Centre for the Fourth Industrial Revolution
In collaboration with Capgemini

WORLD ECONOMIC FORUM

Accelerating the tech-driven bioeconomy

INSIGHT REPORT

JUNE 2024

Images: 1-Pact Edition, Getty Images

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Foreword

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Significant segments of the economy are being transformed by the convergence of physical, digital and biological worlds, accelerated by an avalanche of new technologies. Driven by generative biology, the impacts of these innovations extend well beyond a single industry or application area: healthcare, clean water, energy, chemicals, agriculture and consumer goods represent some of the areas where biology will increasingly deliver commercial impact. As much as 60% of the physical inputs to the global economy could, in principle, be produced biologically.[1] The technology-driven bioeconomy promises to enhance human health and prosperity, and restore ecological balance.

Due to the programmable nature of our genetic code, bio-solutions provide a unique opportunity for customization across these areas (think cancer treatments that have been genetically optimized for the individual patient), as well as the generation of products with properties and performance never seen before. An array of bio-solutions are already on the market today, providing life-saving cures and driving decarbonization in transport, agriculture and food, manufacturing and other sectors. Given the significant potential to deliver better outcomes for people and the planet, now is the time to unleash the true power of bio-solutions. As enabling technological advances continue to evolve and extend the reach of generative biology, the stage is set to accelerate the tech-driven bioeconomy and maximize its commercial impact.

The bioeconomy is here. A variety of scaled bio-solutions have been commercially deployed for decades. The broader US bioeconomy, more specifically, is estimated to have been around $1 trillion in size in 2022. By the end of the decade, synthetic biology is projected to contribute extensively across nearly $30 trillion of global manufacturing industry value, accounting for a third of global output.[2] The impact will be pervasive, with recent projections suggesting that every bio-based job supports 1.4 additional jobs in other sectors of the economy.[3]

Despite the progress and the potential, successfully scaled solutions remain the exception, with bio-based products and services having significant headroom to expand across a broader range of commercial markets. Put another way, much ground remains to be covered before bio-based solutions deliver on their full potential.

While challenges impeding bio-based progress have been the focus of many efforts and coalitions in the past, at no time has the bioeconomy been positioned quite as it is now: as a critical and increasingly capable enabler of a future that puts people and the planet first. Given the humanitarian and planetary challenges of today, the need to take action and capitalize on this opportunity is urgent.

However, such monumental change will not be delivered instantaneously. The bioeconomy must increasingly present a commercially viable and sustainable alternative to current fossil dependencies across all facets of the economy. Adding to the challenge, big banks provided over $0.7 trillion in fossil fuel financing in 2023.[4] Meaningful change will require political reforms combined with investment in infrastructure to ignite such a shift.

The Bioeconomy Initiative of the World Economic Forum and Capgemini is pioneering a global coalition that unites the government, academia, industry leaders and civil society organizations towards a single aim: to advance a scaled bioeconomy that improves health, prosperity and ecological balance. The initiative is built around three core objectives: increased adoption through increasing demand, enhanced awareness to prompt change, and a responsible transition to bio-based solutions.

As businesses, government and society mobilize in this rapidly evolving area, the insights generated by the Bioeconomy Initiative offer valuable direction for the equitable advancement, adoption and regulation of biotechnological innovations. Leaders, innovators and policy-makers are invited to sculpt a future driven by the bioeconomy that champions putting human health and the planet first while safeguarding them for generations to come.

Executive summary

The tech-driven bioeconomy is here, and it is poised to tackle not just one but many of humanity's greatest challenges through the convergence of underpinning technologies that will realize increasingly impactful bio-solutions.

The world is positioned better than ever before to accelerate the global transition to a bio-based economy. Digital advances have expanded the areas where biology can deliver impact, as generative biology is set to disrupt several industries. Capturing increasing quantities of carbon, tackling previously incurable diseases, delivering clean water, sustainably feeding a growing population, remediating environmental damage and reducing carbon emissions represent just a few areas for bio-innovation. The tech-driven bioeconomy is here, and it is poised to tackle not just one but many of humanity's greatest challenges through the convergence of underpinning technologies that will realize increasingly impactful bio-solutions.

The bioeconomy provides a unique opportunity where the physical, digital and biological worlds converge. Coupled with the ever-evolving capacity to read, write, edit and increasingly functionalize deoxyribonucleic acid (DNA), the tech-enabled bioeconomy promises foundational improvements in everyday life. Given the significant human and planetary potential of leveraging biology to overhaul commercial value chains, why haven't markets experienced a mass transition to bio-based approaches? Despite decades of considerable investment, technological progress and significant market projections, the global transition to a bio-based economy has yet to enter the commercial mainstream.

Before such a future can be achieved, significant obstacles must be overcome. Challenge areas range from historically poor public perception to barriers rooted in the cost-effective scaling of the technology itself. Since many bio-based solutions have not yet achieved price parity with conventional alternatives, both adoption and subsequent demand present persistent and at times insurmountable challenges.

Business and market factors also pose challenges as strategies and models fail to capture the unique value inherent in bio-based solutions. And in some regions, a lack of regulatory clarity comprises another significant impediment: many regulatory practices have not kept pace with the rapidly advancing technology to support efficient commercialization. Consequently, groundbreaking technologies frequently remain confined to the laboratory, unable to deliver innovative outcomes where they are most needed.

Given the potential reach of the tech-enabled bioeconomy, a single question remains: **how can these challenges be overcome to accelerate the transition to a commercial bioeconomy?**

To catalyse action, the Centre for the Fourth Industrial Revolution at the World Economic Forum has kick-started a global coalition rooted in public-private partnership. By focusing on increasing adoption, raising awareness and promoting a responsible transition, the coalition aims to prompt the entry of the bioeconomy into the commercial mainstream by establishing a global, multi-year initiative. Working together, leaders from government, business, academia, research organizations and civil society are striving towards a future where prioritizing the planet and its inhabitants will lead to a growing embrace of biological engineering as a key commercial technology. This report presents their shared view of the technology-driven bioeconomy, spotlights impactful examples and explores how wide-scale adoption will play out differently based on regional contexts and priorities.

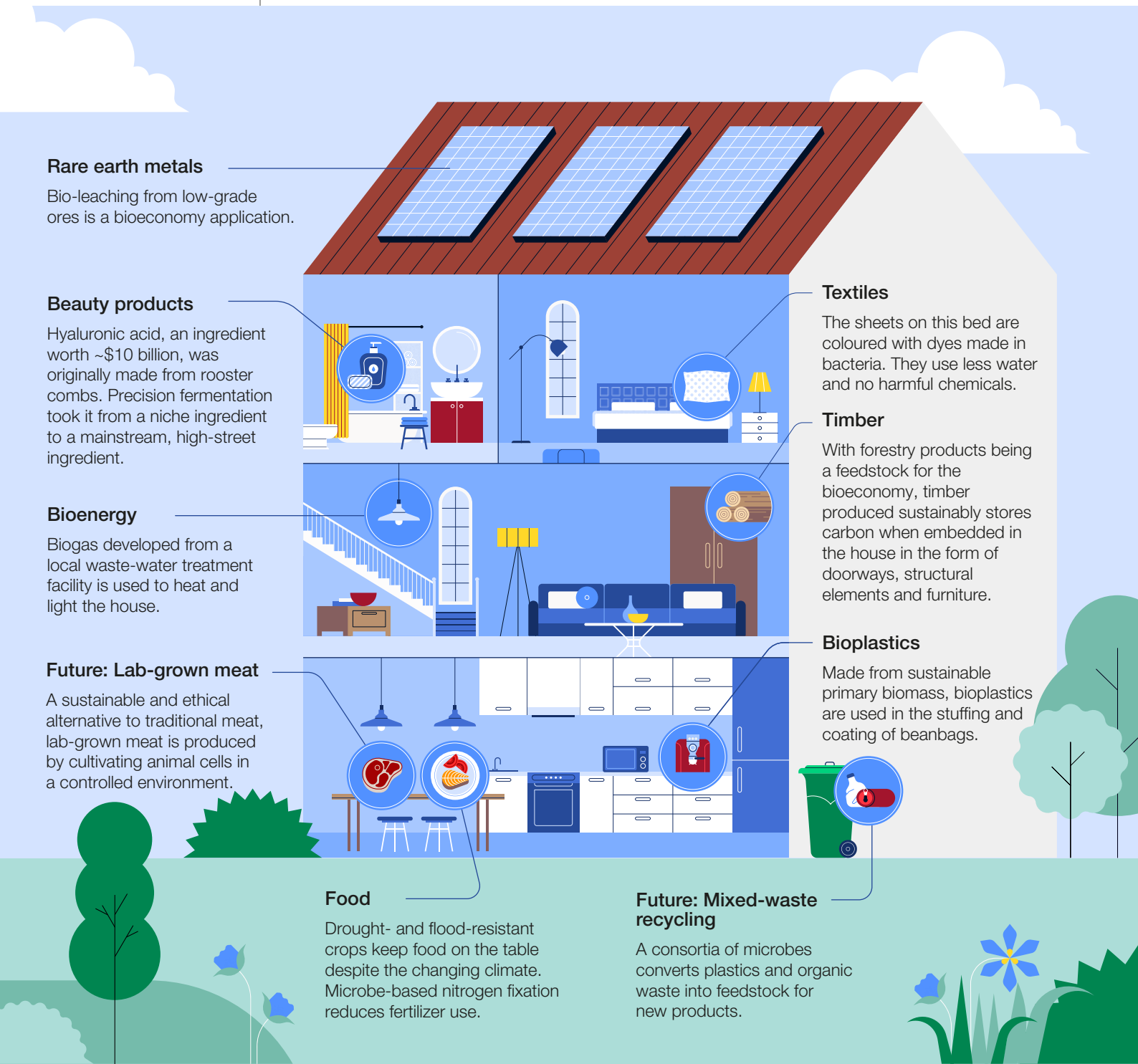
1 Introduction

Why accelerating the bio-based transformation matters

Unbeknown to many, the bioeconomy is becoming a fundamental part of everyday life (Figure 1), with significant potential to create a thriving economy that functions within planetary means. Bio-based solutions (or bio-solutions) offer sustainable pathways to common goods and materials. Bio-solutions have been reported to make use of less water, less energy and fewer harmful chemicals, while also lowering the dependence on fossil inputs.

Furthermore, due to the programmable nature of the genetic code, bio-solutions provide an opportunity for personalization – such as cancer treatments that have been genetically optimized for individual patients – as well as the generation of entirely novel products with properties never seen before.

FIGURE 1 **Examples where the bioeconomy touches daily lives**



While this may sound futuristic, bio-solutions are already delivering impactful outcomes and laying the groundwork for a fully realized bioeconomy. For instance, companies are already engineering biology to turn carbon dioxide (CO_2) and waste materials into valuable products, create new vaccines, reduce the presence of harmful chemicals in the environment, and much, much more.

Bio-solutions are gaining traction as viable commercial alternatives, with projections indicating that broader bioeconomy innovations will experience a step-change in impact thanks to generative biology.[5] For instance, hyaluronic acid (HA), a $10 billion skincare ingredient which was originally derived from animal sources, is now produced commercially through fermentation; furthermore, innovation around new forms of HA are improving product functionality. Recent breakthroughs in HA bioprocessing are reported to show a 91% reduction in environmental impact.[6]

The personal care and beauty industry is realizing the value of bio-based products firsthand; L'Oreal, for instance, aims to produce 95% of its ingredients from bio-based sources, derived from abundant minerals or from circular processes, by 2030.[7]

Considering their $260 billion dollar market cap, this presents tens of billions in value for the tech-driven bioeconomy.[8] As more sectors and companies tap the potential value of bio-solutions, the tech-driven bioeconomy is set to deliver innovative and sustainable commercial alternatives to a range of products.

Since bio-based solutions are "programmable", they are opening the floodgates for never-before, unique and customizable capabilities. In contrast to incumbent products and processes, the tech-driven bioeconomy provides increasingly viable alternatives that operate within the planetary boundaries while delivering improved performance. Multiple enabling factors are now coalescing to advance the tech-driven bioeconomy, signalling a promising future with rapidly expanding possibilities to impact innovation-ready industries.

But owing to lengthy timelines and high costs, the tech-driven bioeconomy claims only a small fraction of commercial activities today. To unlock its potential at scale and expedite the transition to a more customizable and climate-neutral economy, bio-based alternatives must move into the mainstream at an increasingly faster rate.

The time is right

Powerful synergies arise when disparate disciplines bring together advanced capabilities and new ways of thinking, delivering fresh perspectives and innovations (see Figure 2). The tech-enabled bioeconomy is benefiting from recent breakthroughs in game-changing technological convergences and advances. Such advances are translating into more efficient scaling owing to increased predictive power over the biological variables that define commercial outcomes. Technology convergence is a key characteristic of the fourth (and preceding) industrial revolution(s), and the bioeconomy provides a unique opportunity where the physical, digital and biological worlds meet.[9]

The capacity to read, write, edit and functionalize DNA has drastically accelerated while the costs associated with these technologies continue to fall.[10] Meanwhile, the evolution of factors across digital technologies – such as the advancement of generative artificial intelligence (GenAI) algorithms, expanding compute capabilities and explosion of training data – is fundamentally disrupting the speed and cost of bioengineering practices. Because DNA and protein (amino acids) sequences are linear, much like text, foundational large language models (LLMs, widely recognized for their application to text), are now being applied to efficiently recognize patterns across the vast landscape of protein and genome sequences and corresponding functional data. Indeed, the patent growth in LLMs applied to biology is higher than the growth for biotech patents as a whole.[11]

Such convergence across the digital and physical realms is transforming the entire value chain for a wide range of applications (Figure 2). For instance, data analytics and AI are collapsing design and test timelines to provide solutions with reduced costs and timescales. Enhanced predictive powers, digital twins, as well as advanced monitoring and control will streamline business decision-making and engineering scale-up. These and other advances will support the build-out of resilient supply chains in the face of increasing volatility due to climate change and geopolitics.

