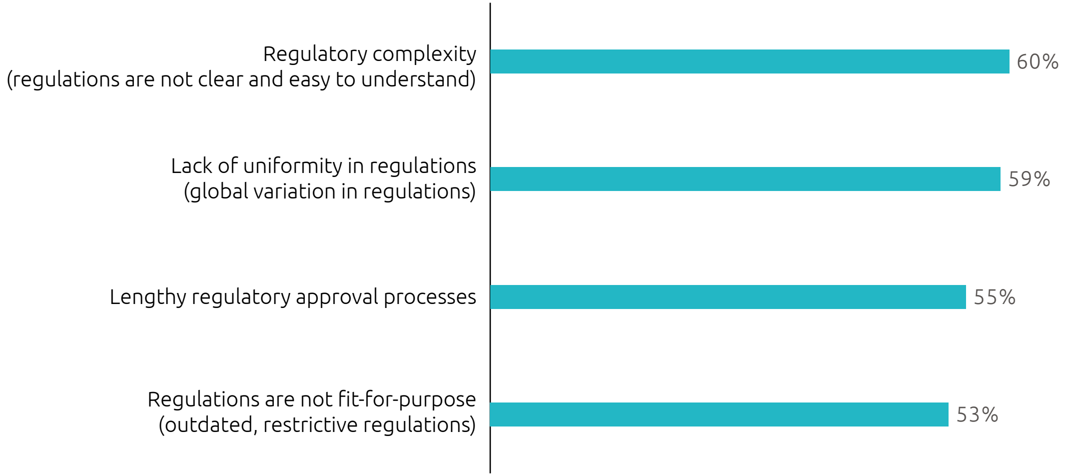
60%

of engineering biology startups cite regulatory complexity as a challenge.

Figure 10.

Engineering biology startups cite regulatory issues as barriers to the development and scale-up of biosolutions

% of engineering biology startups that cite the following regulatory issues as barriers to the development and scale-up of biosolutions



Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=500 engineering biology startups.

05 Digital and engineering technologies will be instrumental in developing and deploying engineering biology

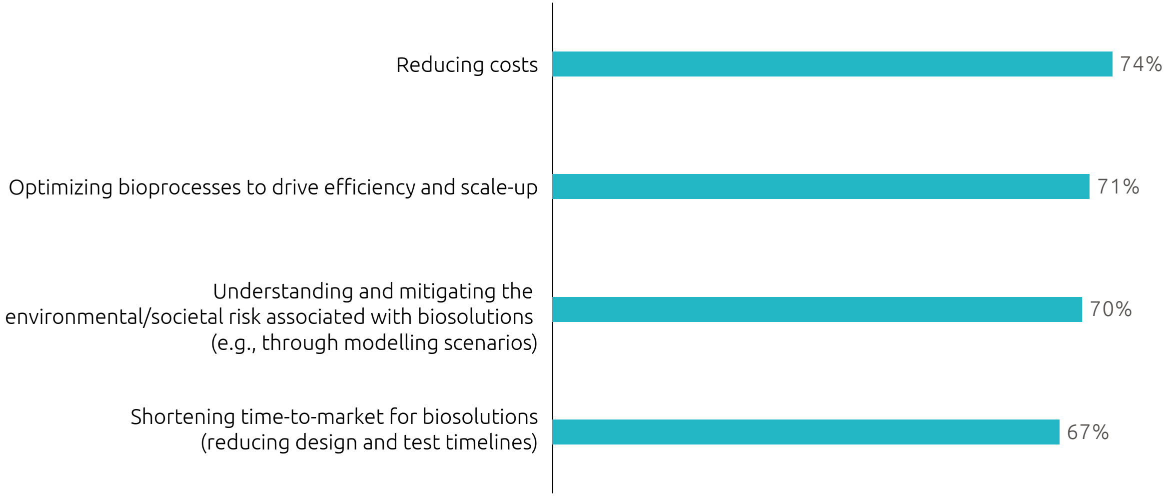
The majority (70%) of corporate executives surveyed believe that digital "in-silico" and engineering technologies such as AI, digital twins, robotics and sensors will be crucial to accelerating the development and scale-up of biosolutions. These are viewed as key to reducing costs, optimizing bioprocesses, shortening time-to-market for biosolutions, and understanding and mitigating environmental and societal risks (see Figure 11).

Digitization of biodesign and bioproduction can significantly reduce unit costs while ramping up productivity. US startup Pow.bio has integrated AI-controlled software into its high-performance continuous fermentation system, reducing commercial biomanufacturing costs by up to 70% and significantly increasing productivity compared with the traditional batch-fed model.[72]

Figure 11.

Almost three-quarters of executives believe that technologies such as AI, digital twins, robotics and sensors can significantly reduce the costs of developing and scaling biosolutions

% of executives who say that technologies such as AI, digital twins, robotics and sensors can contribute significantly towards the following, to accelerate the development and scale-up of biosolutions



Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=1,100 corporate organizations.

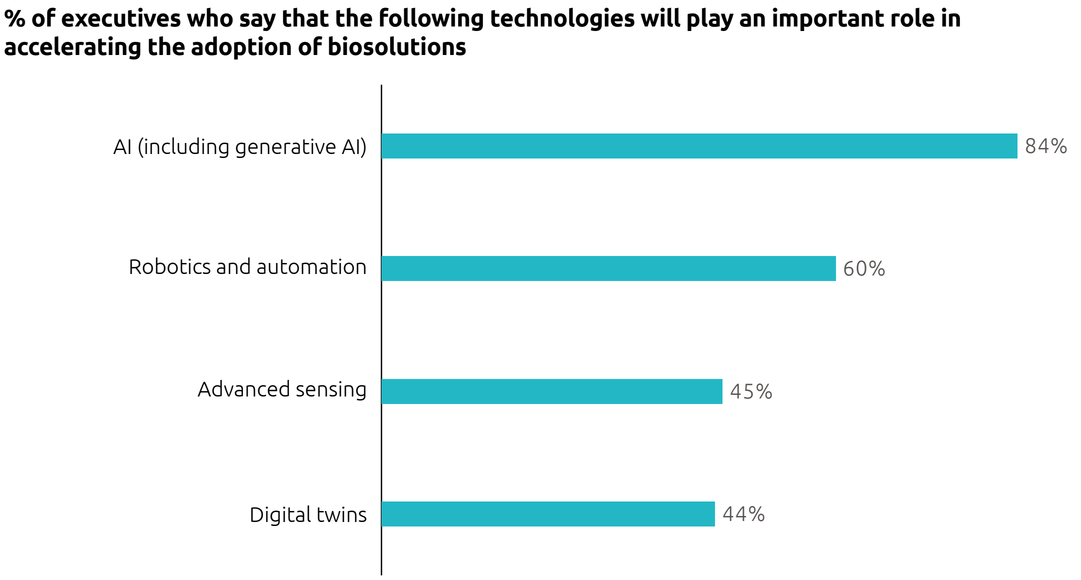
AI will play a prominent role in accelerating the adoption of biosolutions

As shown in Figure 12, 84% of executives see AI as the most significant technology in developing biosolutions. Google's recently launched AlphaFold 3 is one example of an AI model that can predict the structure of proteins, DNA, RNA, and other biomolecules, as well as how they interact, with a 50% improvement in accuracy on existing methods. The application of AI will revolutionize areas such as drug discovery and the development of new biomaterials and crops. Such a capability will radically speed up R&D and testing, significantly reducing the cost of experimentation.[73]

84%

of corporate executives see AI as the most significant technology in accelerating the adoption of biosolutions.

Figure 12.
More than eight in ten executives say that AI will play an important role in accelerating the adoption of biosolutions



Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=1,100 corporate organizations.

Generative AI will significantly increase the efficiency of R&D processes, bringing down development lead times and costs

Some 70% of executives say that generative AI will significantly increase the efficiency of R&D processes, bringing down the lead time for biosolutions. Further, 66% say it will significantly reduce development costs, making biosolutions more financially feasible.

Ginkgo Bioworks and Google Cloud have partnered to develop new large language models (LLMs) to accelerate innovation for bioengineering. Ginkgo's data assets comprise over 2 billion unique protein sequences, on which a foundation model could be trained to enable generative protein design and protein-sequence optimization. From there, a range of new use cases could be developed.[74]

Unilever partnered with Arzeda (a US-based AI startup) to design new proteins and enzymes for use in household cleaning products. Arzeda's platform has accelerated development fivefold. Peter Kulve, Unilever Home Care President: *"As part of Unilever's Clean Future strategy, we're investing in cutting-edge technologies to develop the next generation of sustainable, high-performance cleaning products. The progress made in just 18 months with Arzeda's Intelligent Protein Design Technology™ shows how the convergence of artificial intelligence and biology is a game-changer for an industry like home care."* [75]

In addition to AI, quantum computing offers processing gains for the development of novel proteins with potential applications across drug development, agriculture, industrial processes, and material science. Researchers are exploring the use of quantum computing techniques to develop nitrogenase enzymes that mimic the nitrogen fixation process in plants, providing a potential alternative to the energy-intensive Haber Bosch process for fertilizer production.[76] Quantum computing offers the capability to simulate the complex molecular interactions involved in enzyme function that are challenging to simulate accurately using classical computers. In the consumer products industry, Unilever is partnering with Microsoft to explore the use of quantum computing to accelerate R&D processes. Unilever believes that quantum computing has the potential to significantly reduce the time taken to discover new materials from years to potentially months or even weeks.[77] Advances in the use of quantum technologies for engineering biology are also being driven by organizations such as Wellcome Leap, a US-based non-profit that funds scientific and technological research. As part of its Quantum for Bio program, the organization is providing funding to accelerate applications of quantum computing in healthcare. Examples include the use of quantum computing to predict the structure of large proteins (spanning hundreds or thousands of amino acids) in the human body, with greater accuracy compared to classical computers.[78]

Technology such as digital twins will play a pivotal role in the scale-up of biosolutions

Digital twins of bioreactors can model bioproduction processes, enabling bioengineers to translate low-volume lab results to high-volume bioproduction more effectively. This allows production scale-up to be achieved faster, and in a less resource-intensive manner, than through physical experimentation, reducing development time and cost.

