Accelerating the Biomanufacturing Revolution

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Executive summary

An opportunity to deploy sustainable, scalable and innovative biomanufacturing solutions.

“ The pace of innovation in biomanufacturing is creating an opportunity to rapidly adopt cutting-edge manufacturing approaches while creating synergy with the ecosystem through partnerships and new investment.

The biomanufacturing revolution is here. Recent advancements in the field of synthetic biology have enabled significant cost reductions in foundational bioengineering unit operations such as DNA synthesis and sequencing. As economies of scale continue to drive costs down across this sector, the opportunity to deploy sustainable, scalable and innovative biomanufacturing solutions is becoming increasingly relevant to the broader manufacturing community.

Increasingly, new biomanufacturing solutions are exiting the lab and impacting value chains. However, one of the main challenges to unlocking this future is accelerating the feedback loop between biological design and product design to ensure commercial success. The biomanufacturing ecosystem is expanding to accomplish this. It is attracting pioneers across the public and private sectors to unlock the true potential of biomanufacturing and contribute to the growing bioeconomy, estimated to reach $4 trillion/year over the next decade.[1]

The pace of innovation in biomanufacturing is creating an opportunity for organizations to rapidly adopt cutting-edge manufacturing approaches while creating synergy with this ecosystem through partnerships and new investment. Furthermore, biomanufacturing has shown the potential to replace or enhance a diverse set of traditional industries with sustainable or more cost-effective alternatives while also unlocking solutions to major global crises. For instance:

– Fostering innovation: The bioproduction of existing and novel ingredients and materials is enhancing existing value chains while offering alternatives to petrochemically-derived ingredients and, in some cases, creating entirely new value chains.

– Addressing sustainability goals: Microbes are being engineered to transform pollutants and dangerous greenhouse gases into useful, less harmful by-products, creating solutions for major environmental crises.

– Enhancing biosecurity: Domestic biomanufacturing infrastructure and human expertise are key biosecurity competencies to enable the rapid increase in pharmaceutical production in response to pandemics such as COVID-19.

Recognizing this opportunity, the World Economic Forum brought together a group of leaders comprising the private and public sector, innovators, academia and civil society to identify the key collaborations required to accelerate a sustainable and innovative future of biomanufacturing.

Based on this consultation, in this paper we identify key strategies to enable bioeconomic development together with use cases from the community on:

1. *Strategic partnerships and investment* to accelerate progress in commercializing biomanufacturing concepts (section 1)

2. *Workforce transformation* to foster lifelong learning and upskilling by using key insights from STEM workforce development in adjacent industries such as ICT and pharma (section 2)

In the future, strengthened collaborations across industries and with the public sector will be crucial to continue expanding the potential of biomanufacturing. We are seeing that the most successful organizations are those able to assemble an end-to-end biomanufacturing strategy across the entire value chain through strategic partnerships and investments.

Fostering a robust biomanufacturing ecosystem will require collective action to address bottlenecks in biomanufacturing commercialization and workforce development. The World Economic Forum offers a platform for leaders from business, government, academia and civil society to continue sharing emerging opportunities and best practices in biomanufacturing, align on strategic priorities for public-private sector collaboration to facilitate the emerging bioeconomy and incubate pilot programmes and new collaborations that help accelerate the development of the sector.

Introduction

Biomanufacturing fostering innovation, addressing sustainability goals and enhancing biosecurity.

Biology has long been one of the most powerful manufacturing forces on the planet. Every organism encodes detailed instructions that prompt the self-organization of highly specific biochemical reactions. These instructions result in self-assembly with atomic precision, paired with the natural ability to self-replicate and scale globally. While biology has been the most tangible force of nature shaping the world for billions of years, it is only in the last century that we have developed an understanding of the genetic code: the underlying "programming language" of life. Just in recent decades, we have developed the ability to synthesize and reprogram this language by ourselves.

What is biomanufacturing?