Beyond technological advances, the bioeconomy is reaching the pages of government strategies, and is being recognized for the positive impacts on countries' economies and people's well-being. It is garnering significant funding too – US President Joe Biden signed an executive order to accelerate development of the bioeconomy ($2 billion investment),[12] while China is known to have invested $3.8 billion between 2008-2020.[13]

Venture funding has also attracted significant interest, with a 10-fold increase in early-stage venture funding since 2019, reaching more than $6 billion in 2023 for early-stage companies, as against $12 billion in total venture funding.[14]

A final factor is the sustainability imperative. The core pillars of the net-zero transition are often seen as electrification and renewable energy, but everyday physical goods are also ripe for decarbonization. Bio-solutions can play a key role in this.

Focused action

The synergy across ecosystem factors and substantial technological advancements creates perfect conditions for an economic transformation rooted in biology. Despite the potential, formidable challenges prevent the bioeconomy from entering the commercial mainstream. Uncertainty around commercial readiness and global adoption, the weight of expectations about responsible use and deployment, and a complicated history of public perception comprise some of the more significant barriers. And while such challenges are not new or unique to the bioeconomy, recent digital advances are providing both renewed optimism and an enhanced toolset to address these.

Yet, no single solution can definitively propel bio-solutions into the commercial mainstream – it will take concerted effort on many fronts. Through a multistakeholder approach, the Forum seeks to deliver impact across three complimentary objectives: raising awareness among senior decision-makers and the general public, driving adoption and servicing subsequent demand, and fostering a responsible transition to bio-based products. To effectively devise catalytic actions that can unlock the full potential of the bioeconomy, a comprehensive understanding of the current state of the bioeconomy is beneficial.

FIGURE 2 **Converging trends that will accelerate the bioeconomy**

Evolution of AI techniques

200% growth in LLM patents per year in 10 years – plus copyright, trade secrets and open-source growth

Advances in synthetic biology tools and availability

Synthetic biology has higher CAGR[1] (23%) than electric vehicles

Increased investment

10x early-stage venture funding, >$12 billion invested in 2023

Increased government attention

Multi-billion-dollar funding

Initial ecosystem

Bio-foundries, consulting and contract R&D organizations, research hubs

Sustainability imperatives

60% of physical inputs to the global economy

[1] Compound annual growth rate

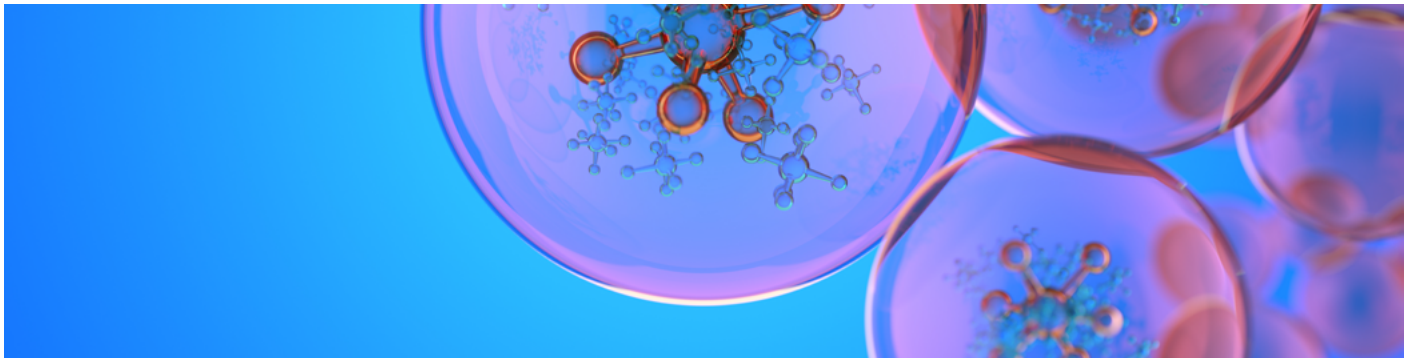
Sources: Various[15]

2 The bioeconomy is already here

The global bioeconomy requires stakeholder alignment to capitalize on the strong foundation for growth.

Depending on the specific region and broader context, various stakeholders comprehend the bioeconomy differently. For this report, bioeconomy is defined as: **"The production, trade, distribution, management and consumption of goods, processes, tools and services that arise from biological resources or biological transformation."**

To enter the commercial mainstream, the promise of the bioeconomy must expand beyond a core group of specialists via a consistent, clear and compelling narrative to portray not only what is at stake, but also how bio-based products are uniquely poised to create a better future for people and the planet. This report presents a shared view of the technology-driven bioeconomy, spotlights impactful examples and explores how wide-scale adoption will play out differently based on regional contexts and priorities.



2.1 The technology-driven bioeconomy

The future of the bioeconomy will be shaped by a core set of convergent, technology-driven approaches.

The bioeconomy is an incredibly diverse and evolving space. Understanding what bio-solutions look like to different industries and stakeholders across the whole bioeconomy is a complex exercise.

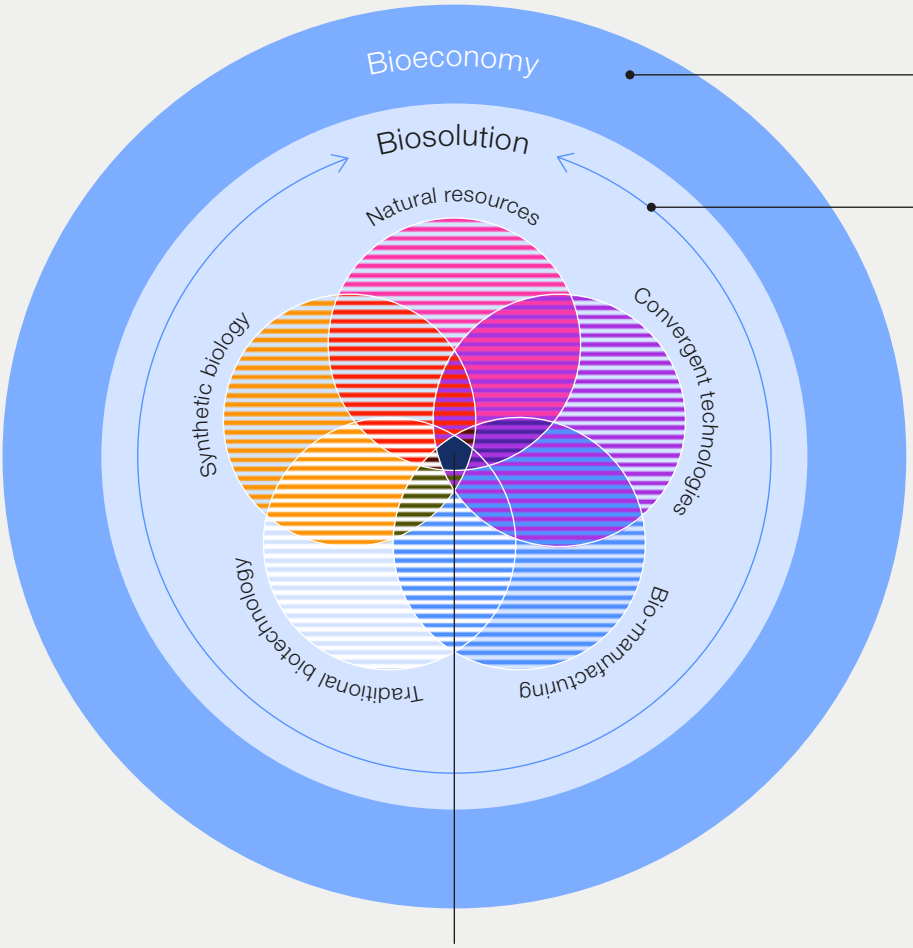
How can stakeholders align on a shared view of the bioeconomy to catalyse its mainstreaming?

The bioeconomy's most significant opportunity for improving human health, well-being and sustainability arises at the intersection of biotechnology, synthetic biology, biomanufacturing and convergent technologies. As such, these elements serve as catalysts for achieving this goal and are therefore the core focus of the community.

Figure 3 outlines the core underpinning elements fundamental to delivering new and innovative bio-solutions at scale and speed. Different combinations of these underlying elements will address specific needs and practical applications with varying degrees of technological complexity (Figure 4). It is the increasing use and combination of technologies that will power the future bioeconomy.

The ability to deliver diverse and increasingly technology-driven bio-solutions depends on the capabilities and capacity of each of these elements, as well as the ability to effectively navigate their intersection by leveraging traditional industry strengths and investing in developing others.

The bioeconomy is enabled by a core set of resources, technologies and approaches that can deliver unique bio-solutions



Bioeconomy: The production, trade, distribution, management and consumption of goods, processes, tools and services that arise from biological resources or biological transformation

Biosolution: The products, services, processes and tools derived from the engineering of biological resources (synonymous with "bio-based solutions")

Natural resources: Natural resources and renewable biomass that can be leveraged as feedstock or vehicles for biotechnology processes

Convergent technologies: A multidisciplinary method that brings together biotech, engineering and computerized systems to address unresolved challenges (e.g. AI and sensing)

Bio-manufacturing: The application of biotechnology to biomanufacturing at scale

Traditional biotechnology: Technologies, tools and processes that leverage biology to generate products and services

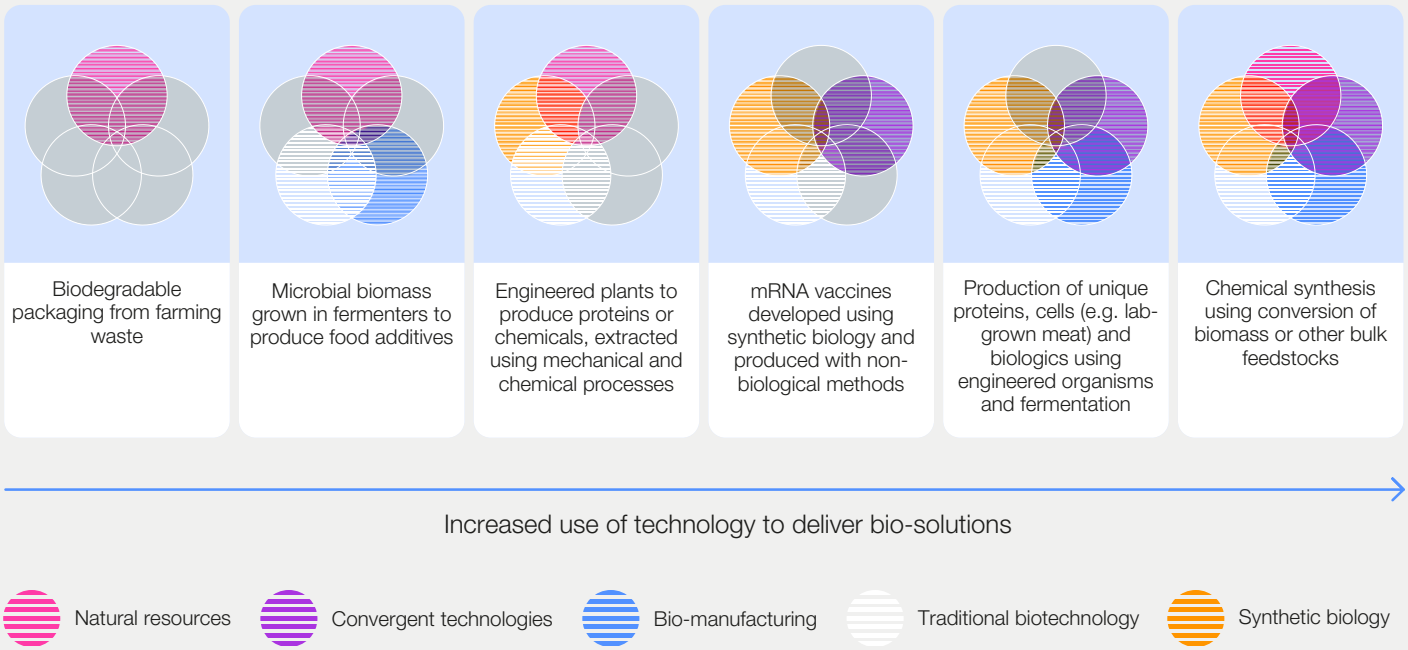
Synthetic biology: A field of science that involves redesigning organisms for useful purposes by engineering them to have new abilities

Note: Depending on varying definitions of the bioeconomy, the management of biodiversity and natural resources such as forestry and marine resources is sometimes considered part of the bioeconomy. This framework allows for that; however, it is not the core focus for this initiative.

Source: World Economic Forum analysis

FIGURE 4 | **Variability of bio-solutions**

Bio-solutions vary considerably in the application of technology and level of complexity to deliver*



* Examples of bio-solutions not exhaustive

Source: World Economic Forum analysis

2.2 Converging technologies

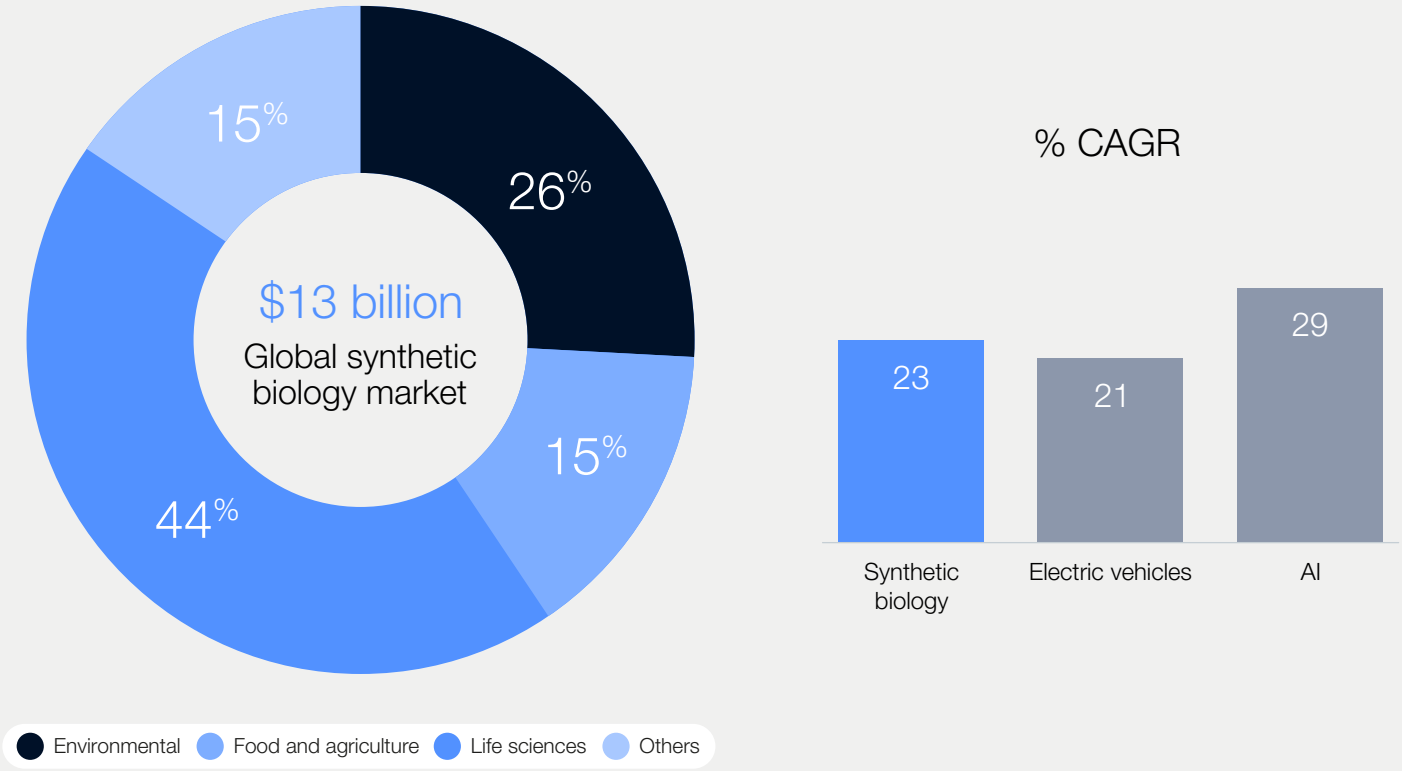
Converging technologies present growing opportunities to scale supply.