Chueh Loo Poh, Associate Professor at the National University of Singapore, whose lab is developing models and tools to apply predictive insights to large-scale bioproduction: *"A model-driven approach provides a faster and more cost-efficient means to evaluate many different conditions in silico, reducing the need for expensive and time-consuming experiments. We are utilizing the models to gain insights about the bottlenecks of the process and to identify the desired operating conditions."*[79]

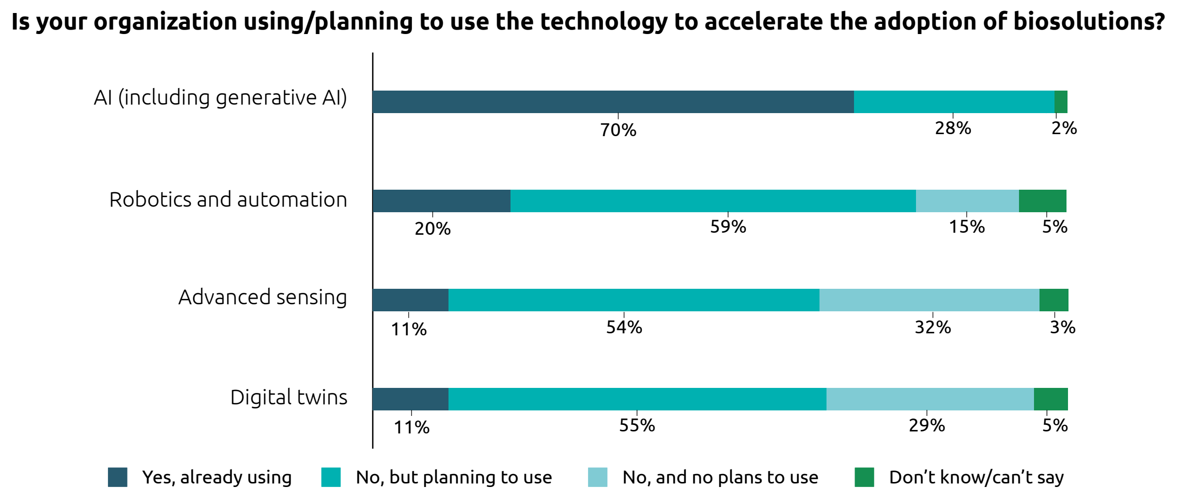
70%

of corporate executives say that generative AI will significantly increase the efficiency of R&D processes, bringing down the lead time for biosolutions.

Most organizations are yet to apply robotics, advanced sensing, and digital twins to develop and scale biosolutions

With the exception of AI, which 70% of organizations are already using to accelerate their adoption of biosolutions, relatively few organizations are using technologies such as robotics and digital twins. However, the majority recognize their potential and plan to use them (see Figure 13).

Figure 13.
Seven in ten organizations are using AI to accelerate their adoption of biosolutions



Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=1,100 corporate organizations.

06 Recommendations

This section contains guidance to help corporates, engineering biology startups, regulators and government agencies accelerate the development, scale-up and adoption of biosolutions.

Corporates and engineering biology startups

- **Formulate an informed strategy and roadmap.** Biosolutions are widely expected to disrupt a range of industries and provide valuable new business opportunities. This change to the status quo makes it vital to build a strategy and roadmap to prepare for the upcoming change. Key elements include:
  - Identifying the areas of opportunity, or threat, and developing a comprehensive and robust business case
  - Assessing economic viability and early-stage feasibility to identify target biosolutions
  - Forming the expert multidisciplinary teams necessary to support the development of biosolutions
  - Defining a technology and data strategy to support the adoption of biosolutions
  - Seeking external advice and practical development capabilities, together with a partner ecosystem to accelerate progress
  - Planning for the broader organizational transformation, including operational changes in procurement, quality, and regulatory processes.

  Corporates and startups that are more advanced in their deployment of biosolutions should also review their existing strategy regularly, given the rapidly evolving landscape.

- **Support demand generation through industry collaborations to drive down costs through economies of scale.** A clear demand signal is crucial to helping biosolutions commercialize and scale, and consequently reduce costs. Long-term offtake agreements, that make longer-term commitments to future purchases, will help generate demand for biosolutions. For example, United Airlines has signed an offtake agreement with Cemvita, an engineering biology startup, to buy up to one billion liters of sustainable aviation fuel from Cemvita over 20 years. Cemvita engineers microbes to convert CO_2 from existing carbon emissions into sustainable aviation fuel. United Airlines' long-term commitment supports Cemvita's journey toward commercialization, helping it scale production and reduce costs.[80] Additionally, platforms such as the World Economic Forum's First Movers Coalition facilitate corporate purchase commitments to signal demand for emerging technologies.[81] For startups, participation in such platforms provides access to early markets and guaranteed demand, helping to scale production and drive wider adoption of biosolutions.

- **Work closely with customers and end-users to understand performance expectations for a biosolutions alternative.** It is crucial for corporates and startups to understand the performance expectations that customers and end-users have of biosolutions, relative to legacy approaches, as well as the challenges their adoption is likely to pose.

  Kenji Higashi, executive vice president of sustainability at biomaterials startup Spiber: *"We've learnt a tremendous amount from our brand customers about textile manufacturing, performance requirements and quality control since we started working with apparel companies almost a decade ago. When we first started, we had completely underestimated the complexity and difficulty of creating apparel products from new materials and how high the quality expectations are."*[82]

- **Harness digital and engineering technologies to deliver performance and cost-efficiency that surpass traditional approaches.** As previous technology disruptions have proven, biosolutions need to outperform legacy approaches on performance and cost if they are to be adopted. Especially when broader changes in areas such as operations, procurement and supply chain need to be accommodated to make the switch. Digital and engineering technologies can reduce development and scale-up costs, optimize bioprocesses and resultant performance, and shorten time to market for biosolutions.

  Hamid Rismani Yazdi, Senior Project Director at Novonesis: *"AI accelerates the development of tailored microorganisms and biological pathways by narrowing down the most promising microbial candidates from a vast pool of options. It also plays a crucial role in the scale-up and deployment of the final solution by optimizing fermentation conditions and providing real-time insights for effective monitoring of fermentation processes."*

- **Focus on ease of integration with existing processes to facilitate adoption.** To simplify the adoption of biosolutions, corporates and startups must focus on minimizing the need for extensive modifications to existing industrial and supply chain processes. Developing solutions that can act as drop-in replacements, where possible, or be seamlessly integrated with existing processes when not, is advantageous. For example, Colorifix, a startup that produces sustainable dyes, has designed its products as plug-in solutions compatible with current industrial infrastructure to minimize barriers to adoption and reduce social disruption and job loss.[83] Pivot Bio's nitrogen-fixing microbe product also offers the advantage of being a "plug-and-play" solution, enabling farmers to adopt it easily.[84] However, in cases where the disruption is more fundamental, thinking about the broader transformational needs will be necessary.

- **Conduct robust impact assessments and focus on sustainability and circularity during the design phase.** Realizing the sustainability benefits of engineering biology requires careful planning. Our research shows that 59% of corporate organizations and 49% of engineering biology startups struggle to quantify the sustainability benefits of biosolutions, accentuated by the fact that models and data points for this emerging area may be new. Organizations must conduct robust lifecycle assessments (LCAs), certified to ISO standards, that comprehensively assess the environmental and societal impacts of biosolutions throughout the product lifecycle. In addition, long-term risk assessments must be conducted at regular intervals to monitor impacts, including "cocktail effects,"[85] on environmental and human health. Further, feedstocks for biomanufacturing processes must be responsibly sourced (for example, Amyris uses sugarcane feedstocks certified by Bonsucro – a global non-profit that promotes sustainable sugarcane production.)[86]

  Circularity is not a given with biosolutions; it needs to be intentionally built in. The use of waste feedstocks is a key element of this, ensuring that feedstocks for fermentation do not divert resources required for food or lead to deforestation and land clearing. Japanese biotech startup Spiber's Brewed Protein™ process transforms waste textiles and agricultural by-products into nutrients

49%

of engineering biology startups struggle to quantify the sustainability benefits of biosolutions, accentuated by the fact that models and data points for this emerging area may be new.

for microbial fermentation, converting them into novel materials. The use of textile waste to produce new fabrics contributes to a circular textile ecosystem.[87]

- **Build a strong partner ecosystem to access the capabilities required to develop and scale biosolutions.** Nearly three-quarters (73%) of corporates say that a partner ecosystem is an important way for them to support the adoption of biosolutions. Partnerships are crucial to accelerating development, commercialization and scale-up. In Switzerland, for instance, Givaudan, Bühler (an equipment manufacturer for food processing plants), and Migros (a major Swiss retailer) have partnered to set up the Cultured Food Innovation Hub – a company that provides lab and fermentation facilities to assist organizations in developing and scaling cultured meats and precision fermentation products.[88]

  Corporates and startups must invest in partnerships to access specialized professional service and R&D capabilities to support planning, development, commercialization and scale-up. The emerging ecosystem of bioengineering service providers such as biofoundries and contract development firms provides access to essential expertise and capabilities (e.g., lab infrastructure and fermentation facilities) to accelerate commercialization. For instance, 21st.BIO offers pilot and commercial-scale fermentation capacity to help startups scale up fermentation processes.[89]

73%

of corporates say that a partner ecosystem is an important way for them to support the adoption of biosolutions.

"AI accelerates the development of tailored microorganisms and biological pathways by narrowing down the most promising microbial candidates from a vast pool of options. It also plays a crucial role in the scale-up and deployment of the final solution by optimizing fermentation conditions and providing real-time insights for effective monitoring of fermentation processes."

Hamid Rismani Yazdi
Senior Project Director at Novonesis

David Breslauer, Co-founder and Chief Technology Officer of Bolt Threads, an engineering biology startup: *"Engineering biology needs to become more cost-effective. Infrastructure and tool development are crucial to bring down costs and cycle time. Companies now offer contract services to develop biological systems, a capability that was not available a decade ago. While scale-up and manufacturing costs need to come down further, accessibility has improved."*

- **Raise public awareness on the benefits of biosolutions, address any misconceptions, and ensure transparency in reporting to build public trust.** Raising awareness of and dispelling unfounded biases toward biosolutions is crucial for driving acceptance. Of the corporate executives surveyed, 45% cited a lack of market acceptance due to negative public perception as a barrier to the adoption of biosolutions. Further, nearly two-thirds (63%) of engineering biology startups cited facing challenges in obtaining financing due to misconceptions or unfounded biases towards biosolutions – 84% encountered the misconception that engineering biology has limited market applications, and 57% that it is unnatural.

Corporates and startups must work with industry peers, government, academia, and non-profits to raise awareness of the benefits of biosolutions and address misconceptions. Raising awareness is a core objective of the World Economic Forum's Bioeconomy Initiative[90] – a global coalition of public and private sector stakeholders that seeks to accelerate the adoption of biosolutions.

The Precision Fermentation Alliance (PFA), an industry association of nine US-based precision fermentation startups, aims to promote understanding of precision fermentation.[91] Highlighting that these technologies and products derived from them (such as insulin) are already part of everyday use is key. Similarly, choosing the right nomenclature and avoiding terms that could be misleading is key (for instance, the use of the term "animal-free" to describe proteins made by microbes could be wrongly conflated with "plant-based"[92]).

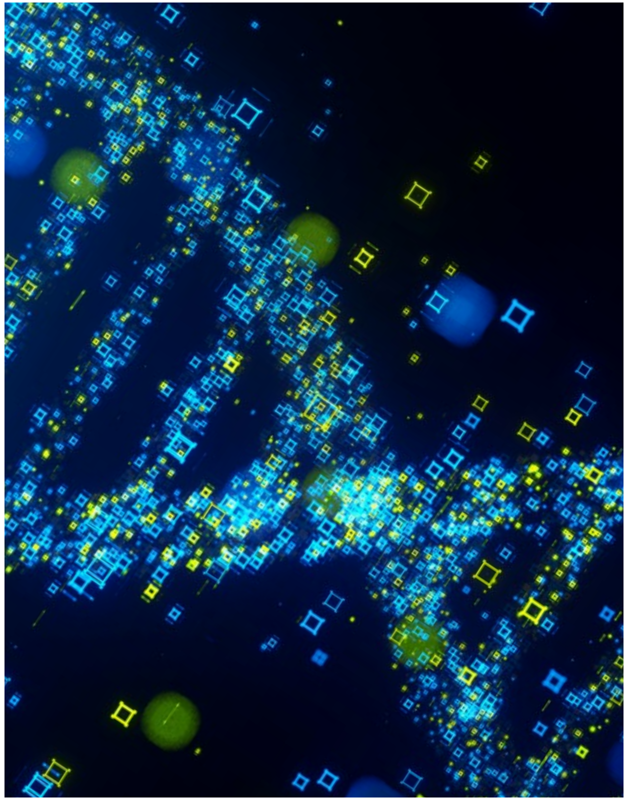
Corporates and startups must also report transparently on the potential risks posed by biosolutions, including ethical and environmental implications, to build public trust.

63%

of engineering biology startups cited facing challenges in obtaining financing due to misconceptions or unfounded biases towards biosolutions.

“Engineering biology needs to become more cost-effective. Infrastructure and tool development are crucial to bring down costs and cycle time. Companies now offer contract services to develop biological systems, a capability that was not available a decade ago. While scale-up and manufacturing costs need to come down further, accessibility has improved.”

David Breslauer
Co-founder and Chief Technology Officer of Bolt Threads



Regulators and government agencies

- **Establish a level playing field for biosolutions.** Executives expect governments to enact policies that help biosolutions compete with traditional alternatives. For example, 62% of executives from large organizations and engineering biology startups say that regulators should remove subsidies for fossil fuels to establish a level playing field for biosolutions (see Figure 14). In 2023, fossil-fuel subsidies rose to a record $7 trillion.[93] Scaling these back would make biosolutions more financially viable.
- **Create clear and progressive regulatory frameworks.** As Figure 14 shows, 78% of engineering biology startups and 62% of corporates see government support in the form of establishing clear regulatory frameworks as critical. Regulations need to be progressive and fit for purpose, while driving responsible use of engineering biology. More than seven in ten (72%) engineering biology startups believe that a progressive regulatory framework is crucial to drive the adoption of biosolutions. Regulatory frameworks must also address the need for robust LCAs and long-term impact assessments to ensure biosolutions are sustainable.

78%

of engineering biology startups see government support in the form of establishing clear regulatory frameworks as critical.

- **Provide funding to support scale-up.** Engineering biology startups require a mix of venture capital and non-dilutive funding to commercialize and scale biosolutions. Governments have a crucial role to play in supporting startups and in growing biomanufacturing capacity by providing funding and incentives. The US, for instance, has allocated more than $2 billion in funding to support domestic biomanufacturing.[94] Other countries that have earmarked funding for domestic biomanufacturing include the UK, China and Saudi Arabia.[95]

- **Promote informed public discourse on engineering biology.** Governments must play an active role in dispelling misconceptions and promoting informed discourse on engineering biology, including potentially negative connotations of "synthetic" biology. This requires public educational campaigns that provide scientifically validated information on the benefits and risks of engineering biology. Policy-making processes should involve a diverse group of stakeholders including industry experts, ethicists, environmental organizations and consumer advocacy groups to ensure an informed, balanced and inclusive dialogue. In addition, defining clear reporting, advertising, and labeling guidelines for biosolutions are necessary to promote transparency, prevent misleading claims, and help customers make educated choices.

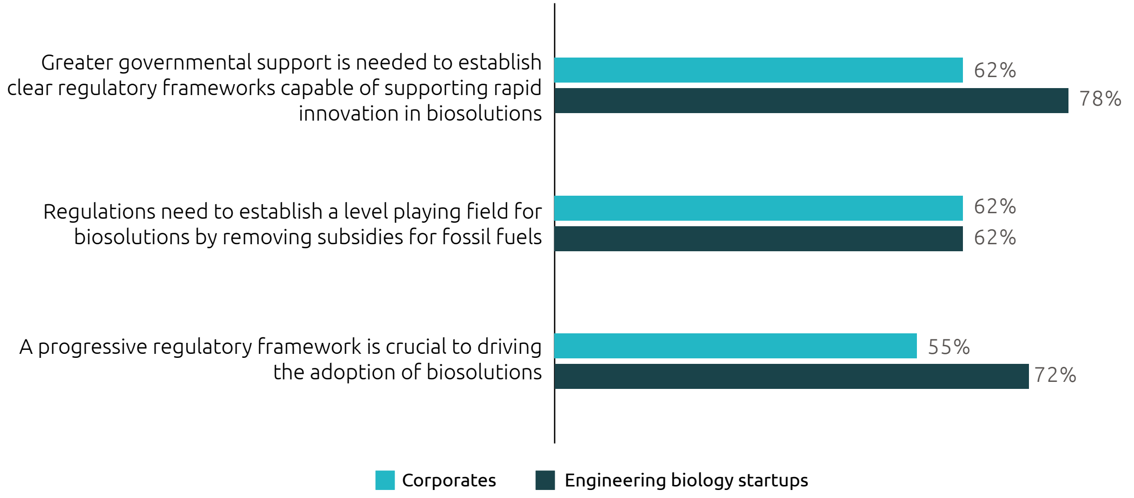
72%

of engineering biology startups believe that a progressive regulatory framework is crucial to drive the adoption of biosolutions.

Figure 14.

Executives cite the need for greater governmental support and a progressive regulatory environment for biosolutions

% of executives who agree with the statements



Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=1,100 corporate organizations and N=500 engineering biology startups.

Conclusion

Biosolutions herald a new era of innovation and sustainability, with major societal benefits. Advances in biological and computational science and engineering have already delivered significant improvements in the ability to proactively engineer biological systems, paving the way for the development of cost-effective biosolutions for a wide range of industries.

However, challenges remain and need to be addressed at speed to accelerate adoption. This starts with identifying and developing candidate biosolutions quickly and reliably. Next, scaling lab breakthroughs and achieving performance and cost-efficiency are key. Raising public awareness of the benefits of biosolutions and dispelling misconceptions are crucial to driving acceptance and demand. Systemic barriers, such as regulatory complexities and fossil-fuel subsidies that make it harder for biosolutions to compete with conventional fossil-derived alternatives, also need to be addressed. Finally, the promise of biosolutions needs to be nurtured responsibly to offset the potential ethical concerns. New ethical frameworks are required for this. A collective, coordinated approach across both public and private sectors, including academia, is crucial to addressing these issues.

Unlocking the potential of engineering biology could transform our future, delivering groundbreaking solutions that enhance quality of life while protecting the planet. The time to act is now.

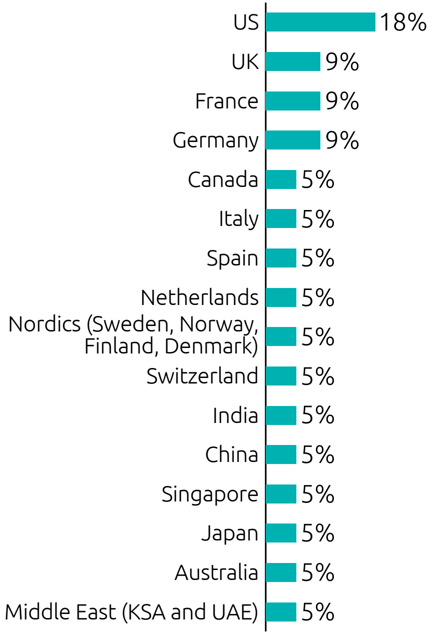
Research methodology

In April–May 2024 we surveyed 1,100 executives at organizations with more than $1 billion in annual revenue across 11 industries in North America, the UK, continental Europe, APAC and the Middle East. Executives surveyed were director-level and above. We also surveyed 500 executives from startups operating in engineering biology and related areas. The distribution of executives and their organizations is provided in the following figures.

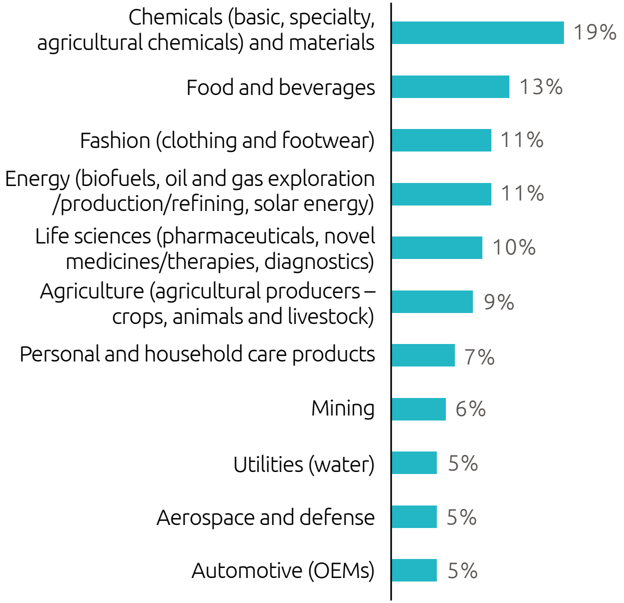
In addition, we interviewed 20 experts, including industry executives, engineering biology startups, VCs, and academics.