As a core enabling discipline of the tech-enabled bioeconomy, synthetic biology often serves as a proxy for industry applications and market size of the bioeconomy. Based on these proxies, a significant proportion of the synthetic biology market remains occupied by the life sciences/healthcare sector (Figure 5). For example, Novo Nordisk has experienced extraordinary growth to become the most valuable company in Europe.[16]

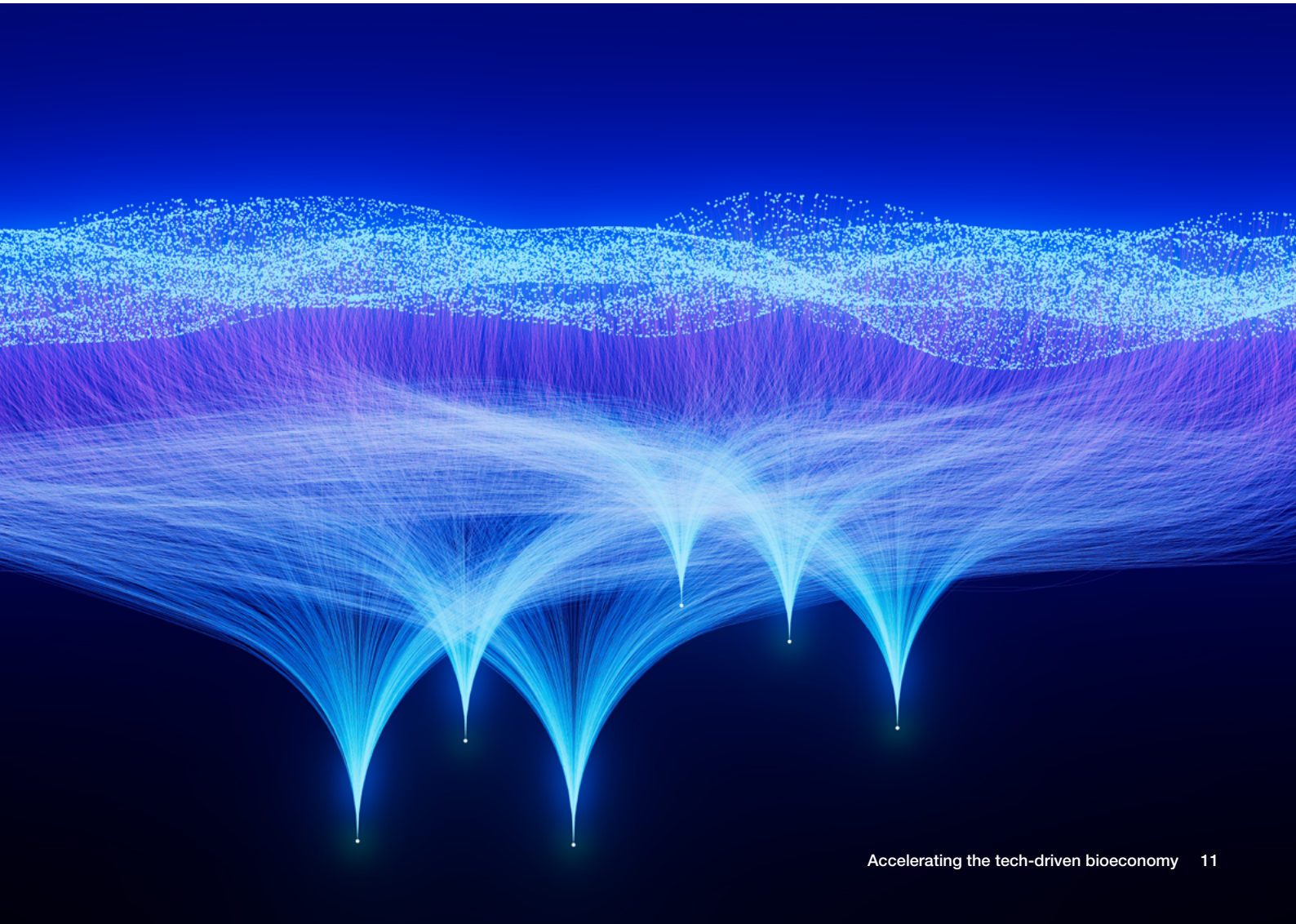
But with evolving technological convergences around bio-based innovations, the specific application areas targeted will increasingly flow towards other application areas. For instance, advances in AI will enable new bio-solutions to be simulated, scaled and reproduced – at reduced cost and in lesser time, and across a range of applications beyond healthcare. For example, biotech company dsm-firmenich is using AI to expand the range of available flavours and fragrances.

LLMs are increasingly being employed in protein and pathway engineering to shorten design and optimization cycles and "write" the desired biological functionalities more efficiently.[17] In the future, as LLMs and AI technologies improve (Figure 6), they will increasingly be leveraged to deliver bio-solutions at decreasing costs to achieve parity at or below those of incumbent solutions.

FIGURE 5 | **Synthetic biology growth** (projection for 2023-2030)

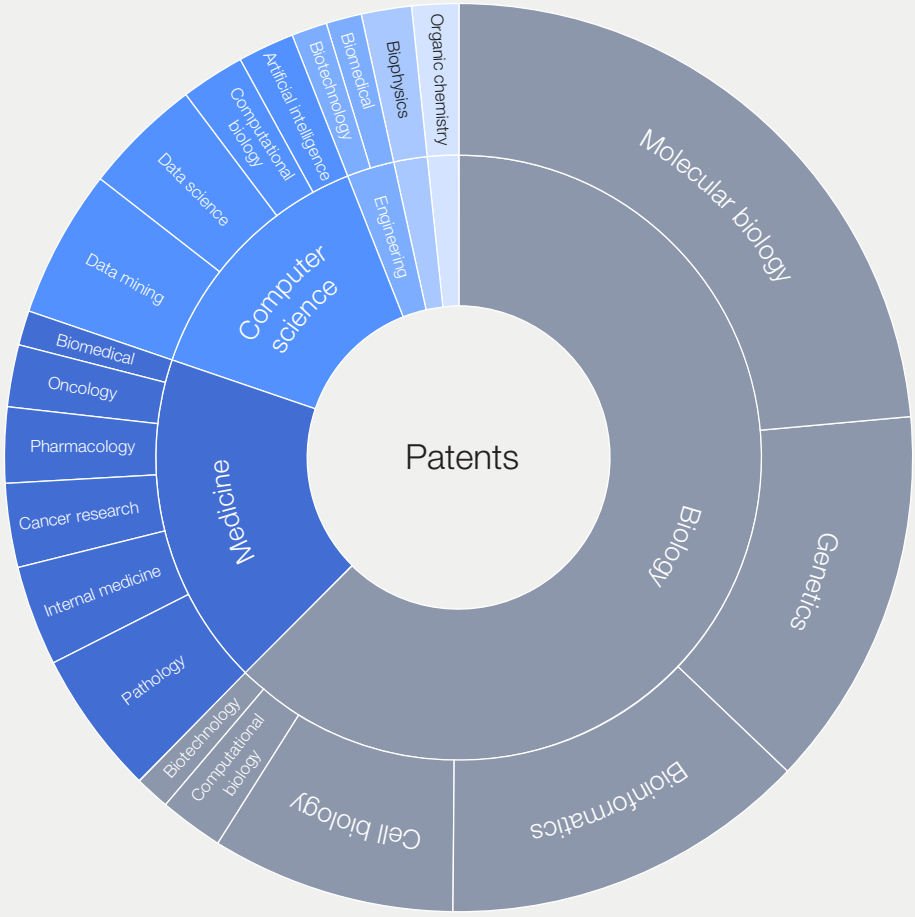


Source: Various[18]

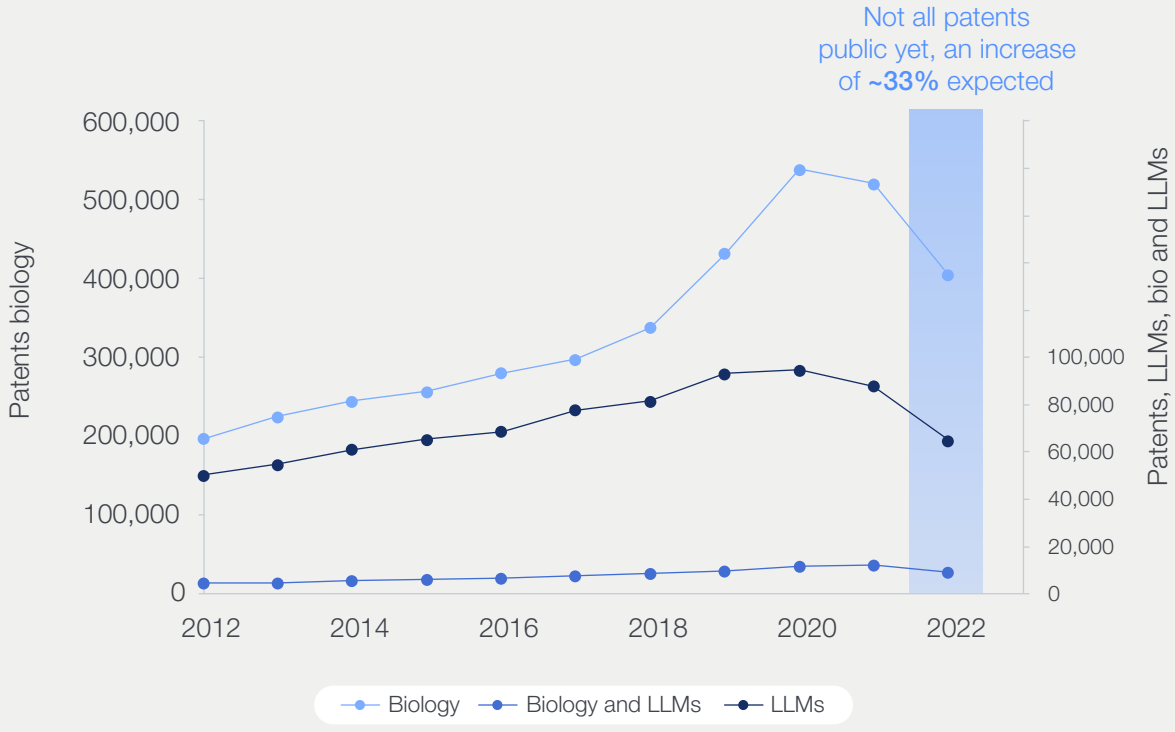


Use of AI in biotechnology is growing rapidly

Technology clustering of the intersection between AI and biotechnology patents



Biology and LLM patents over time



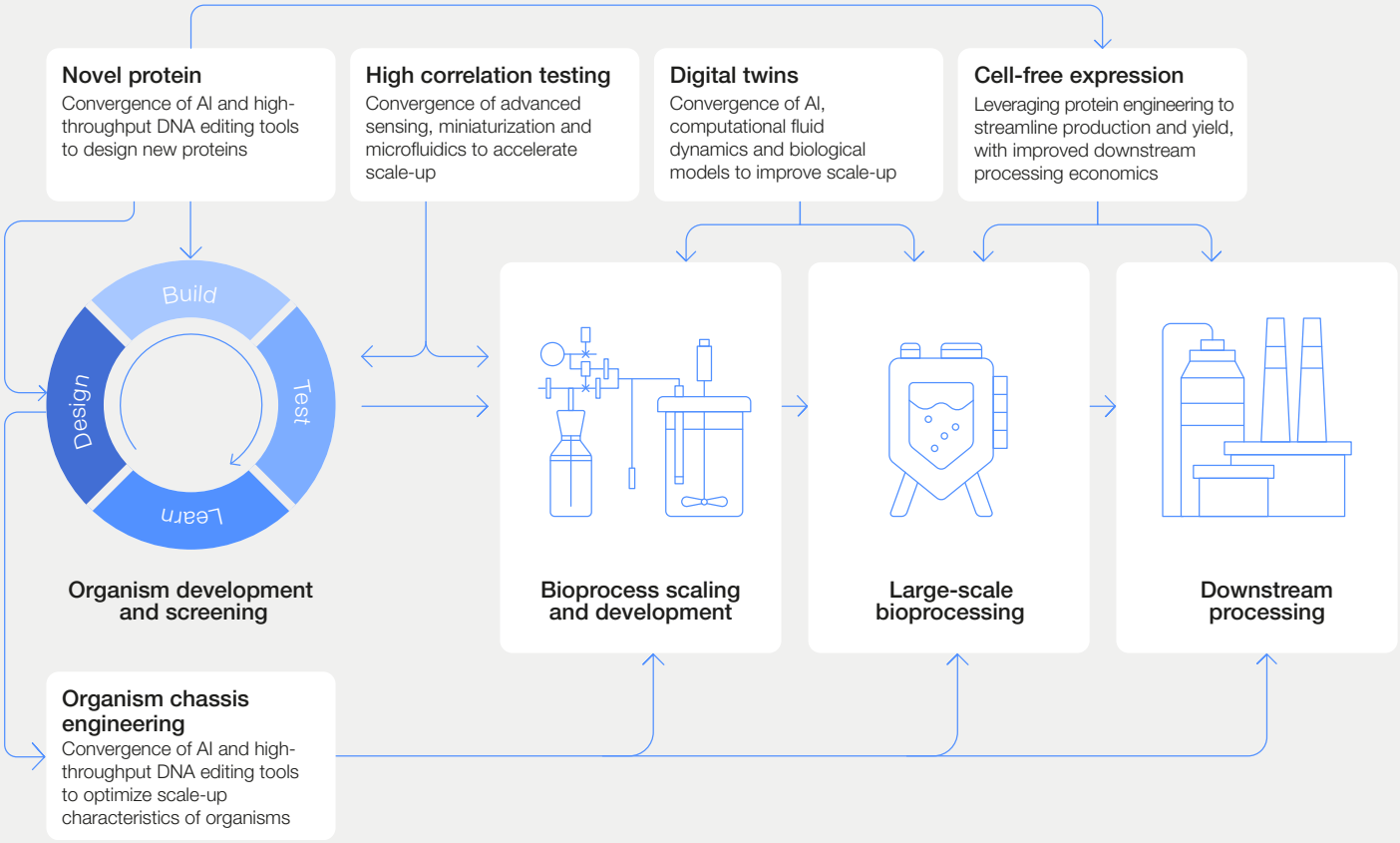
Note: During the past decade, the number of patents relating to AI has grown exponentially, and a growing number of patents reference biotechnology and AI. The pandemic caused disruption to innovation, and therefore patent filing, which would be seen in the data spanning 2020-2021.

Source: Forbes[19]

Despite advances in bio-convergent technologies, a fundamental gap persists in the understanding of how nature works; instrumentation that more accurately measures outputs, while simultaneously applying machine learning to analyse and "learn" from data as it is being generated, will go a long way in enhancing the ability to understand and more efficiently programme biology. For example, biosensors are being developed that can continuously measure compounds including feedstock compounds and toxic byproducts. The analysis of this information could enable better quality control of fermentation and enable continuous fermentation.

Advances in these areas will reduce the existing and inefficient "trial and error" process of programming and scaling biology and could make significant headway in interpreting the mounds of data collected amid the omics frenzy of prior decades. Figure 7 highlights several technologies that enable more accurate programming of biology through the design and scale-up process. Precision control (e.g. using robotics in laboratories to improve efficiency and reproducibility) and more accurate prediction tools will go a long way in developing biological processes "to spec" while also securing favourable financial returns and requisite regulatory approvals.

FIGURE 7 **Emerging biotechnology tools**



Source: Various[20]

2.3 Spotlight on the opportunity

The bioeconomy is poised to impact every aspect of daily life.

FIGURE 8 **Bioeconomy opportunities across industries**

The application areas are diverse and span many core technologies

Example use-cases per industry

Agriculture
Bio-pheromones to replace pesticides; bioengineered plants to improve yield

Beauty and personal care
Production of vegan collagen; production of hyaluronic acid

Biopharma and healthcare
RNA-based vaccines; biologics production; Car-T cell therapy; stem-cell therapy

Consumer goods
Biodegradable packaging materials production

Chemicals industry
Production of fine and specialty chemicals using fermentation; bulk chemical production from waste

Fashion and textiles
Production of textile dyes; production of spider silk using engineered silkworms

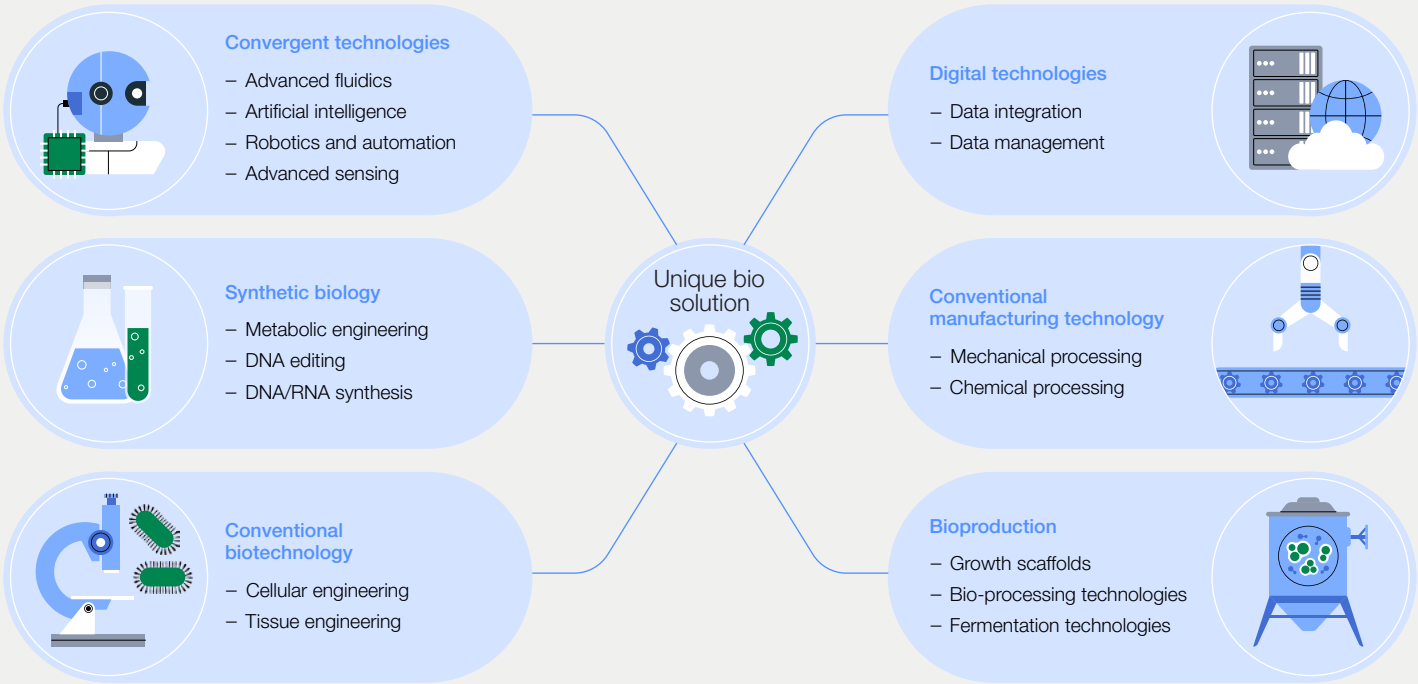
Food and beverage
Alternative protein production; lab grown meat; functional beverages

Energy industry
Biofuel production from algae or carbon capture; biogas production

Mining
Bio-mining of electronic waste for rare metals; bioleaching; bioremediation

Waste management
Enzymatic plastic degradation; anaerobic digestion of waste-water to make biogas

Core enabling technologies



Source: World Economic Forum analysis

Bio-solutions are often associated with healthcare, life sciences and big pharma.[21] The impact of these technologies on the healthcare sector is enormous: for instance, synthetic mRNA vaccines saved nearly 20 million lives in their first year of use during the Covid-19 pandemic and gene therapy provided the first-ever approved treatment for the rare but devastating "butterfly skin disease".[22] The reach of the technology-driven bioeconomy extends well beyond the pharmaceutical industry alone; various sectors, industries and application areas are being reinvented by increasingly using biology as a core underlying technology (Figure 8).

For simplicity, the applications of the technology-driven bioeconomy are categorized as:

- **Red:** Relating to healthcare and medicine, also known as bio-pharmaceuticals.
- **White:** Relating to goods for industry including chemicals, plastics, food and energy carriers, also known as industrial biotechnology.
- **Green:** Relating to agricultural/plant processes and products that make use of biotechnology or life science inputs.

Because the underlying technology and tools are indistinguishable across the technology-driven bioeconomy, innovations from red biotechnology frequently flow into other areas and vice-versa. However, given the volumes and significant cost margins for resulting commercial products, innovations from red biotechnology are often adapted to suit white and green biotechnology applications.

In particular, products of white and green biotechnology are typically referred to as "commodities" (e.g. bulk chemicals) and garner a significantly lower price point per unit as compared to red biotech products (e.g. pharmaceutical drugs). This discrepancy places green and white biotech products and processes at a disadvantage, as they must achieve lower price points before justifying investment in applying "higher cost" innovations that were originally developed for red biotech.

Regardless of the application area, the technology-driven bioeconomy must further penetrate markets and deliver groundbreaking advances to transform industries and sectors.

The global bioeconomy in numbers

A significant part of the potential of the broader bioeconomy arises from the expanding breadth and diversity of bio-based applications that technology convergences are opening up. Beyond its capacity to transform industries and drive significant economic value and job creation, the bioeconomy also provides an increasingly important avenue for reducing carbon emissions and promoting sustainability across a variety of activities and applications (see Figure 9). The bioeconomy not only embodies the principles of the circular economy – reuse, repair and recycle, thereby reducing waste – but also allows the concomitant preservation and restoration of biodiversity.

Despite the potential, care should be taken: inefficient bio-based processes causing significant land-use changes could worsen environmental impact relative to incumbent processes. Utilizing secondary and tertiary feedstocks alongside efficiency optimization is key to reaping environmental benefits.

Biomass availability

Feedstocks represent a critical dependency for the bioproduction arm of the bioeconomy (they serve as the substrates to these processes). One general criticism of bioproduction is that crop biomass shifts agriculture away from food production to making energy and chemicals. In fact, whenever a bio-replacement requires a change in land use, the associated sustainability gains decrease significantly. However, it has been estimated that **30% of all US petroleum consumption could be replaced with bio-solutions (from crops, residues and municipal solid waste) without adversely affecting the environment or production of food.**[23]

By these estimates, current biomass availability will not completely enable a move away from petroleum products, but innovations in the ability to use waste and other feedstocks will allow for significant advances on this front.

Potential to create millions of jobs and reduce carbon emissions by up 70%

In 2023, the US bioeconomy supported nearly

644,000 jobs,

contributing significantly to the country's economic landscape. This sector added $210 billion to the US GDP and generated $49 billion in wages.

The bioeconomy will be a key driver of jobs within the green economy*

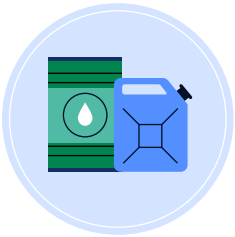
8%

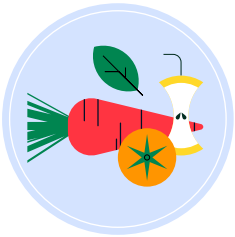
of the workforce in Europe is already employed in the bioeconomy, adding €614 billion ($661 billion) to the economy annually with the potential to create 1 million new green jobs by 2030. Meanwhile, the Indian bioeconomy provides jobs for 2 million people.

0.4-10

jobs created per 1,000 oven-dried-tonnes (ODT) of biomass feedstock, with variation by bio-solution type and value.

The bioeconomy will be a fundamental driver of the net-zero economy**





	Biofuels	Bioplastics	Biomass energy
Reduction excluding land-use changes	50-75%	0-50%	50-70%
Reduction including land-use changes	Up to 50%	Up to 30%	No data available

Notes: * The bioproduct-related job creation numbers illustrate the direct and indirect job opportunities created by bioproduct manufacturing. This encompasses the entire supply chain, from feedstock harvesting to processing to bioproduct manufacturing.

** Refers to global warming potential of bio-based products in comparison to fossil fuels.

Source: Various[24]

3 Catalysing the technology-driven bioeconomy

Acceleration requires coordinated action across a global, multistakeholder community.

This report has been curated using an array of valuable insights provided by the Bioeconomy Initiative Community – a global, multistakeholder community of government, academia, large companies, start-ups and civil society organizations. For more information on the community and the methodology for this report, please refer to the Appendix.

The community critically evaluated the challenges and underlying root causes impeding the acceleration of the tech-driven bioeconomy. All through these activities, a high degree of interdependency was identified across the core challenge areas. The combination of community prioritization, core team analysis and additional engagement with industry and government leaders revealed three critical levers that could provide catalytic impact in advancing the bioeconomy into the commercial mainstream:

1. **Driving demand**
2. **Servicing demand**
3. **Unblocking the system through regulation and policy**

In the sections below, each of the three solution areas is unpacked, highlighting the core challenges identified by the community and revealing potential areas where global cooperation could deliver better commercial outcomes for the tech-enabled bioeconomy.

3.1 Driving demand

If supply exceeds demand, investor, government and public confidence erodes.

Market success often involves a combination of technology push and market pull. For the bioeconomy, market pull often lags behind rapid technological advances (e.g. in synthetic biology and AI). Market pull brings urgency to investors, government and the public to effect change. The section below summarizes community perspectives on the challenges and key opportunities in driving demand.

Positioning bio-solutions as central to global challenges

Consumers underestimate the gains and overestimate the losses associated with new products. Positioning bio-solutions as central to tackling global challenges moves the needle.

A popular Harvard Business Review article[25] suggests a three-fold mismatch whereby consumers undervalue the benefits of a new product by three times and overvalue the benefits for an incumbent product by three times. Together, these create the "9x effect": a new product must perform 9x "better" than the incumbent to be adopted.

By positioning bio-solutions as central to solving global challenges and underscoring the unique benefits of leveraging biology as technology, it is possible to highlight the gains from switching to bio-based alternatives. Conveying these benefits in a way that consumers, non-specialists and the general public can readily perceive how they improve their daily lives and habits will go a long way, especially if accompanied by a targeted approach to drive the adoption of bio-replacements among consumers and organizations. For certain sectors, quantifying the benefits to consumers remains challenging.