Survey of executives from corporate organizations

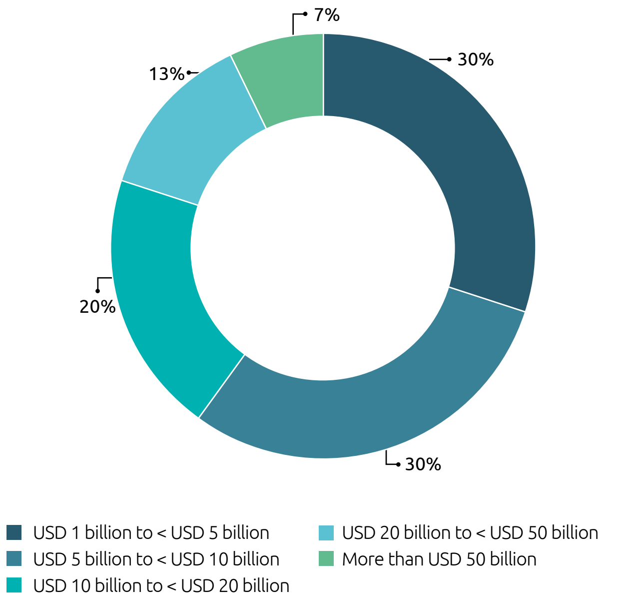
Organizations by headquarter location



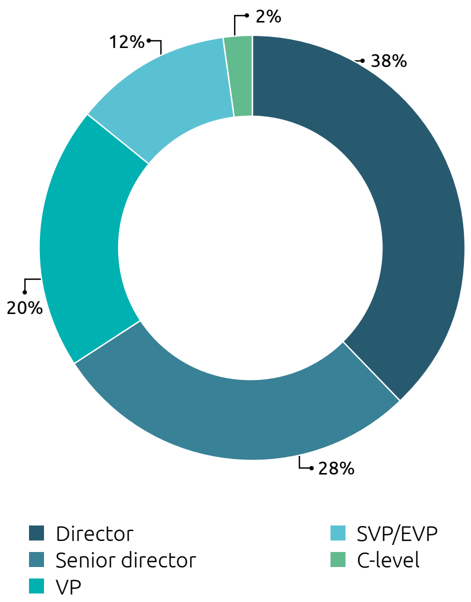
Organizations by industry



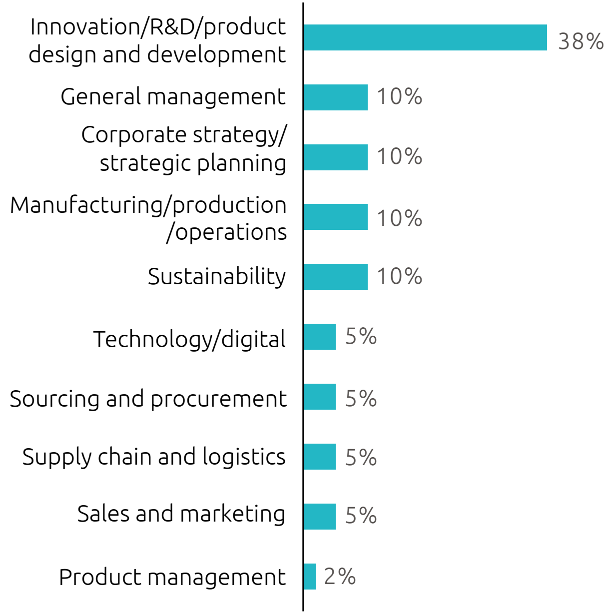
Organizations by annual revenue



Respondents by current job title



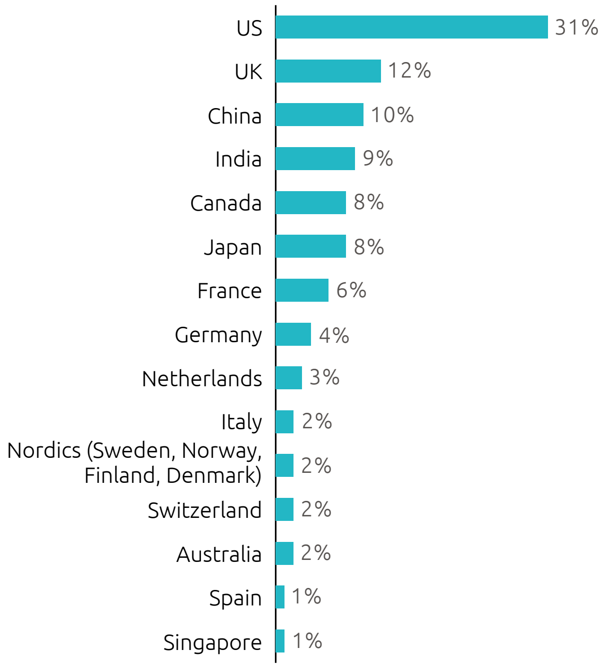
Respondents by department/function



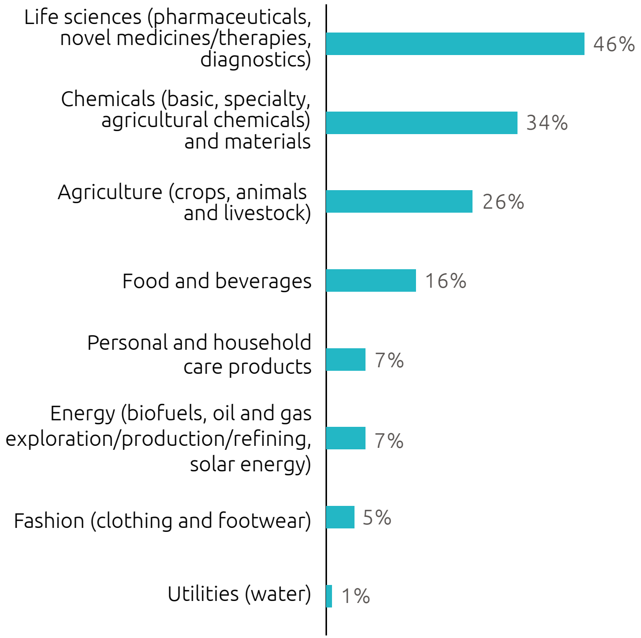
Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=1,100 corporate organizations with annual revenue over $1 billion.

Survey of executives from engineering biology startups

Engineering biology startups by headquarter location

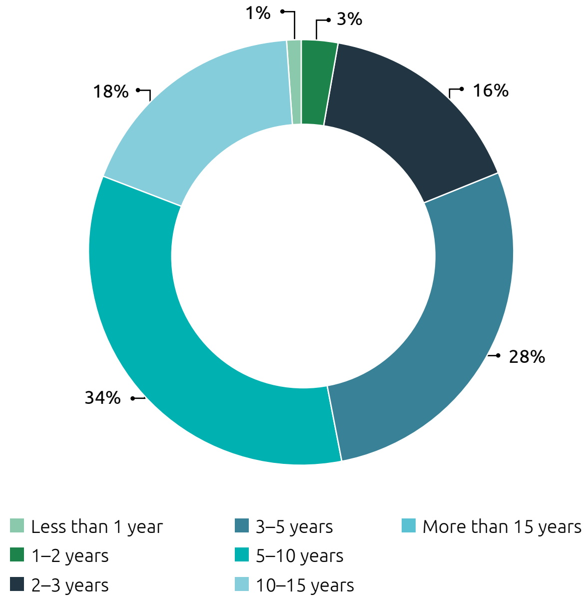


Engineering biology startups by industry



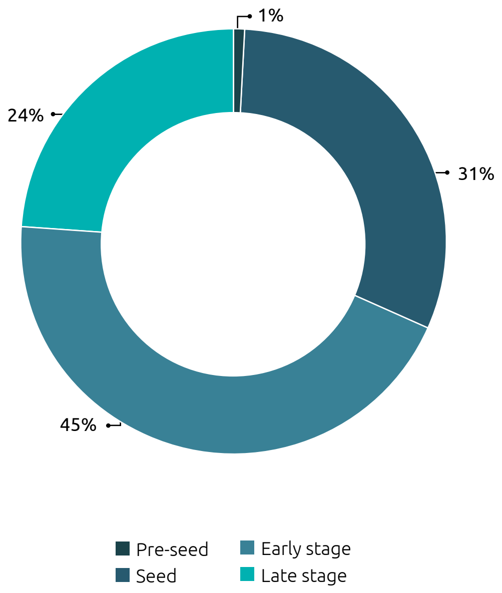
*Percentages do not add up to 100 as a single startup could be operating in multiple industries

Engineering biology startups by tenure of operation

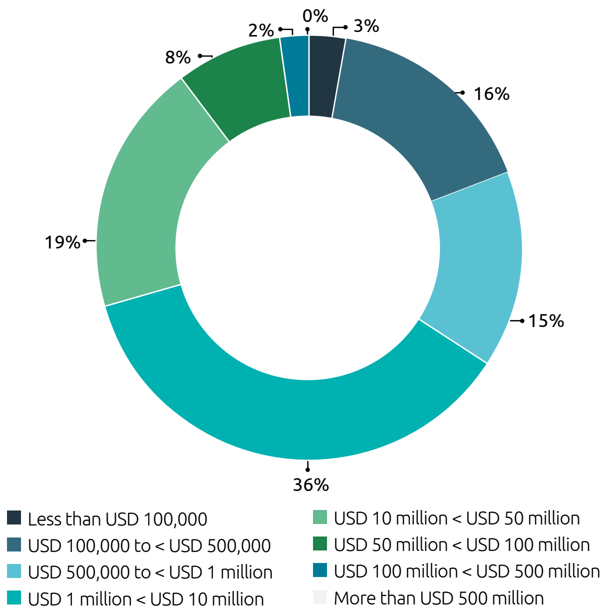


Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=500 startups operating in engineering biology and related areas.

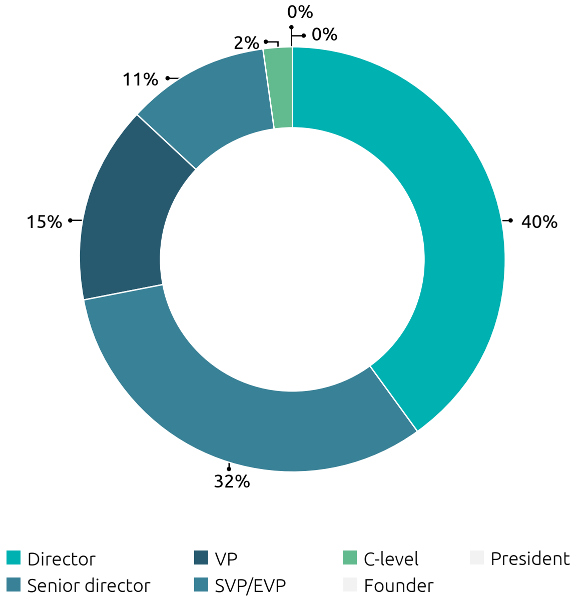
Engineering biology startups by funding stage



Engineering biology startups by annual revenue



Engineering biology startup executives by current job title



Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=500 startups operating in engineering biology and related areas.