Healthcare companies have been successful in articulating the benefit (e.g. to improve and prolong the "healthspan") to a distinct audience (patients and specialist professionals). Making a clear case that positions bio-solutions as delivering upon individual Sustainable Development Goals could help drive clarity around the benefits of bio-solutions beyond human health.[26]

Finally, the First Movers Coalition[27] provides an example of how demand signals can be built across technologies not yet available at scale, bringing the collective purchasing power of members to focus on decarbonizing the world's heavy-emitting and hard-to-abate sectors.

Addressing public perceptions around bio-solutions

Variable public perception is impacting acceptance of and demand for certain bio-solutions.

Public perception of biotechnologies is highly dependent on region, application area and demographics (e.g. level of education and religious values). This dependency leads to debate, especially in Europe, and bio-solutions can be perceived as controversial. Celebrating the unique value unlocked by the bioeconomy in a way that the public can embrace it will empower non-specialists to make informed decisions about the future.

To that end, a multifaceted approach could drive a step-change in perception. For example, messaging could highlight the successes in emerging application areas while focusing on their value and potential impact and avoiding technical jargon and unnecessary details. Public perception greatly affects the decisions that politicians make; without the deep technical expertise necessary to conduct a science-based risk assessment of bio-solutions, developing supportive regulation and policy can be challenging. Engaging the public to better understand the underpinnings of scepticism or concern and learning from best practices will be equally vital.[28]

The 54th Annual Meeting of the World Economic Forum, convened under the theme "Rebuilding Trust", highlighted the need for transparency, consistency and accountability. Community members conveyed a sense of public mistrust regarding pharmaceutical and chemical giants, which impacts new application areas for biology, and highlighted how the convergence of AI and biology must be pursued responsibly. Moving forward in a fashion that carefully balances innovation and societal risk could improve social consensus and change the tide of perception.

In sum, certain bio-solutions will more naturally be readily understood, appreciated and adopted by the public. Leading with narratives that highlight improved performance and reduced environmental impact could drastically improve awareness and in turn increase market pull.

Articulating evidence-based value propositions is critical

Underestimating the value of bio-solutions must be countered.

Conveying the value of bio-based solutions beyond a non-specialist audience remains challenging, and a compelling value proposition could prompt significant change that favours increased adoption. Several factors complicate the development and communication of a compelling value proposition:

- The difficulties of predicting scale-up often lead to unclear and overestimated business cases. Start-ups often fall into the trap of focusing on achieving a technical proof of principle without a comprehensive understanding of the proof of value.
- To be truly compelling, value propositions should be evidence-based and supported by adequate data. For example, if a bio-replacement is "more sustainable", the specific quantifications should be clearly conveyed.
- The green premium is challenged in tough economic conditions; when consumers are faced with making tough choices, basic needs are prioritized over higher priced green products. This is especially challenging in the bioeconomy as incumbents are often subsidized.
- Bio-solutions are less economically competitive as compared to petrochemical products, especially in the bulk chemicals or crop spaces.
- When framing solutions by impact, appealing to the end-consumer is a challenge if the specific consumer profile is not taken into consideration.

Establishing a clear and consistent value proposition that takes into account the above points will be paramount in advancing the commercial bioeconomy. Moreover evolving values are bringing planetary concerns into greater focus; recent research indicates a significant shift in thinking around the business case for sustainability among top leaders compared with 2022.[29] Furthermore, sustainability is increasingly viewed as a priority investment area and companies are looking to take a more proactive approach on this front.[30] As the business environment becomes more optimistic, selecting the right applications and articulating clear value propositions for emerging technology plays will be critical.

Alongside these activities, providing companies with the foundational tools to embed these value propositions into their fundamentals could aid adoption.

Increasing demand for bio-based solutions. Tailoring value propositions to specific sectors that are not yet "all in" on leveraging biology as commercial technology could increase their impact. Value propositions should be based on evidence, to build trust, measure impact and then communicate it. Meanwhile, efforts should remain focused on reducing production costs while emphasizing the technology adoption curve (which is not linear; economies of scale and time for optimization will, in time, also reduce costs).

Wider systemic factors can also drive demand. For instance, support from governments, prominent innovation leaders and philanthropists can accelerate progress. Furthermore, policies that adequately price in the "true" cost of existing products could position bio-alternatives as more competitive than incumbent, unsustainable technologies.

Investment priorities: Demand vs. funding

Raising awareness can unlock broader investment and subsequent fulfilment of demand.

Current investment is centred on synthetic biology

As enabling technologies continue to mature, synthetic biology has steadily captured venture capital (VC) interest over the past decade. The field had previously experienced significant VC funding across all life-cycle phases (including pre-seed all the way through to later-stage funding rounds to support commercialization and scale up). More recently, decreasing investor risk tolerance has reduced the appetite for investment in later-stage companies. This trend was born out of a downturn in VC funding for synthetic biology overall in 2022, which reflects general market trends and is not specific to synthetic biology start-ups.

Investors in biotechnology are focused on red biotech

Regardless of recent downturns in funding, healthcare and medicine remain the dominant application areas representing 80% of overall synthetic biology investment and 63% of total VC investment.

Geographically, these investments centre around the US: 81% of major investment (of more than $100 million) in healthcare in 2023 was from the US, followed by 10% from Europe and 9% from Asia.

As compared to the pharmaceutical industry, the path to market for industrial and agricultural biotech applications should be much shorter (e.g. lengthy clinical trials are avoided). However, lucrative applications and corresponding high margins ensure that pharma and healthcare attract the most synthetic biology investment. With shifting narratives around planetary outcomes, application areas beyond healthcare will prove increasingly attractive for investment.

Where are the investments in the bio-solutions space?

Due to their inherent technological complexity and commercial infancy, capturing investor interest from more traditional sectors remains challenging; the uncertainty surrounding the economics of commercialization further compounds such challenges.

Bio-based solutions can have high capital costs, high shutdown costs from existing facilities and relatively low margins. At the same time, the value proposition of bio-solutions is too often poorly and inconsistently conveyed to draw significant interest from traditional sectors. Taken together, the risk-reward profile of bio-based developments is often less favourable to more traditional investors, restricting the private capital available as non-specialist investors approach the emerging sector with caution.

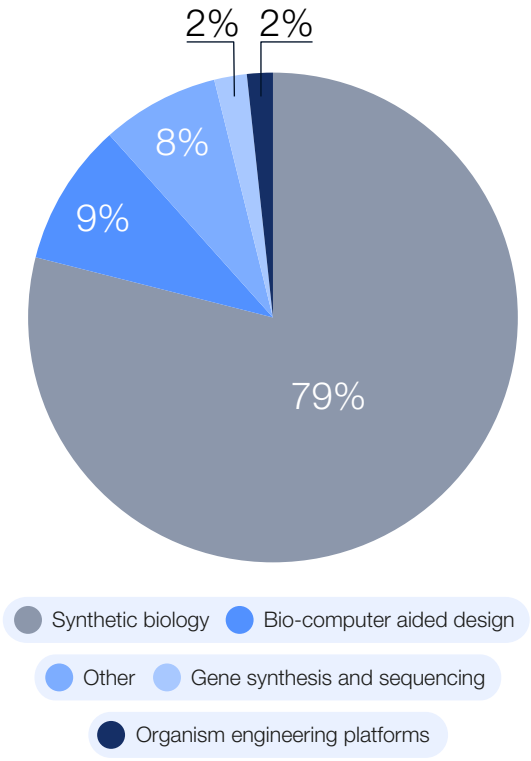
Moreover, building an investment case for bio-solutions where evidence-backed environmental considerations are built into financial decisions can be challenging for investors, as the sustainability "score" of traditional and fossil-based approaches is not built into the product pricing.

Forecasting cash flows presents another layer of difficulty due to the competition with established manufacturing processes, as well as the inherent volatility in the availability of feedstocks and products, which are closely tied to commodity prices.

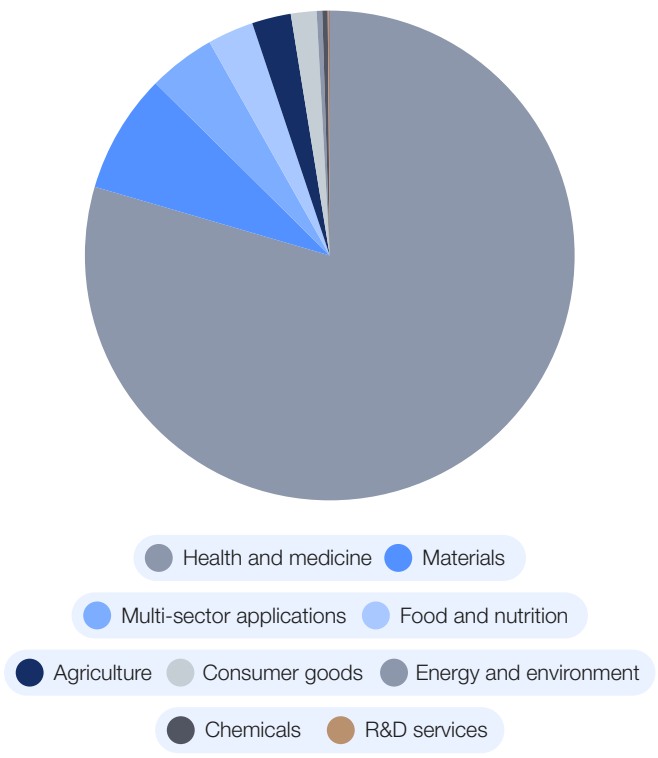
Increased demand will simultaneously alleviate many of these barriers by initiating a positive feedback loop: unlocking funding models to support and scale bio-solutions will provide new insights, risk mitigation opportunities and favourable public perception. The resulting demand will further stimulate investment, thereby accelerating the development, adoption and deployment of commercial bio-solutions.

Investment is predominantly focused on synthetic biology in health and medicine

Distribution of VC investment in first quarter of 2023



Distribution of investment in synthetic biology applications



Major investments in synthetic biology

Ginkgo Bioworks: $350 million in 2020 to expand its platform for engineering custom microbes

Mammoth Biosciences: $195 million to build next-generation CRISPR based therapeutics and diagnostics

Evonetix: $54 million for developing a new approach for gene synthesis

Biggest healthcare biotech investments in 2023

ElevateBio: $401 million ($1.2 billion total funding) for cell and gene therapies

ReNAgade Therapeutics: $300 million for RNA therapeutics

Generate Biomedicines: $273 million ($693 million total funding) for drug discovery

Source: Various[31]

3.2 Servicing demand

Delivering bio-solutions in response to growing demand requires value-chain transformation and efficient transition from the laboratory to commercial scale.

The need to increase adoption and demand was emphasized in all scoping and community-building exercises. Two key challenges were highlighted:

1. The high barrier to entry for bio-based solutions limits their adoption, often requiring a transformation of organizational capabilities, operations and supply chains, and often, a willingness to accept a green premium.

2. As adoption grows, efficient transition from the lab becomes crucial to meet future demand; currently, effective technology transfer and predictability around scaling biology are key hindrances.

Bioeconomy value chain and ecosystem

Technology-driven bio-solutions will require collaboration across a diverse ecosystem to ensure viability.

Value chains for incumbent products will, at times, require adaptation to incorporate bio-solutions. Value-chain transformation provides many potential entry points for businesses looking to "bio-cize" their commercial activities, enabling long-term human and planet-centric gains. Value chain transformation is complex, but possible with a high degree of cooperation and a mindset open to change and uncertainty.

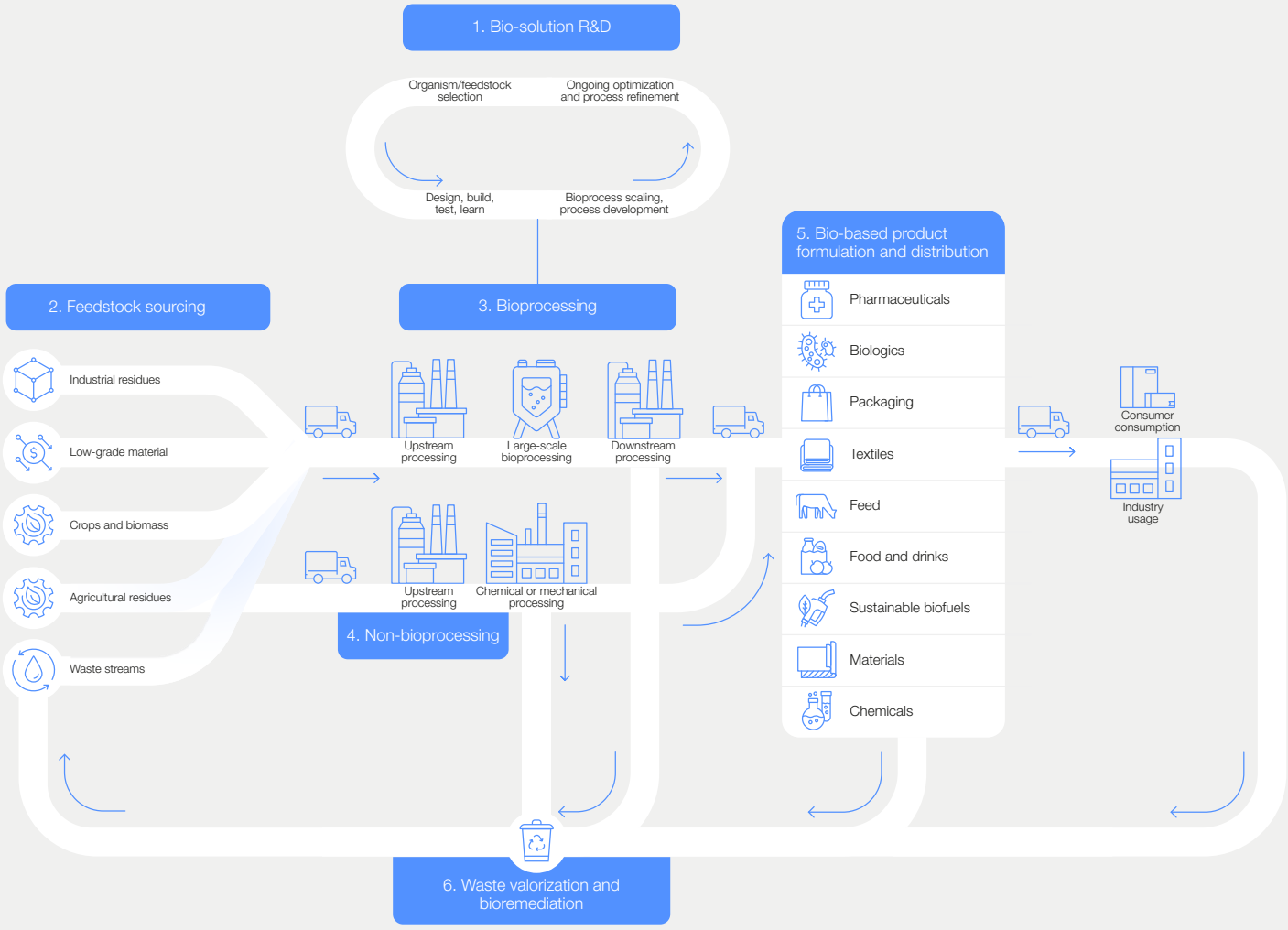
To that end, commercial-scale implementation of bio-solutions necessitates bringing together a combination of the right players with appropriate capabilities to meet industry or consumer needs. Figure 11 illustrates this using the example of a fermentation-based value chain, highlighting its key elements as well as the direct and indirect ecosystem players, and outlining important considerations.