The study findings reflect the views of the people who responded to our online questionnaire for this research and are aimed at providing directional guidance. Please refer to the methodology for details of respondents and get in touch with a Capgemini expert to understand specific implications.

Appendix

Key concepts and tools of engineering biology

1. DNA sequencing, synthesis, and editing

DNA sequencing is the process of determining the sequence of nucleotides (adenine, thymine, cytosine, and guanine) that encode genetic information. This sequence guides the order of amino acids in a protein, which determines how the protein folds into a three-dimensional structure. This, in turn, determines the protein's function. **DNA synthesis** is the process of creating DNA molecules artificially, now available as a large-scale commercial service. It involves connecting nucleotides in a precise sequence to create DNA tailored for specific applications. Advances in DNA synthesis technologies and platforms have enabled rapid and more cost-effective synthesis of DNA sequences. Further, accessibility is enhanced through desktop approaches (i.e., desktop DNA synthesizers which are further democratizing availability). **DNA editing** involves the modification of genetic code by making targeted changes to DNA sequences to correct genetic defects or introduce beneficial traits in organisms. CRISPR (clustered regularly interspaced short palindromic repeats) is a breakthrough **DNA editing** tool that acts like a pair of "molecular scissors," enabling DNA to be cut and replaced with precision and efficiency. Taken together, DNA sequencing, synthesis, and editing are fundamental to understanding and programming genetic information for the design of biological systems for a wide range of applications (e.g., engineering microbes such as bacteria and yeast to produce valuable compounds such as drugs, chemicals and fuels, engineering human cells to treat genetic diseases, engineering crops to be climate resilient).

2. Standardization, modularity, and abstraction

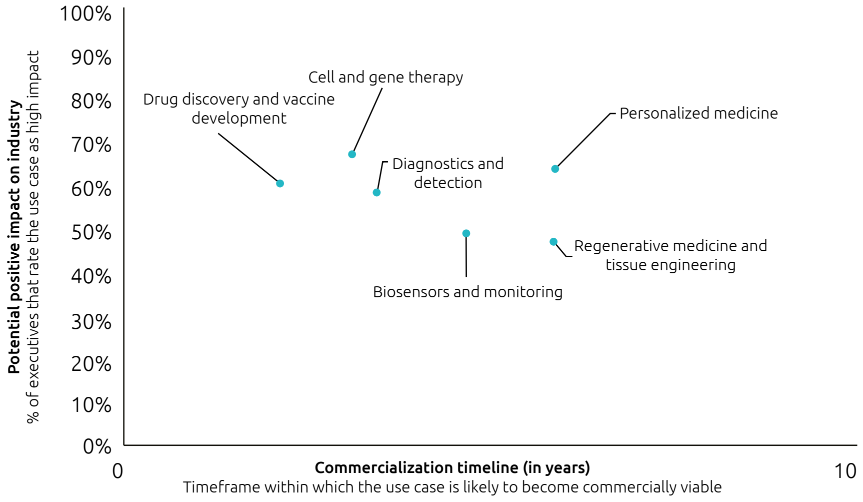
Engineering biology employs engineering principles such as standardization, modularity, and abstraction to design and construct biological systems. **Standardization** involves the development of standardized biological parts, such as DNA fragments, with well-defined functions and interfaces, that can be assembled to build biological systems. BioBricks™, for instance, is a standard for the development of interchangeable biological parts that can be assembled to form useful biological devices (such as genetic circuits programmed to perform specific functions within living cells, biosensors to detect environmental conditions, metabolic pathways to produce useful compounds). **Modularity** entails breaking down complex biological systems into reusable components. Standardized modules can be easily combined to construct novel biological systems, speeding up the prototyping and testing of biological designs. The incorporation of **abstraction** into engineering biology helps simplify biological systems by focusing on high-level design principles rather than complex molecular interactions, increasing the efficiency with which biological systems can be designed.

3. AI and data-driven computation

The application of computational models and techniques to engineering biology is revolutionizing the design and optimization of biological systems. **Simulations** enable researchers to model and predict the behavior of biological systems by testing hypotheses and designs prior to experimental implementation. The use of **AI** enables the analysis of large-scale biological datasets, such as DNA sequencing data, to identify patterns that help predict biological behaviors. Advances in "generative biology" (the use of AI to design novel biomolecules such as protein and DNA) including the emergence of biological large language models (e.g., NVIDIA's BioNeMo AI model) are transforming protein engineering. The emergence of firms offering AI services tailored for biological data (e.g., BioLM, Form Bio) is expanding access to bio-related AI capabilities. Further, computational tools and software platforms such as biological computer-aided design (BioCAD) help automate the process of designing biological systems. These technologies together accelerate the iterative design-build-test-learn cycle in engineering biology and increase the efficiency with which novel biological systems with desired functionalities can be developed.

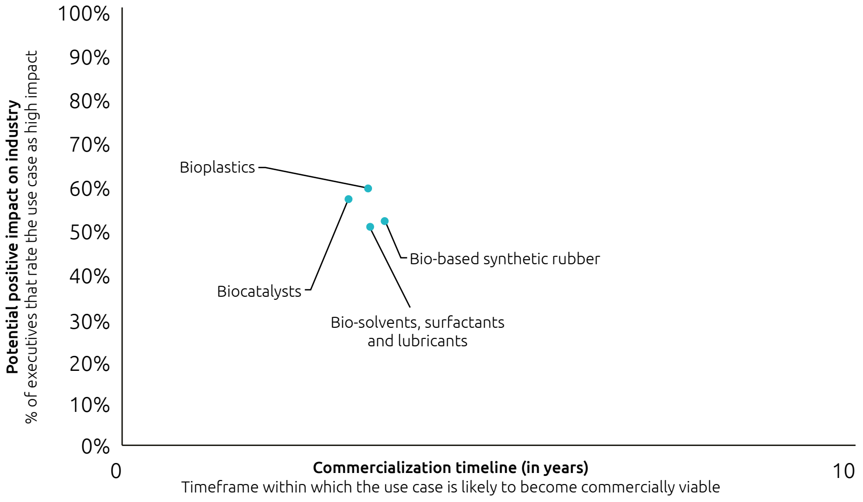
Comparison of engineering biology use cases based on impact and commercialization timelines – by industry

Life sciences



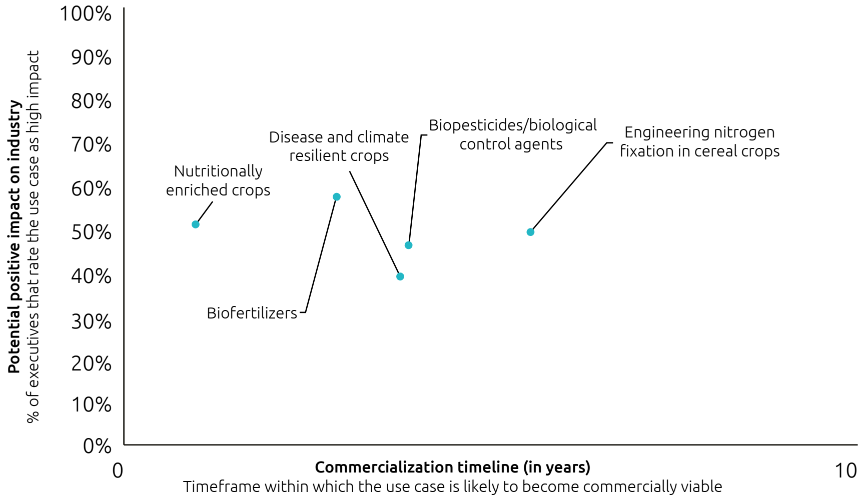
*Commercialization timelines are based on the assessment of surveyed executives and Capgemini experts.
Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=110 corporate organizations from the life sciences industry.

Chemicals and materials



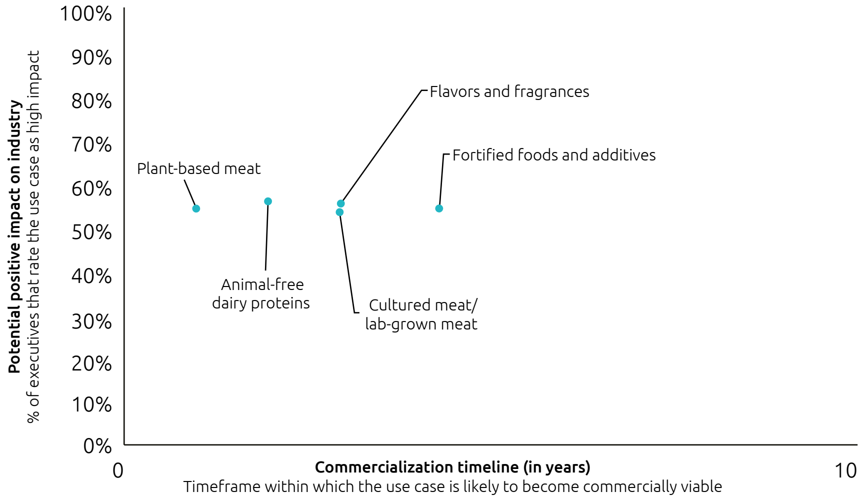
*Commercialization timelines are based on the assessment of surveyed executives and Capgemini experts.
Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=210 corporate organizations from the chemicals and materials industry.

Agriculture



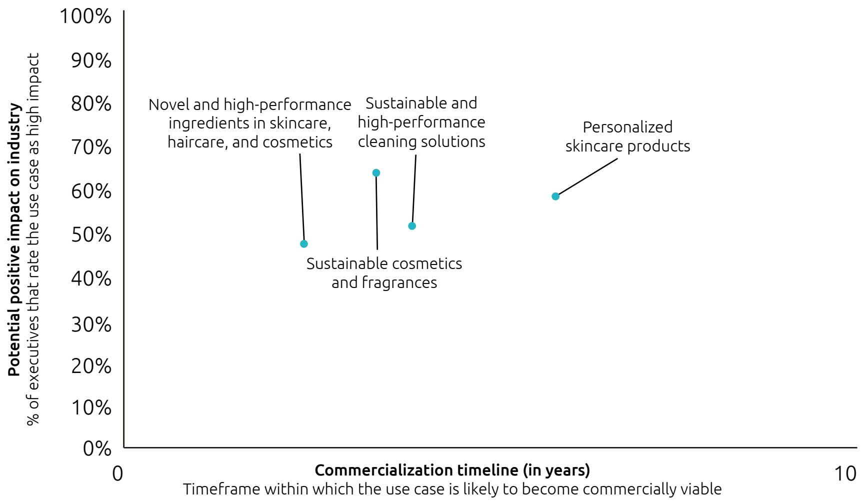
*Commercialization timelines are based on the assessment of surveyed executives and Capgemini experts.
Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=100 corporate organizations from the agriculture industry.

Food and beverages



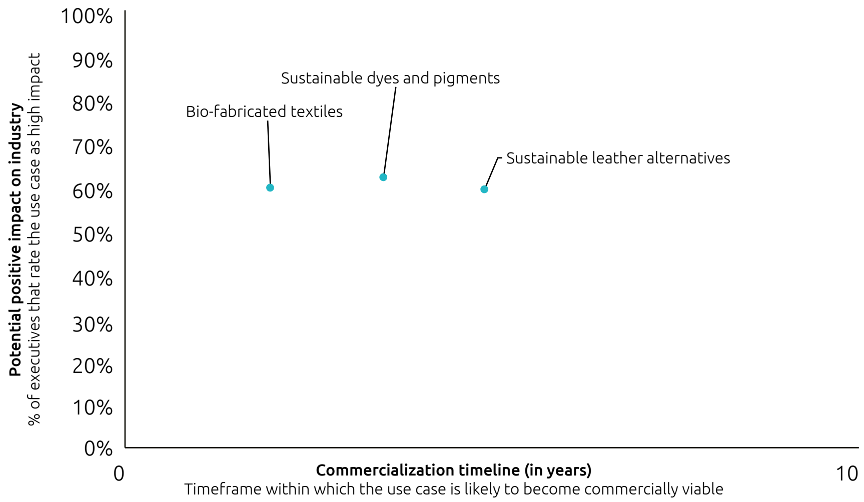
*Commercialization timelines are based on the assessment of surveyed executives and Capgemini experts.
Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=140 corporate organizations from the food and beverages industry.

Personal and household care products



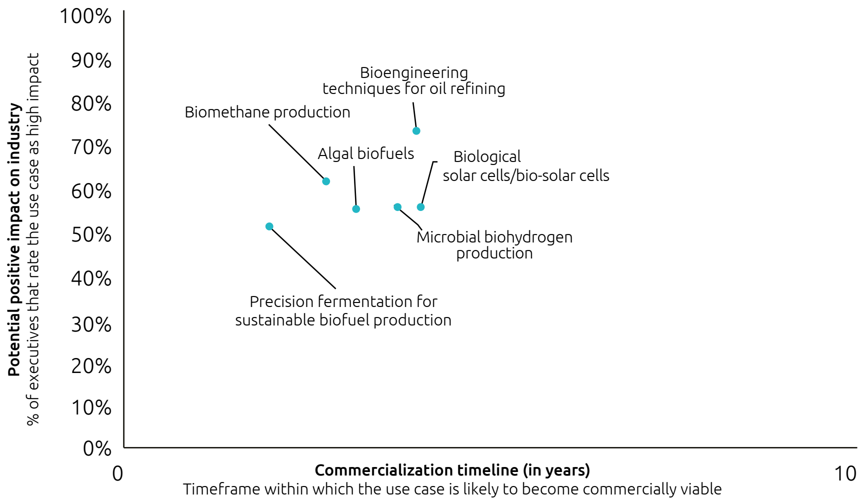
*Commercialization timelines are based on the assessment of surveyed executives and Capgemini experts.
Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=80 corporate organizations from the personal and household care products industry.

Fashion



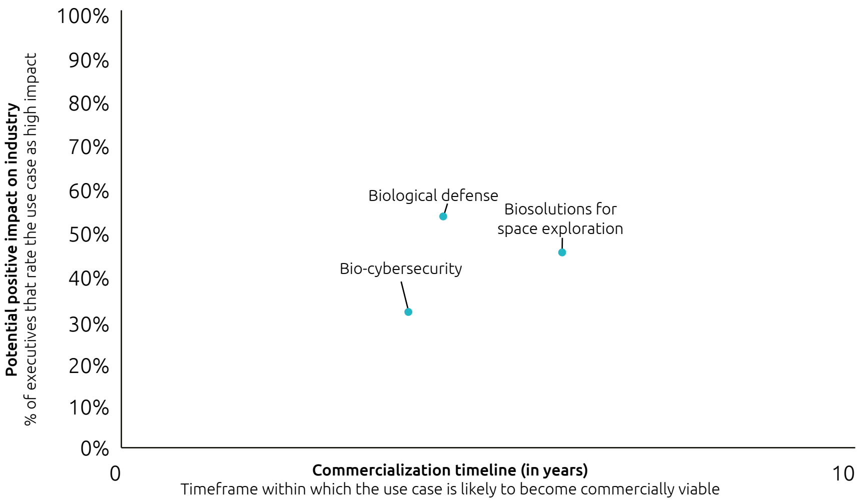
*Commercialization timelines are based on the assessment of surveyed executives and Capgemini experts.
Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=120 corporate organizations from the fashion industry.

Energy



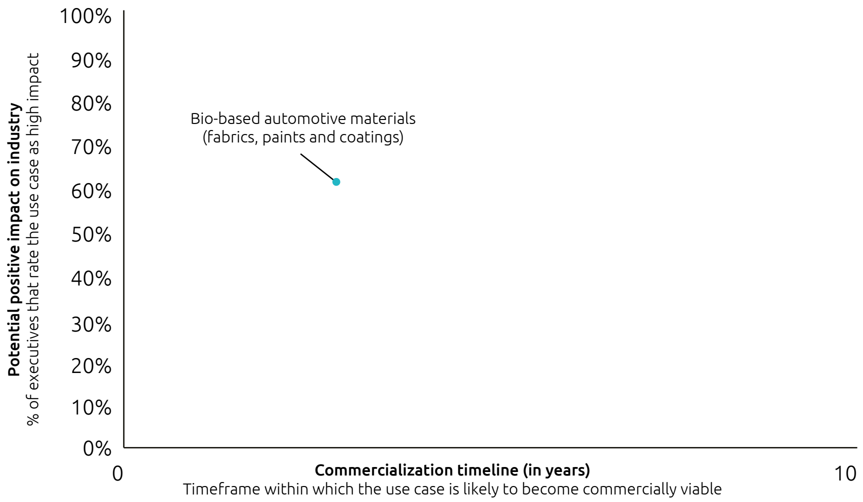
*Commercialization timelines are based on the assessment of surveyed executives and Capgemini experts.
Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=120 corporate organizations from the energy industry.

Aerospace and defense



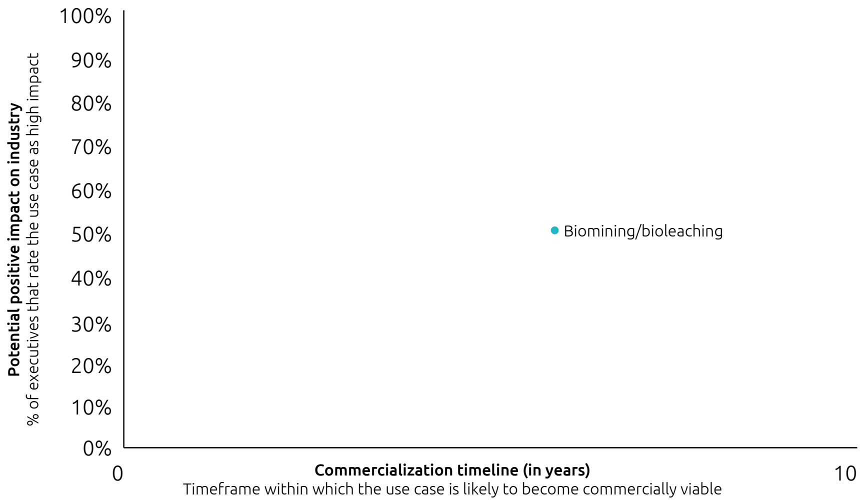
*Commercialization timelines are based on the assessment of surveyed executives and Capgemini experts.
Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=50 corporate organizations from the aerospace and defense industry.

Automotive



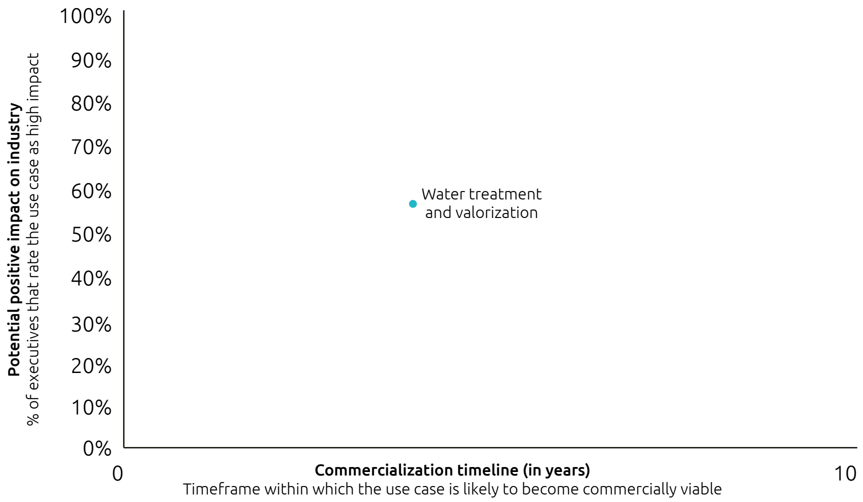
*Commercialization timelines are based on the assessment of surveyed executives and Capgemini experts.
Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=50 corporate organizations from the automotive industry.