When considering value chain transformation from this angle, the increasing capacity to rewire microbial metabolism and pre-process substrates means that engineers can now select from an increasing array of feedstocks. This expansion is key to bolstering supply chain resilience, capturing CO_2 and even valorizing waste.[32] For example, Ginkgo Bioworks helped a leading fermentation company decrease their reliance on an expensive feedstock by using metabolic engineering to improve the organism's assimilation of a new, less expensive feedstock by 25 times.[33]

Not all companies have the capabilities to conduct early-stage bio-solution R&D through to commercialization under a single roof, necessitating collaboration across the ecosystem. Furthermore, costly and highly specialized equipment often varies based upon the target product profile. Indeed, an extensive variety of bio-solution requirements adds increased pressure for companies and contract development and manufacturing organizations (CDMOs) to innovate and adapt. In addition to the industrial infrastructure required for commercial-scale production, a constellation of support industries remains essential in ensuring value chain success. For instance, data and information technology companies provide critical digital capabilities for essential compute and data analysis capabilities.

Equally important across the value chain are the advisory and finance providers that ensure commercial viability. Governments, regulators, educators, media, non-governmental organizations (NGOs) and local communities play an important role in creating a conducive environment for commercial success and in raising the public profile of the bioeconomy. Open-source R&D platforms can help with accelerating bio-solution R&D and innovation.[34] By enabling free exchange of ideas and data, such platforms democratize access to technology and reduce barriers to entry.

FIGURE 11 | **A complex value chain and ecosystem underpins the bioeconomy**



Direct ecosystem (example of company types)

1	2	3	4	5	6
– Farms/aggregators – Industrial players – Mining companies – Waste collectors – Infrastructure companies	– Bio-foundries and specialist R&D firms – Contract development and manufacturing organizations (CDMOs) – Chemical companies	– CDMOs – Chemical companies – Manufacturing companies – Pharmaceutical companies	– CDMOs – Chemical companies – Manufacturing companies – Pharmaceutical companies	– Consumer brands – Formulation companies – Business-to-business (B2B) suppliers – Manufacturing companies – Agriculture – Energy companies	– Waste collection infrastructure/companies

Indirect ecosystem (example of company types)

R&D
Academia
Specialist equipment/supplies
Advisory
Data and IT
Financiers
Media
Educators
Community
Non-governmental organizations
Governments/regulators

Note: This is a representative value chain and does not cover all of the bioeconomy. Certain bio-solutions where organisms are bioengineered and deployed directly without the need for an industrial process are not represented (e.g. engineering plants to produce insulin).

Source: World Economic Forum analysis

Value chain transformation

It will take greater investment and understanding to broaden the adoption of bio-solutions and drive the transformation of value chains.

While many companies have adopted bio-solutions, many sectors and industries have yet to implement bio-based practices and instead rely on incumbent technologies. In these cases, adopting bio-solutions often requires a complete transformation across value chains, meaning the barrier to entry can be prohibitive at the onset. Failures and challenges in industry are often proprietary and those from academia never published, slowing the learning rate across the sector and therefore its acceleration.

To facilitate the transition from incumbent and extractive technologies, the practical aspects would have to be addressed; for example, providing clear guidance on how to implement such transitions, along with transparent assessments of the associated risks and timelines across various industries and regions.

Additionally, identifying sources of financing to support these transitions will be crucial. Providing information on such practical aspects, while offering a straightforward portrayal of risks, timelines and financial support options can act as a catalyst for the much-needed transformation towards bio-based solutions. The community highlighted two basic areas in this regard:

Investment models geared for broader adoption: Technology transfer and investment models are deeply intertwined; bringing new technologies to market requires a complex interplay of public and private interests. The industry model for red biotech is well established and understood, which allows investors and decision-makers to more accurately assess the value of and the risks associated with longer commercialization timelines.

The same cannot be said for white and green biotech, where timelines are often longer and more uncertain. Thus, investors with shorter horizons are fundamentally at odds with the timescales inherent in commercializing biology. It is important to offer consistently balanced and realistic estimates of timelines and costs involved in taking innovations from the lab to commercial scale. This will enable investors, and national/international investment support ecosystems, to better tailor funding models to relevant stages of commercialization for individual companies.[35]

Adapting approaches to regions: The diverse regional approaches to technology transfer and investment, coupled with the inefficiencies and bureaucracies inherent in operating across these variations, pose substantial barriers when evaluating investment opportunities.

Understanding the regional nuances and the maturity of local ecosystems will be an important factor as it informs partnerships, joint research projects and the sharing of best practices. Section 3.3.3 delves deeper into regional technology access, but it is important to draw the connection here to investment models and technology transfer. Enhanced regional understanding will more effectively address demand on a broader scale to assist in overcoming the challenges posed by regional approaches to technology transfer and investment.

Streamlining technology transfer remains a barrier

To activate value chain transformation, core technology transfer barriers must be addressed.

Efficient technology transfer from lab to commercial scale is a critical factor in the commercial deployment of bio-solutions. While many features in transferring a particular technology out of the lab will be unique to each bio-solution, several underlying challenges can be identified. The community emphasized the following:

Designing R&D to scale: There is a wide disconnect between R&D specifications during the early laboratory research stage of development and those necessary to ensure effective, commercially viable scaling of production. For instance, in fermentation-based bioproduction, organism designs can easily overlook key factors for successful large-scale production (e.g. oxygen availability). While a variety of causes underlie such costly oversights, better equipping players with the tools to efficiently translate out of the lab and onto a commercial scale remains critical in advancing the commercial bioeconomy.

Bio-production equipment that is fit-for-purpose: For those bio-solutions where bioproduction is a key component, one option is to purchase commercial biomanufacturing equipment from red biotechnology suppliers. Given the low-volume, high-margin nature of the application area, the equipment designed for pharma is not optimal for the demands of high-volume, low-cost production. Furthermore, research equipment remains highly manual and is often not suited to large-scale production.

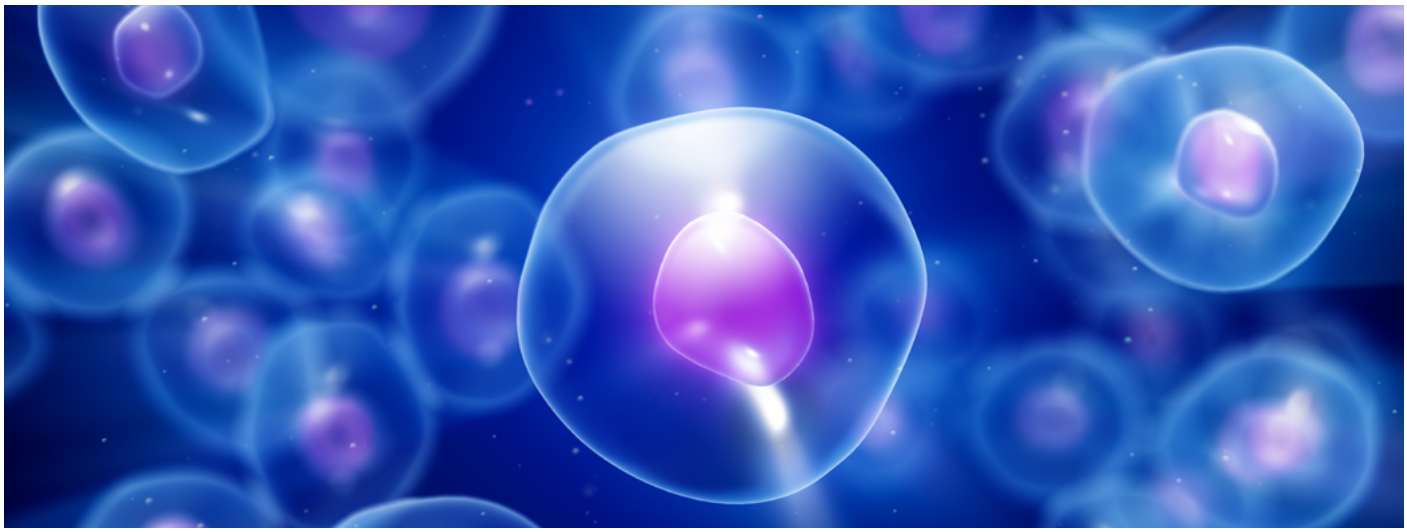
Modular equipment can be more easily adapted for different uses. To enable modularity and provide fit-for-purpose equipment to those enterprises for whom custom-built infrastructure is not an option, standardization could be achieved with greater visibility across the value chain to aid in identifying common and crucial needs. Further, capacity constraints can hinder novel (i.e. beyond standard organisms/feedstocks/processes) bio-solutions.

For companies without in-house capabilities, fermentation capacity and infrastructure remain a critical element for scaling and have been studied in recent reports.[36]

Standardization and innovation in downstream processing: Downstream processing (DSP) can be up to 80% of bioproduction costs.[37] As with bio-production equipment, this is often adopted from pharma and is not suited to high-volume applications. DSP is also highly bespoke to each bio-solution, requiring investment and time to refine for techno-economic impact. Some estimates indicate that nearly half of bio-process models share common DSP needs and processing characteristics.[38]

Innovation to develop DSP technologies that are standardized and widely deployable across diverse bio-solution applications would play a significant role in making bio-solutions cost-effective and competitive.

These are just some of the challenges for technology transfer that the community flagged. Bioproduction is just one part of the bioeconomy and a number of other challenges exist where technology transfer will play a crucial role in transforming value chains, ranging from sourcing and supply-chain complexity to leveraging technology to drive greater synergies across ecosystems. Many more will vary by industry and application.



Predictability in lab-to-scale translation

Even with rapid scientific advancement, biology is unpredictable.

Predictability holds the key to success, especially when delivering a commercial service or product. Industrial processes are optimized to run in a fashion that is both reliable and predictable: once initial scaling, development and optimization have been completed, large-scale production should be highly repeatable. Similar levels of control are more difficult to extend into processes that leverage biology as their core technology. Yet, consistent with what has been observed in other emerging technologies, the predictability of commercial bio-solutions will undoubtedly improve over time as bio-based scaling practices mature.

Predictable lab-to-scale translation is critical: The tech-driven bioeconomy has evolved considerably over the last decade with the capacity to read, write, edit and now functionalize DNA. This has provided an incredible toolset to "write" functional proteins, pathways and now even entire organisms.

While many of the processes involved in developing a microbe "to spec" remain reliant on observation or firsthand experience, which can be highly prone to "trial-and-error", generative biology fuelled by advances in computing and machine learning will help in significantly improving predictability in bioengineering. Predictability challenges are not limited to protein and pathway design but extend to the process of transitioning bioprocesses from the lab to commercial scale (think 100 millilitre shake flasks to 100,000 litre commercial bioreactors). Much like the advances that will revolutionize the ability to predict DNA designs that meet commercial specifications, new advances are being applied across other areas of the value chain to make the process of scaling up biology more predictable, streamlined and efficient.

The key to predictability is data: As the number of measurable parameters increases, and hence the volume of data collected, the "learning" phase holds much potential. A paradigm shift is underway as biology meets digital, creating capabilities to predict failure modes before they occur. This will empower researchers and engineers to pivot and address potential disasters and undesirable outcomes pre-emptively, resulting in significant cost savings across the value chain.

3.3 Unblocking the system through regulation and policy

Streamlined infrastructure can accelerate the bioeconomy.

The extent to which bio-solutions impact global standards of living hinges on interconnected factors across political, ecological, social and economic variables. From a systems perspective, regulation and policy exert the greatest influence on accelerating the bio-based economy.

Bioeconomy through a regional lens

Regional bioeconomies vary by geographical context and approach.