Mining



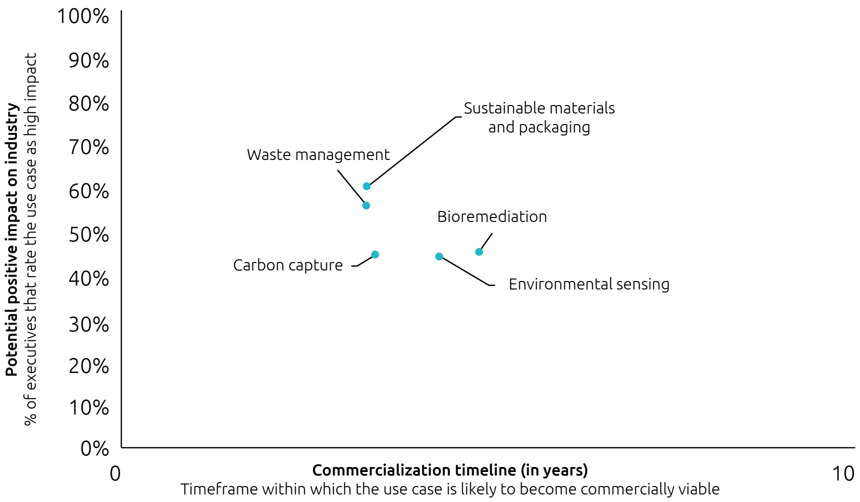
*Commercialization timelines are based on the assessment of surveyed executives and Capgemini experts.
Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=70 corporate organizations from the mining industry.

Water utilities



*Commercialization timelines are based on the assessment of surveyed executives and Capgemini experts.
Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=50 corporate organizations from the water utilities industry.

Environmental use cases (common across industries)



*Commercialization timelines are based on the assessment of surveyed executives and Capgemini experts.
Source: Capgemini Research Institute, Engineering biology survey, April–May 2024, N=1,100 corporate organizations.

Industry-wise list of biosolutions (engineering biology use cases)

Life sciences

- Drug discovery and development (engineering of new molecules for pharmaceutical production, improving efficacy, development cost, and outcomes)
- Cell and gene therapy (modification of genes and genetic pathways in carrier cells of a patient, to change the cell's function to address a variety of genetic disorders)
- Vaccine development (engineered microbes to rapidly and efficiently produce vaccines, design novel vaccine candidates and streamline their production)
- Regenerative medicine and tissue engineering (creating artificial tissues and organs by engineering cells to perform specific functions has the potential to address organ shortages for transplantation)
- Personalized medicine (engineering cells, proteins or microbes to create tailored treatments and therapies that are specifically based on an individual's genetic makeup)
- Diagnostics and detection (engineered biological systems designed to detect specific molecules or pathogens in complex samples, leading to the development of advanced diagnostic tools)
- Biosensors and monitoring (engineered biological systems designed to perform real-time monitoring of physiological parameters and detection of specific molecules in the body for disease management and health monitoring)
- Biomanufacturing (engineering organisms for large-scale production of essential chemicals and products for the pharmaceutical industry)

Chemicals and materials

- Bio-acrylic (using bioengineered approaches to produce bio-based acrylic to be subsequently used in paints, adhesives, diapers, detergents, etc.)
- Bio-based adipic acid or related (using bioengineered approaches to produce adipic acid – a chemical intermediate used in nylon production)
- Biocatalysts (using bioengineered approaches to produce enzymes used to synthesize chemicals at industrial level)
- Bio-solvents (using bioengineered approaches to produce solvents such as ethers, acetone, butanol, ethanol, propanol, etc.)
- Bio-surfactants (using bioengineered approaches to produce surfactants to be used in detergents, dyes, etc.)
- Bio-lubricants (using bioengineered approaches to produce lubricants)
- Lactic acid or related
- Succinic acid or related
- Bioplastics (e.g., PLAs, PHAs)
- Bio-based synthetic rubber

Agriculture

- Nutritionally enriched crops (genetically engineering crops to enhance their nutritional content such as increased concentration of vitamins, minerals or protein)
- Disease and pest resistant crops (genetically engineering crops for disease and pest resistance, reducing the need for chemical crop protection products)
- Climate resilient crops (genetically engineering crops to better withstand climatic stresses such as drought, heat, and salinity)
- Biofertilizers (products containing engineered microorganisms such as nitrogen-fixing bacteria that enhance soil fertility, reducing the need for chemical fertilizers)
- Biopesticides/biological control agents (engineering microbes to produce compounds with the ability to combat plant pathogens and pests)
- Phytoremediation (engineering plants to remove pollutants such as heavy metals, pesticides, and industrial chemicals in soil, water, or air, in agricultural environments)
- Carbon sequestration (genetically engineering crops to capture and store carbon dioxide)
- Engineering nitrogen fixation in cereal crops (genetically engineering cereal crops to replicate legumes in nitrogen fixation, to increase crop yield and reduce reliance on chemical fertilizers)
- Enhanced animal feed (engineering microorganisms to produce high-value nutrients for use in animal feed)

Food and beverages

- Plant-based meat (meat substitutes made from plant proteins)
- Cultured meat/lab-grown meat (meat produced from animal stem cells)
- Cell-based milk (milk produced from animal cells grown in a controlled environment outside of the animal's body)
- Animal-free dairy proteins (engineering microorganisms to produce dairy proteins such as casein and whey protein without the need for livestock)
- Nutritionally enhanced food/beverage/dairy products (engineering microorganisms to produce vitamins, minerals and other beneficial compounds to enhance the nutritional value of food/beverage/dairy products)
- Natural flavors and fragrances (genetically engineering microorganisms to synthesize aroma and flavor compounds, reducing the need for traditional extraction methods that can be resource intensive)
- Bio-based food additives (using microbial fermentation processes to produce food additives to reduce reliance on synthetic chemicals)
- Sustainably sourced ingredients (genetically engineering microorganisms to develop sustainable alternatives to ingredients – e.g., Omega-3 fatty acids produced using fermentation processes to prevent overfishing)
- Bio-preservation (designing microorganisms, enzymes or bioactive compounds to preserve food, inhibit spoilage and increase the shelf life of food products)

Personal and household care products

- Novel and high-performance ingredients in skincare, haircare, and cosmetics (enzymes, proteins, botanical extracts produced using engineering biology)
- Personalized skincare products (engineering cells, proteins or microbes to create products customized for specific skin types or conditions based on DNA analysis and microbiome testing)
- Sustainable cosmetic ingredients (using bioengineered approaches to produce sustainable bio-based alternatives to traditional ingredients sourced from plant, animal or petrochemical sources)
- Sustainable fragrances (engineering microorganisms to produce aroma compounds, reducing the need for traditional extraction methods that can be resource intensive)
- Novel and high-performance cleaning solutions (enzyme engineering for enhanced stain removal or odor control in detergents and cleaners)
- Environmentally friendly surfactants (bio-based surfactants for use in laundry detergents, dishwashing liquids and household cleaners for reduced environmental impact)

Fashion (clothing and footwear)

- Bio-fabricated textiles (engineering microorganisms to produce alternatives for fabrics such as nylon, silk and cotton – e.g., engineering microorganisms to produce proteins such as spider silk that can be spun into fibers to create sustainable silk)
- Sustainable dyes and pigments (engineering microorganisms to produce natural dyes and pigments, reducing the need for harmful synthetic dyes)
- Sustainable leather alternatives (engineering microorganisms to bio-synthesize collagen and other proteins that mimic the properties of animal-derived leather)

Energy (biofuels, oil and gas exploration/production/refining, solar energy)

- Precision fermentation for sustainable biofuel production (engineering microorganisms to enhance fermentation processes for the conversion of starch, sugar, or cellulosic feedstocks into ethanol)
- Algal biofuels (engineering algae strains for desirable traits such as high lipid content and rapid growth to enhance their use as a feedstock in the production of biodiesel)
- Biohydrogen production (engineering microbes to produce biohydrogen that can be used as a renewable energy source)
- Biogas production (engineering microbes to break down organic waste and produce biogas, a mixture of methane and carbon dioxide that can be used as a renewable energy source)
- Bioengineering techniques for oil refining
- Biological solar cells/bio-solar cells (designing biological systems – using photosynthetic microorganisms such as cyanobacteria and algae – that can capture and convert solar energy into usable forms, potentially leading to more efficient solar energy harvesting)
- Microbial electrosynthesis (engineering microorganisms for conversion of carbon dioxide and electricity into valuable chemicals, providing a way to store excess renewable energy in the form of chemical compounds)

Aerospace and defense

- Sustainable aviation fuel (SAF) (engineering microorganisms to produce aviation fuels more efficiently and sustainably)
- Biological defense (developing strategies and countermeasures against biological threats – e.g., rapid pathogen detection using engineered biosensors, development of vaccines and drugs to protect military personnel from biothreats)
- Bio-cybersecurity (e.g., engineering microorganisms to recognize specific biological markers for authentication purposes, or to develop biological encryption methods)
- Biosolutions for space exploration (e.g., biomanufacturing of essential materials and resources in space)

Automotive

- Bio-based materials such as bioplastics and leather-alternatives for interiors (seats and flooring)
- Bio-based paints and coatings
- Bio-based alternatives for battery materials

Mining

- Biomining/bioleaching (use of engineered microorganisms to extract metals from ores as an environmentally friendly alternative to conventional mining methods, avoiding harsh chemicals and high energy consumption)

Water utilities

- Wastewater treatment (use of engineered microorganisms for wastewater treatment)
- Bio-filtration (use of engineered microorganisms or biomaterials to improve water filtration efficiency and improve water quality)

Environmental use cases (common across industries)

- Carbon capture (designing microorganisms that capture atmospheric CO_2, transforming it into valuable items such as chemicals or biofuels, offering a way to counterbalance carbon emissions)
- Environmental sensing (tailoring microbes to act as biosensors, detecting pollutants or temperature shifts, providing timely data essential for climate oversight)
- Bioremediation (designing microbes that detoxify pollutants such as metals or pesticides, aiding in the restoration of polluted ecosystems)
- Waste management (designing microbes to decompose organic wastes from various sources, promoting improved waste practices and yielding beneficial by-products)
- Sustainable materials (designing organisms to create sustainable and biodegradable alternatives to materials such as plastics, textiles and construction materials, to reduce the environmental impact of traditional manufacturing)
- Sustainable packaging (designing organisms to produce environmentally-friendly packaging, lessening waste's environmental impact in retail)