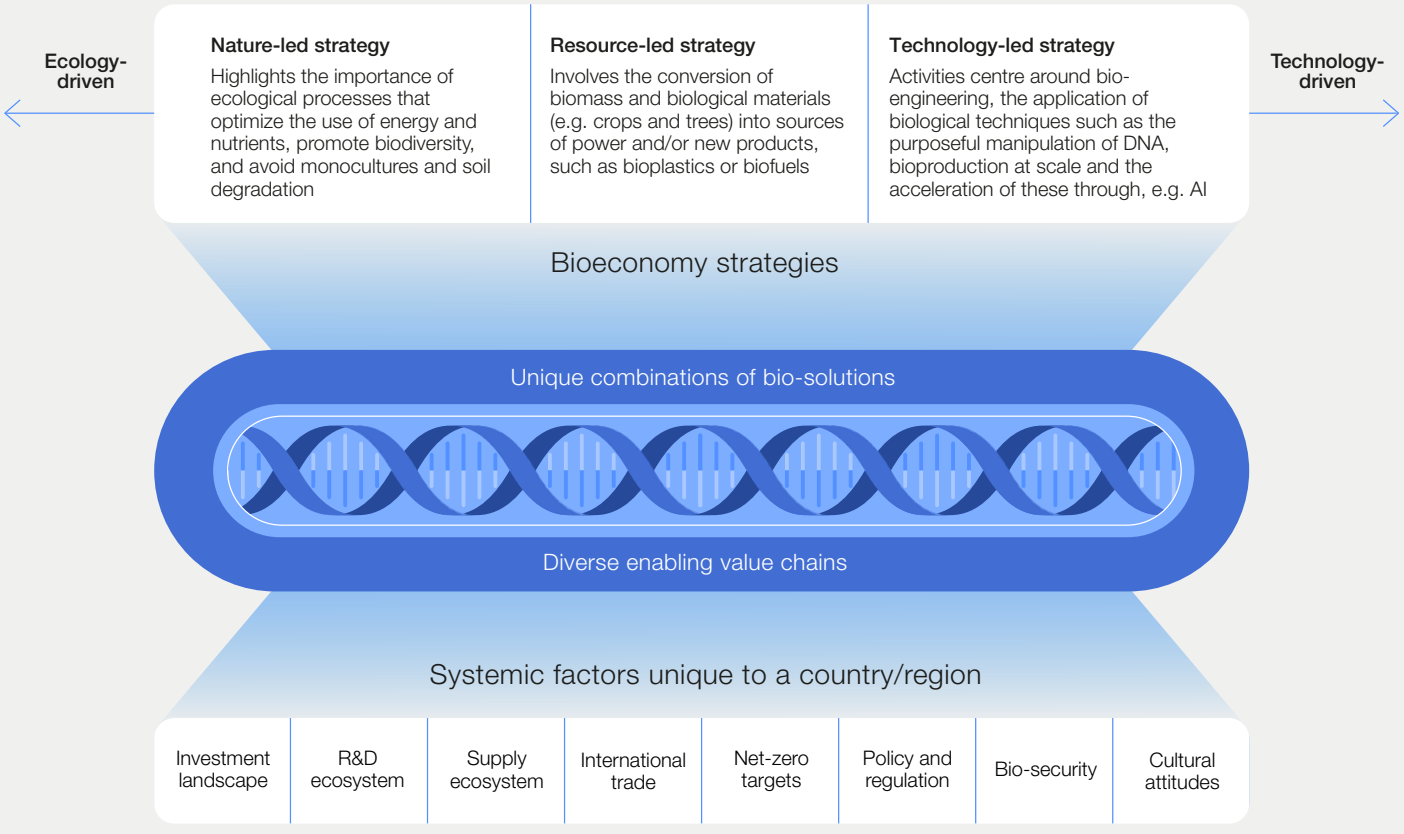
The scope and emphasis of national bioeconomy strategies varies based on regional natural resources and systemic factors (Figure 12). Along with various sectoral strengths, the make-up of the enabling ecosystem also influences the mix of bio-solutions adopted in a given country/region.

Ultimately, each region will apply a unique blend of strategies based on factors including natural resource base, industrial capabilities and political/strategic objectives to tailor regional bioeconomies to local circumstances. The diverse approaches and systemic factors inherent to each country or region will shape demand for a different set of products, services, technologies, ecosystems and value chain dynamics within the bioeconomy. Such diversity will be a critical factor in accelerating adoption and driving demand globally.

The private sector will play a central role in delivering viable bio-solutions, operating within regional constraints, when delivering scaled commercial outcomes. Public-private cooperation that transcends borders and strives for equitable outcomes will be a critical factor in overcoming the multi-faceted challenges that prevent the bioeconomy from entering the commercial mainstream.

FIGURE 12 **Regional factors in bioeconomy strategies**

Bioeconomies vary by region and require different kinds of bio-solutions



Note: Systemic factors listed above are illustrative and not exhaustive.

Streamlining regulation and policy

Streamlining regulation allows for broader adoption.

Driving and servicing demand constitute major challenges, but without supportive policies, demand remains stifled. The first moves are the most expensive as they influence how fast or how broadly tech-driven bio-based approaches can be adopted. The cross-cutting and technologically complex nature of the tech-driven bioeconomy poses significant barriers in devising comprehensive yet efficient policy and regulatory frameworks. Bioeconomy stakeholders indicate that establishing clear-cut regulation and supportive policies will propel the tech-driven bioeconomy into the commercial mainstream.

Other stakeholders recommend that solution providers work within current regulatory boundaries to provide "proof of value" in the market, while simultaneously building trust and educating regulators. While working within the current regulatory boundaries may stifle the disruptive potential of bio-solutions, regulatory precedence remains limited to a handful of geographies and use-cases. If the green transition is to be accelerated, companies can't wait for regulation to catch up and will need to, where possible, raise awareness and create momentum for regulatory change.

The pace of technological advancement and subsequent broadening of the knowledge gap presents another complicating ecosystem factor. When considering new approaches, community members conveyed that biotechnology can be perceived as "unnatural". Addressing common misconceptions and concerns around the tech-driven bioeconomy is important to better convey its real-world potential. A more comprehensive understanding on this front will enable the community to better address public concerns around those areas that matter the most in leveraging biology for a better future.

Regardless of misconceptions, genetic modification remains a polarizing technology, and corresponding regulation remains highly variable across geographies (Figure 13).

Two types of laws are bottlenecks

Some of the variability in regulation across jurisdictions centres around "contained use" and "deliberate release" laws, which reflect regional political and public sentiment around genetic modification.

Contained use specifies that the resulting products are allowed to be used so long as they are contained within a controlled environment, whereas deliberate release stipulates that the product can be used outside of a controlled environment (e.g. crops that have been modified for increased yield, and soil microbes that have an enhanced natural ability to turn atmospheric nitrogen into fertilizer).

These restrictions determine which bio-solutions can be commercialized where.

FIGURE 13 | **Regulatory landscape**

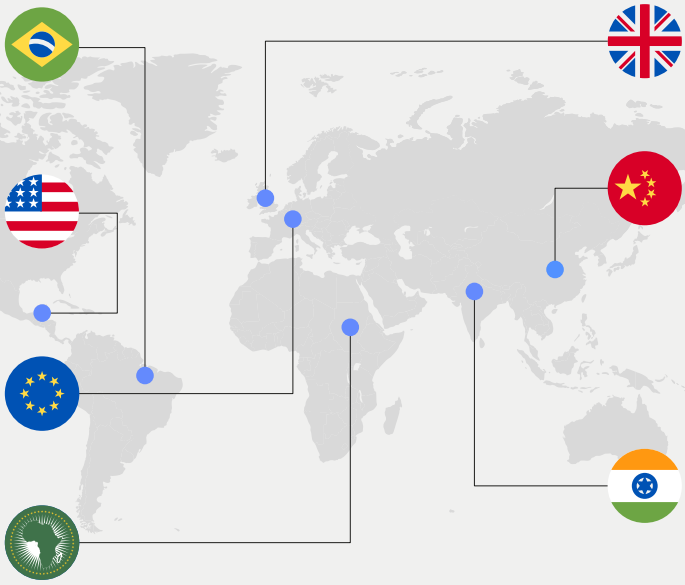
Variable regulation of genetically-modified organisms (GMOs) is driving inconsistency across regions

Contained use and experimental release are described in legislation that includes innovative precision improvement techniques. 152 GM products were commercially approved as of 2020.

Liberal. FDA[1], EPA[2], USDA[3] work together as the Co-ordinated Framework for the Regulation of Biotechnology. Unclear regulatory precedence for deliberate release for non-crop applications.

Cautious. Overarching directives on contained use and deliberate release, but member states free to choose how to achieve these goals. Regulation on deliberate release of GM food and feed.

Focus on crops and human health. Limited regulatory precedence outside of this.



Clear guidance on contained-use GMOs. Deliberate release only for clinical trials and agricultural trials.

Between the US and the EU in terms of cautiousness. Regulations focus on crops, food and feed. 10% of the country's pesticides are biopesticides. Biosecurity laws are in place. Is starting to explore introduction of commercial GM crops again as no new ones have been licensed since 2000 due to public opposition.

Has guidelines for genome-edited plants and a Biological Research Regulatory Approval Portal that streamlines approvals for biological R&D.

Key terminology:

Contained use: The process of making or using GMOs where barriers (physical, chemical or biological) are used to limit contact with and provide protection for people and the environment.

Deliberate release: Any intentional introduction into the environment of a single or multiple GMOs for which no specific containment measures are used to limit contact with the population and the environment.

1. US Food & Drug Administration
2. US Environmental Protection Agency
3. United States Department of Agriculture

Note: The information presented in this figure is as of March 2024, and is not exhaustive.

Sources: Various[39]

The geographical inconsistency of regulation was perceived as a considerable hindrance to acceleration of the tech-driven bioeconomy; in particular, the prevalent perception is that the EU is lagging while the rest of the world forges ahead with progressive and planet-forward regulation. One notable example included new genomic techniques, such as CRISPR, that fall in the crosshairs of GMO regulation. Overall, community insights for this report reveal an eagerness to advocate for streamlined regulation across borders, with a push to apply innovations such as regulatory sandboxes.

What are regulatory sandboxes?

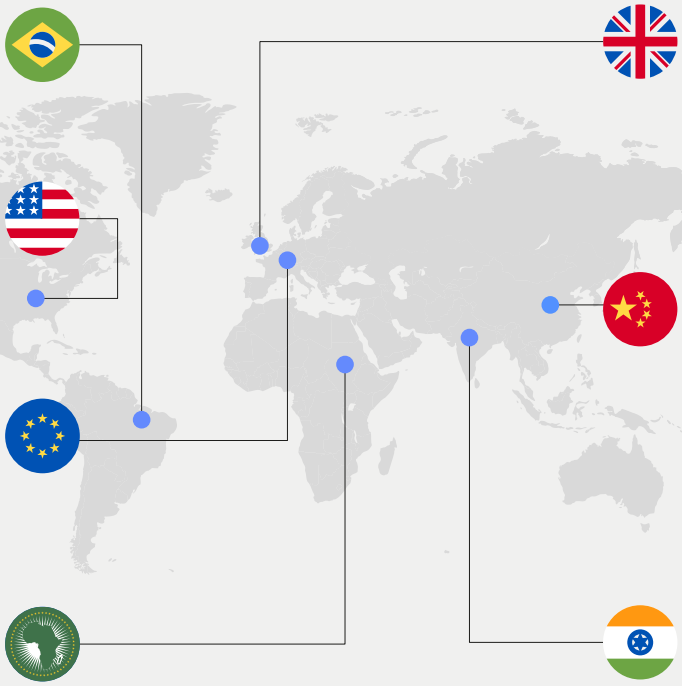
These are frameworks set up by regulators that permit innovators to conduct experiments in controlled environments under regulatory supervision. These make it possible to reduce the time to market while ensuring environmental and consumer protection.

Other regulatory innovations include the use of technology for regulatory (RegTech) and supervisory (SupTech) purposes, plus innovation hubs where regulators and innovators work closely together.

Increased use of these and other supportive regulatory and policy mechanisms, along with greater government focus, will provide a significant boost to the bioeconomy, as outlined in Figure 14. And while many promising policies have recently been implemented to advance the bioeconomy, government subsidies of conventional extractive technologies persist. These subsidies present a dual threat: not only are they damaging to the planet, they also actively reduce the economic competitiveness of bio-solutions. Furthermore, for every subsidy that goes into a bio-based solution, there is five that go into a fossil-based one, exacerbating the challenge of competitiveness with incumbent processes. Moreover, $8 trillion are being spent each year on subsidizing fossil-based products. Reallocating these subsidies towards policies that support living within the planetary boundaries and towards technologies that facilitate this goal is the obvious remedy. Such measures could go a long way in levelling the playing field in support of mainstreaming environmentally conscious technologies and practices.

FIGURE 14 **Strategy and policy landscape**

Increasingly, governments are recognizing the potential of the bioeconomy for their own economies – promoting high-quality, skilled jobs alongside encouraging entrepreneurship and innovation[40]



The understanding of the term "bioeconomy" can be different in Latin America, with more of a focus on forestry resources. Brazil is a global pioneer of the biofuel agenda, with numerous successful policies.

Biden's Executive Order and accompanying strategy document set out clear goals, policies and departmental responsibilities for advancing the US bioeconomy. There's a lot of activity from this administration, with $2 billion of investment.

The EU has a Bioeconomy Strategy, with many member countries having a dedicated Bioeconomy Strategy at a national level. The strategy currently focuses on R&D but further developments are underway within the European Commission.

The African Union has a Bioenergy Policy Framework to enhance energy security, access and rural development. East Africa has a Bioeconomy Strategy focusing on agriculture and also forestry, health and industry.

Engineering biology is identified as one of five critical technologies in the UK Science and Technology Framework. They recently released a UK National Vision for this and plans for a £2 billion investment.

The Chinese "14th Five-Year Plan for Bioeconomy Development" offers three pathways to improve the bioeconomy including technological innovation, industrialization and policy support. It covers biomedicine, bio-agriculture, bio-manufacturing and bio-security.

The flagship Make in India 2.0 Plan has a "Facilitation Cell" for Biotechnology while work is afoot to streamline policy and regulation, establish technology clusters and promote biomanufacturing and bio-foundries.

Note: Information as of March 2024; not exhaustive.

Ensuring responsible deployment: Supporting growth and innovation while anticipating and removing unintended or harmful outcomes remains critical for regulators. Despite the benefits of technological convergence, the rapid pace of technology evolution heightens the probability and impact of potential risks. Threats are emerging at the interface between the biosciences, cybersecurity, information technology and operational technology. These impact businesses, national security and the general public.