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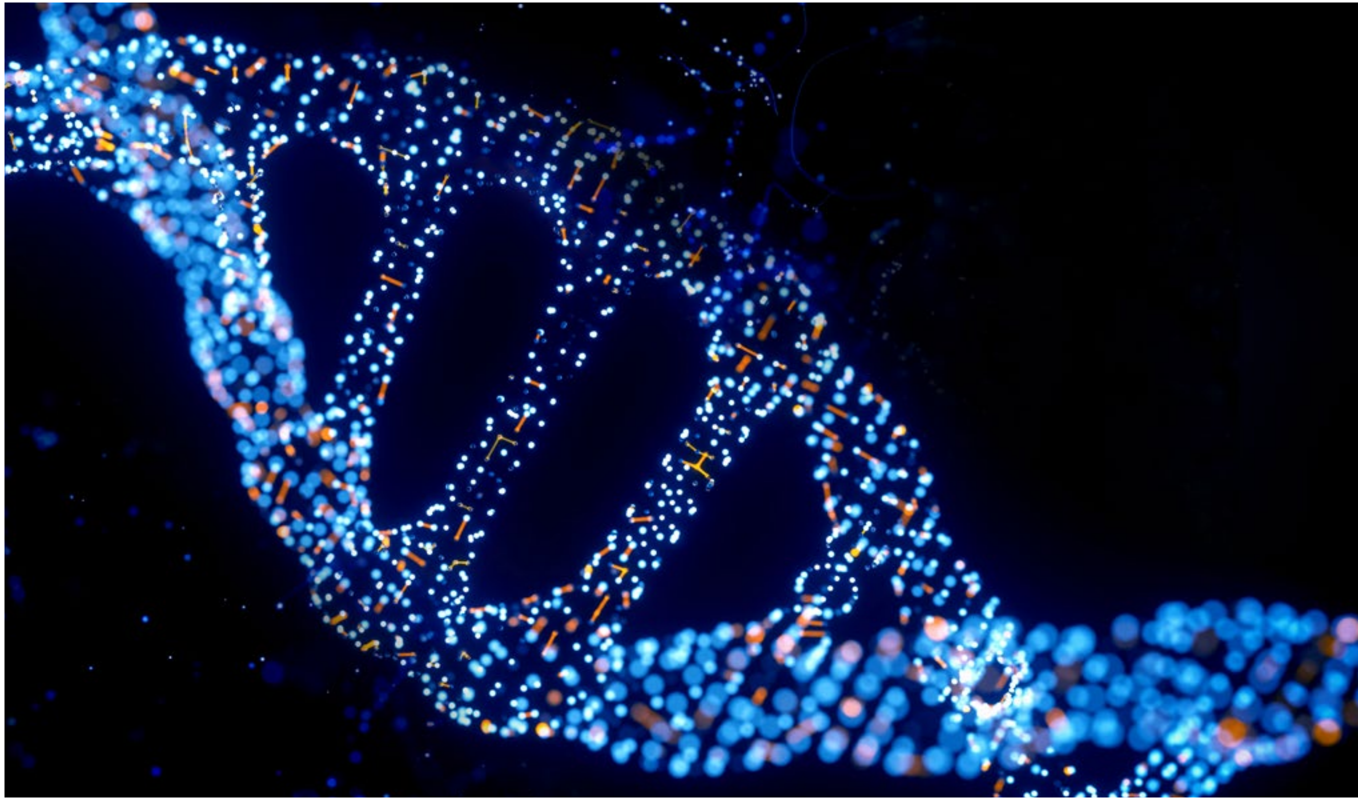

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The key contributors would like to thank Karan Dhingra and Amrita from the Capgemini Research Institute for their contribution to the report.

The key contributors would also like to thank Chris Price, Niall Hunt, Ian Taylor, Frances Metcalfe, Chris Roberts, Sajith Wimalaratne, Will Addison, Catherine Joce, Christopher Yates, Sally Epstein, Joseph Corrigan, Pascal Brier, Julien Van Velzen, Etienne Grass, Sebastien Neyme, Laura de Oliviera, Kary Bheemaiah, Ivana Knyght, Barnabé Lecouteux, Martine Stillman, Thorsten Rall, Sam Genway, Dorothea Pohlmann, Frederic Burger, Patrick Chareyre, Manuel Joaquim Garrido, Noemie Lauer, Liza Garay de Vaubernier, Sriya Mohanti, José Maria Baus, Ashwin Kumar Premkumar, Vincent Charpiot, Marie Neige Couriaut, Jean-Baptiste Pichon, Ophélie Petit, James Forrest, Peter King, Jeff Larsen, Vivek Sandell, Oliver Lofink, Lindsey Mazza, Emmanuel Fontaneau, Bragadesh Damodaran, Emmanuel Lochon, Gert-Jan Schoppert, Mollie Mellows, Aparajita Paul, Suparna Banerjee, Vibha Palekar, Jaydeep Neogi and Mithun Dutta for their contribution to the report.

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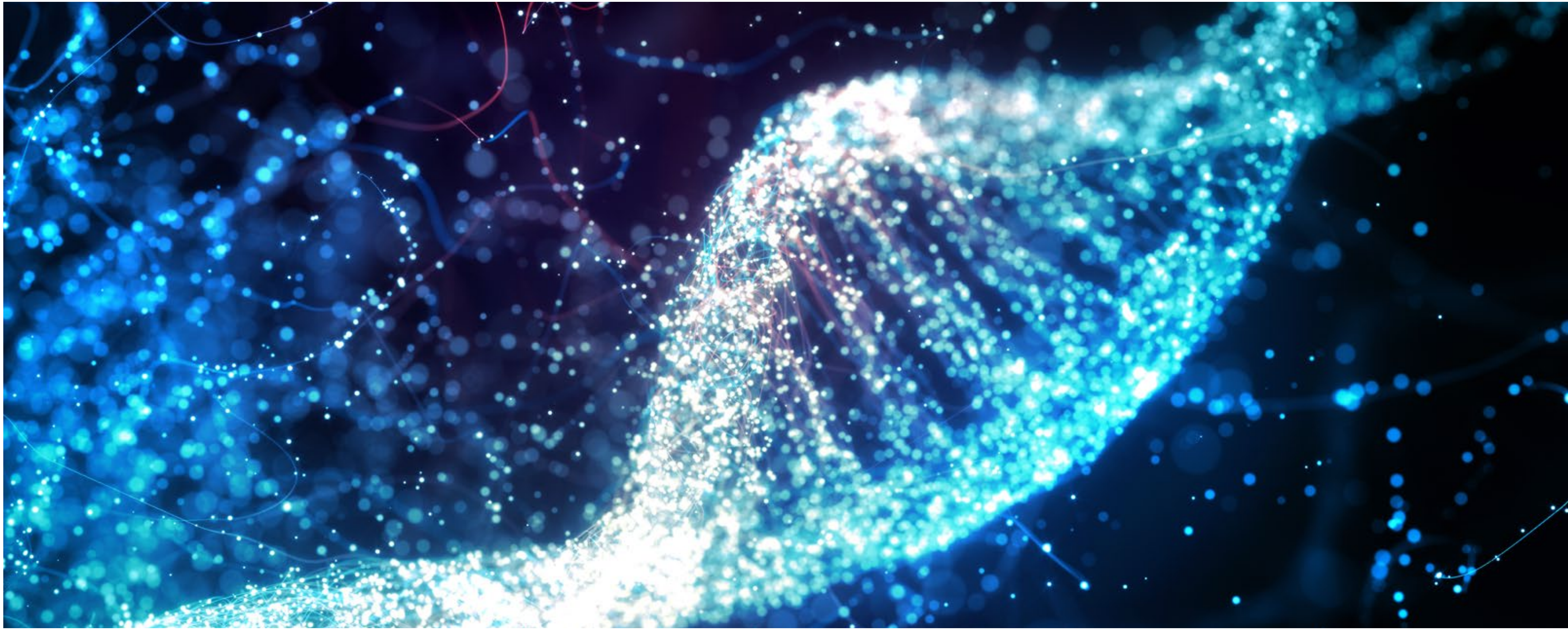

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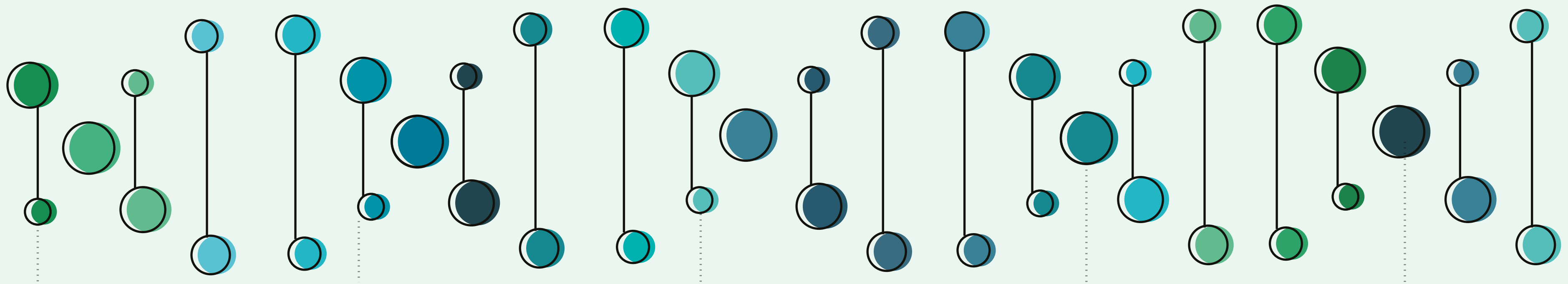

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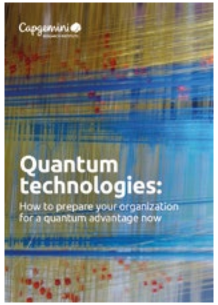

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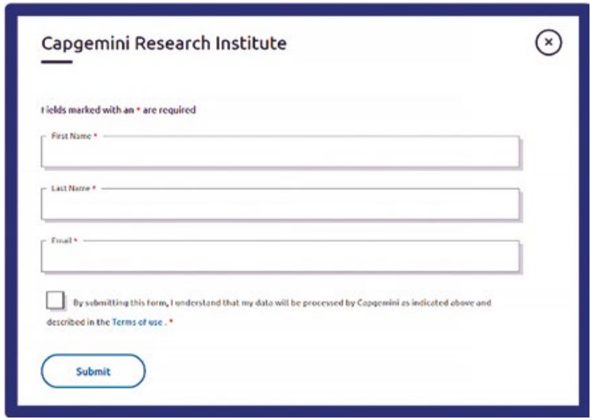

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Capgemini is a global business and technology transformation partner, helping organizations to accelerate their dual transition to a digital and sustainable world, while creating tangible impact for enterprises and society. It is a responsible and diverse group of 340,000 team members in more than 50 countries. With its strong over 55-year heritage, Capgemini is trusted by its clients to unlock the value of technology to address the entire breadth of their business needs. It delivers end-to-end services and solutions leveraging strengths from strategy and design to engineering, all fueled by its market leading capabilities in AI, cloud and data, combined with its deep industry expertise and partner ecosystem. The Group reported 2023 global revenues of €22.5 billion.

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