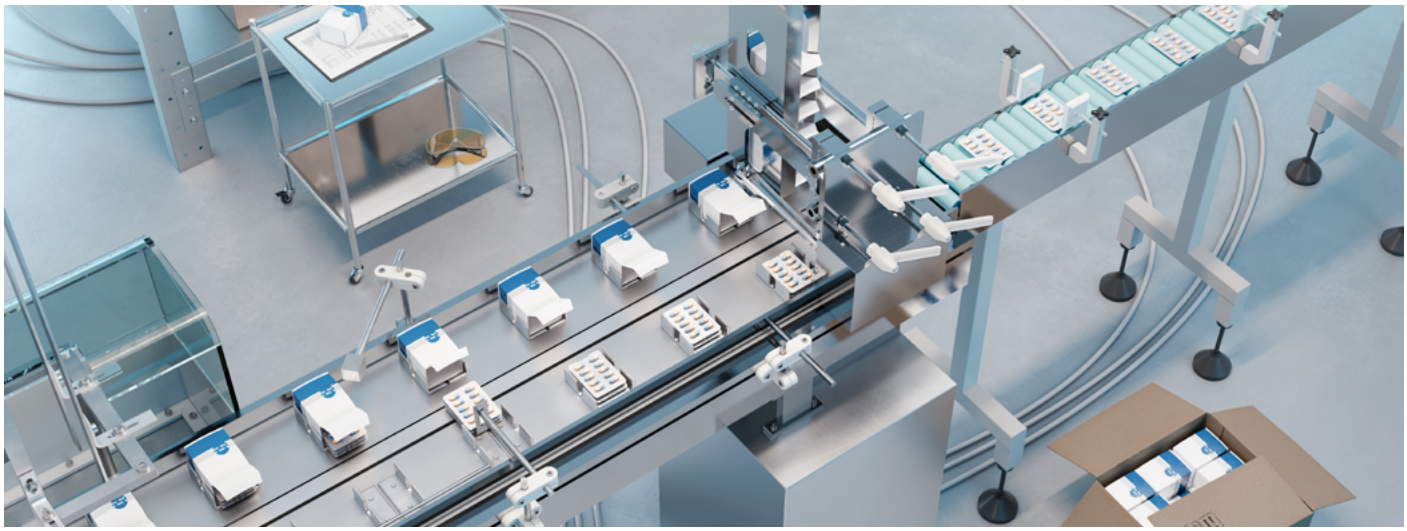
Nonetheless, a variety of mitigation measures can be deployed at a regulatory and policy level, including:

- Demystifying the commercialization process to bolster transparency.
- Mapping accountability proposals onto each phase in the process of bio-innovation and subsequent commercialization.

- Fostering a culture of responsibility across technology developers and users.
- Supporting co-evolution of regulatory frameworks with technological advancements.
- Resourcing the development and implementation of global legislation (such as the Biological Weapons Convention).

Biosecurity is also likely to become a larger topic as the ability to edit and manipulate biology becomes democratized and the potential for misuse increases.

This becomes more urgent as the convergence of AI will make this easier and faster. AI assurance will need to increasingly be used in tandem with the application of AI to biology to ensure trustworthy, unbiased and secure bio-solutions.



Equity and access

Democratizing global access to technology, skill and infrastructure is an imperative.

Root cause analysis of challenges in translating laboratory findings to large-scale production reveal that emerging economies and smaller markets are actively developing their bioeconomies and are often already engaged in large-scale bio-processing. Access to essential infrastructure, skills and technology required for initial research and development remains limited. The solutions include:

1. **Creating opportunities for homegrown innovation.** Underdeveloped local innovation ecosystems, which lack a critical mass of talent and capability, will benefit from fostering international partnerships to accelerate commercial progress, enhance local training programmes, exchange knowledge across borders, and boost investor sentiment where concerns around intellectual property (IP) restrictions abound.
2. **Incentivizing large companies to enter smaller markets and share technologies.** Often, the overheads of exporting into a new country are compounded by the lower revenue generated from smaller/lower-paying markets, as well as IP protection concerns, limiting commercial attractiveness for large companies. Identifying mechanisms to overcome these and other barriers will be necessary to foster more and larger joint ventures to drive broader benefits.
3. **Increasing access to broader markets.** Geographical and political constraints can make cross-border supply costly or inefficient, particularly when dealing with biological or biologically derived materials and trade policies not designed for their transport. Additionally, trade relationships are often not conducive to accessing the necessary foreign infrastructure (e.g. fermentation capacity) to augment local infrastructure. Also, while trade blocs are usually trade enablers, they can be restrictive for those outside of them.

Many avenues exist to address accessibility issues including making better use of trading blocs, designing technology for adaptability (such that markets with differing needs can adapt technology), open science programmes, blended finance and concentration on low-capital innovation.

The community also highlighted the potential for traditional and indigenous knowledge to expand homegrown innovation. For example, traditional and indigenous medicine has been the source of key landmark drugs such as aspirin and artemisinin as well as natural products that form the basis for more than 40% of pharmaceutical formulations.[41]

The bioeconomy can become a fundamental part of the political, economic and societal ambitions of emerging countries, who face unique and diverse challenges. New and innovative bio-solutions can accelerate the transition to a better world for all.

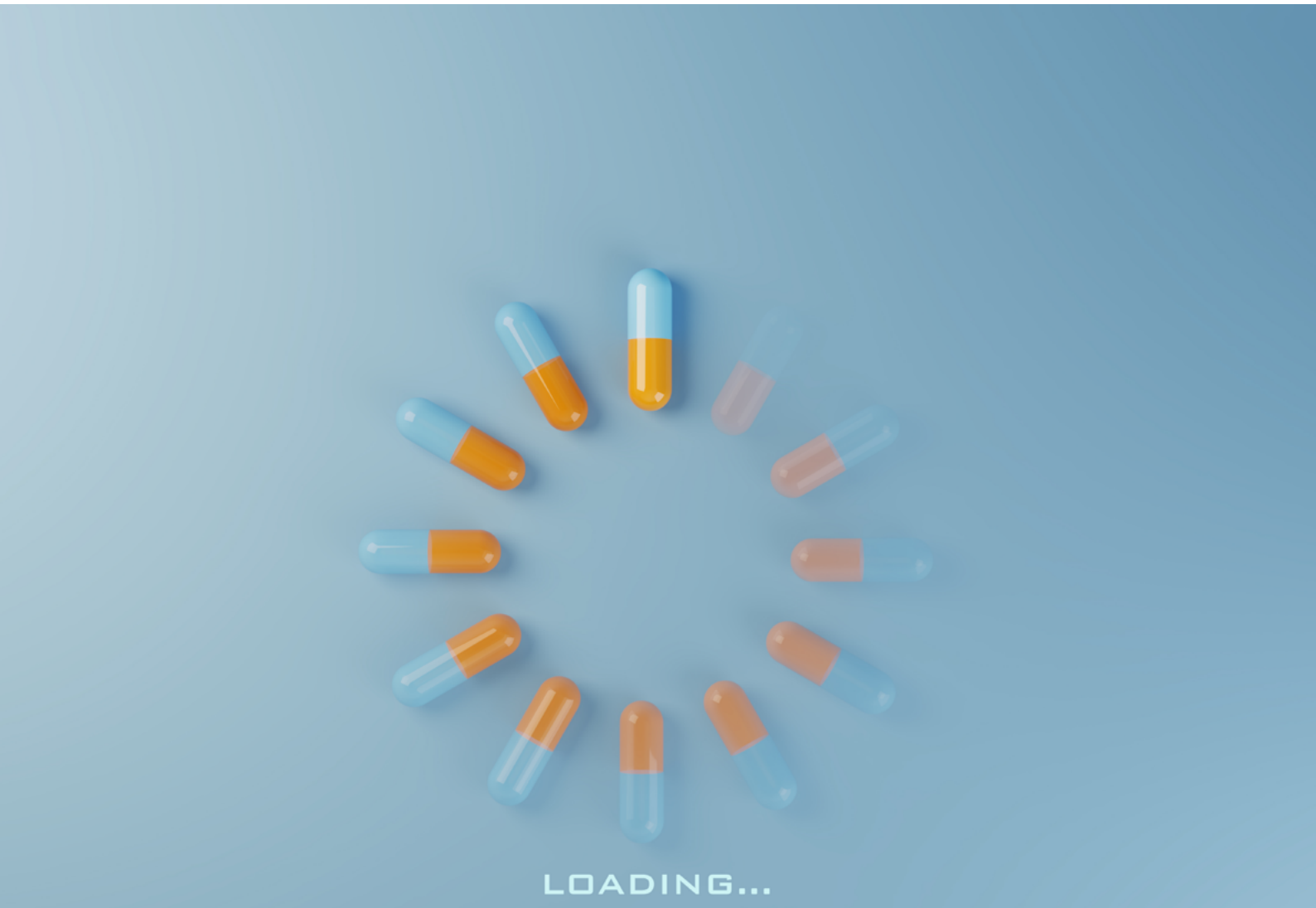
BOX 1 | **Examples of best practices in promoting equitable access to biotechnology**

SynbioAfrica is "a forum for researchers, students, citizen scientists, policy-makers and the public at large to develop successful pathways for the propagation of synthetic biology technologies, products and services throughout Africa".[42] They organize projects, such as a biosensor that detects disease in Ugandan cattle, and also work to spread awareness and conduct events.

iGEM is a global competition involving over 400 teams, from a community of around 75,000 people from 66 countries, that develops knowledge and skills among synthetic biology students and other innovators. It pioneered "BioBricks", a standard for interchangeable biological parts to make biological programming more accessible and interoperable. It runs an annual start-up competition (250 start-ups have taken part so far) to stimulate new players and has educated more than 75,000 individuals in synthetic biology including through a "responsibility programme" that promotes biosafety, biosecurity and dual use.[43]

Open Bioeconomy Lab is a collaboration between the University of Cambridge, United Kingdom, and researchers in Cameroon and Ghana that creates a variety of open-source tools for biotechnology to overcome the problems with access to reagents and equipment in the Global South.[44]

Efforts to increase accessibility of biotechnologies are important for ensuring that biotechnology reduces inequality rather than exacerbates it. Nonetheless, this democratization of technology poses security threats as it lowers the barriers to bad actors abusing it. For example, a class at the Massachusetts Institute of Technology (MIT) gained information on pandemic-causing diseases, mutations that could increase transmissibility, techniques to produce this and laboratories that could print the genetic material without screening it – all in one hour.[45] A portfolio of risk-mitigation strategies should be used against biological threats, particularly those enabled by the convergences of biotechnology with other technologies.



Conclusion

With an operating system that runs on biology at its core, the tech-driven bioeconomy represents one of the most significant opportunities of the century. The promise of bio-solutions is vast and extends from revolutionizing value chains to providing better commercial outcomes where both humankind and the planet remain in focus. The transition to bio-based solutions is already upon us and is being extended through generative biology: bio-solutions are transforming disparate sectors from healthcare to chemicals and many more. Although the bio-transition has been underway for several decades, many companies have yet to embrace biology as a core commercial technology.

No single action will succeed in enabling the bioeconomy to enter the commercial mainstream; rather concerted efforts will continue to advance the tech-enabled bioeconomy to commercial scale. Campaigns that span the ecosystem will also be necessary. For instance, re-imagining policies and regulations to level the playing field against incumbent and extractive technologies will provide a necessary catalyst, along with supportive regulatory frameworks for more efficient commercialization of innovative outcomes where they are needed the most. But regulatory and policy advancements alone are not sufficient.

To capitalize on the critical convergences of today and fundamentally accelerate the ability to more accurately predict and deliver innovative bio-based solutions, the interface with biology must be overhauled – across businesses, the public sector and, with renewed focus, among the general public. Embracing the potential and the promise must extend well beyond the core group of technical experts and enthusiasts who have been championing bio-based solutions all along.

As generative biology advances, the bio-revolution continues to gain momentum. The ecosystem must come together to catalyse the worldwide transition to a bio-based economy and drive the tech-driven bioeconomy into the commercial mainstream.

Appendix

About the initiative

The World Economic Forum is establishing a global, multistakeholder, action-orientated community to pioneer an initiative that unites leaders from the public sector, private sector and civil society with the goal of accelerating the transition to a bio-based economy.

The community vision for the initiative is:

"**Publicly championed as a vital solution for global challenges, the commercial bioeconomy enhances** human health, prosperity and ecological balance."

To spark demand and catalyse the bioeconomy's entry into the commercial mainstream, the Forum will build on its policy, industry and expert communities, as well as its global network of independent Fourth Industrial Revolution Centres, to establish a global coalition aimed at delivering the following objectives:

- **Adoption.** Facilitate increased cross-sector demand and enhance adoption of commercial bio-solutions in business operations.
- **Awareness.** Raise awareness among senior leaders and the public with a human and planet-centred value proposition.
- **Equity.** Promote a responsible transition that fosters equitable bioeconomy development across sectors and geographies.

Community engagement approach

To establish the community and identify challenges central to accelerating the global bioeconomy, a series of four regional convenings were held to infuse diverse public, private and regional perspectives into the discussion.

Diversity of representation to ensure all perspectives are considered:

- Attendees represented 59 organizations spanning public and private sectors, and originated from 19 countries.
- 53% were senior decision-makers from diverse private-sector companies (e.g. Novo Nordisk Foundation, dsm-firminech, Bota Biosciences, Ginkgo Bioworks and Takeda).
- 47% were key representatives from governments and public entities (e.g. Korea Advanced Institute of Science & Technology (KAIST), European Commission and SynBio Africa).

Using a core agenda for convenings ensured a consistent assessment of challenges: The methodology used across each workshop was carefully curated to unravel the core challenges and key insights to advance the tech-driven bioeconomy. Core exercises were comprised of the following:

1. Align around a shared understanding of the bioeconomy, its potential and the focus of the Forum's bioeconomy initiative.
2. Explore regional perspectives and understand what the bioeconomy means to different stakeholders.
3. Prioritize a core set of 15 challenges across the bioeconomy, ranging from techno-commercial through to systemic, with an emphasis on regional variation.
4. Deep-dive into the highest priority challenges to understand root causes and identify potential solutions.
5. Explore what the bioeconomy would mean to stakeholders if these challenges were addressed.

Identification of solution areas to accelerate the technology-driven bioeconomy: To identify and brainstorm solution areas for impact, community insights were surfaced and further developed as follows:

- Participants voted for one priority challenge in each convening to highlight the consensus on critical solution areas.
- Solution areas were cross-validated through perspectives raised in interviews with key stakeholders and themes raised at the 2024 Annual Meeting in Davos.
- Desktop research was used to supplement community insights.

Limitations

This report reflects the highest-priority perspectives and opinions of the community members who engaged in this process. While all effort has been made to be comprehensive across the bioeconomy, there will be topics of relevance to various stakeholders that have been omitted or not covered due to space constraints.

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Acknowledgements

This work could not have been achieved without the passionate support and cooperation of the Bioeconomy Initiative Community through their attendance of workshops, sharing of insights and engagement with the Forum team in various capacities.

A number of senior leaders provided direct feedback that was key to shaping this report, including:

Alok Anil
Managing Director, Next Big Innovation Labs

Igor Balaz
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Sebastian Buckup
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Helen Burdett
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Production

Bianca Gay-Fulconis
Designer, 1-Pact Edition

Tanya Korniichuk
Illustrator, 1-Pact Edition

Madhur Singh
Editor, World Economic Forum

Endnotes

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