Recent advances in life sciences have led to the growth of several different vertical markets with many applications in use today and many more on the horizon (see Figure 1). Biomanufacturing broadly refers to the use of a biological system to transform a component of a product or service's value chain. This definition can be applied to many aspects of production: raising livestock, such as using a cow to transform grass and grain into muscle mass to be harvested for food; in farming, traditional biomanufacturing uses plants to convert sunlight, soil and water into nutritive food. In the world of biotechnology, biomanufacturing is most commonly understood in the context of pharmaceutical production (e.g. insulin and vaccine raw materials) via fermentation processes taking place in liquid cell culture tanks, akin to a brewery set-up. Liquid-state fermentation is the most common approach for most modern biomanufacturing concepts today. However, new applications using solid-state fermentation to grow more complex biological tissues are already in development towards the growth of synthetic organs for human transplants and lab-grown meat products such as those produced by Upside Foods.

FIGURE 1 **Biomanufacturing across industries**

Emerging applications on the 10-year horizon

Human health & performance	– Nucleic acid vaccine technology enabling rapid pandemic response – Stem-cell derived transplantable organs
Agriculture & food technology	– Large-scale production of low-cost cultured meat ingredients replacing animal-derived alternatives – Optimization of crop microbiome to enhance growth metrics
Consumer products & services	– Custom personal care and nutrition services derived via treatment of gut and skin microbiome
Chemicals & materials	– Performance biopolymers offering innovative sustainable alternatives to plastics and animal-derived materials
Sustainability	– Biosequestration of CO_2 from atmosphere – Bioremediation of polluted wastewater

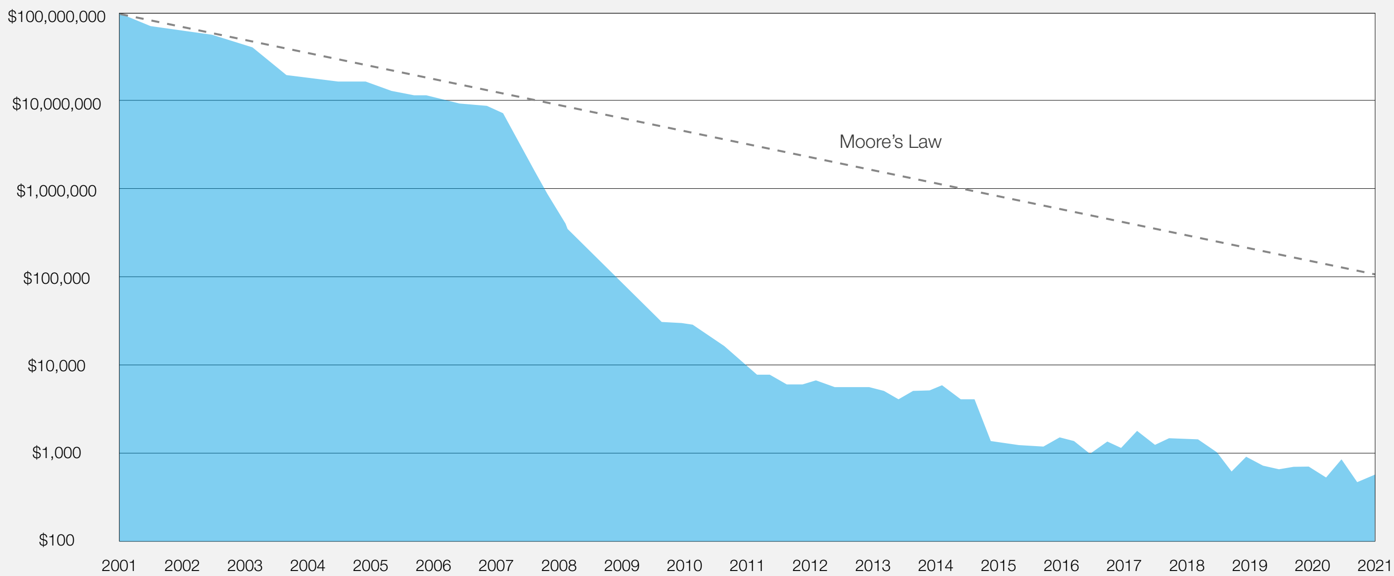
Source: McKinsey Global Institute, *The Bio Revolution: Innovations transforming economies, societies, and our lives* (2020)

Development trends

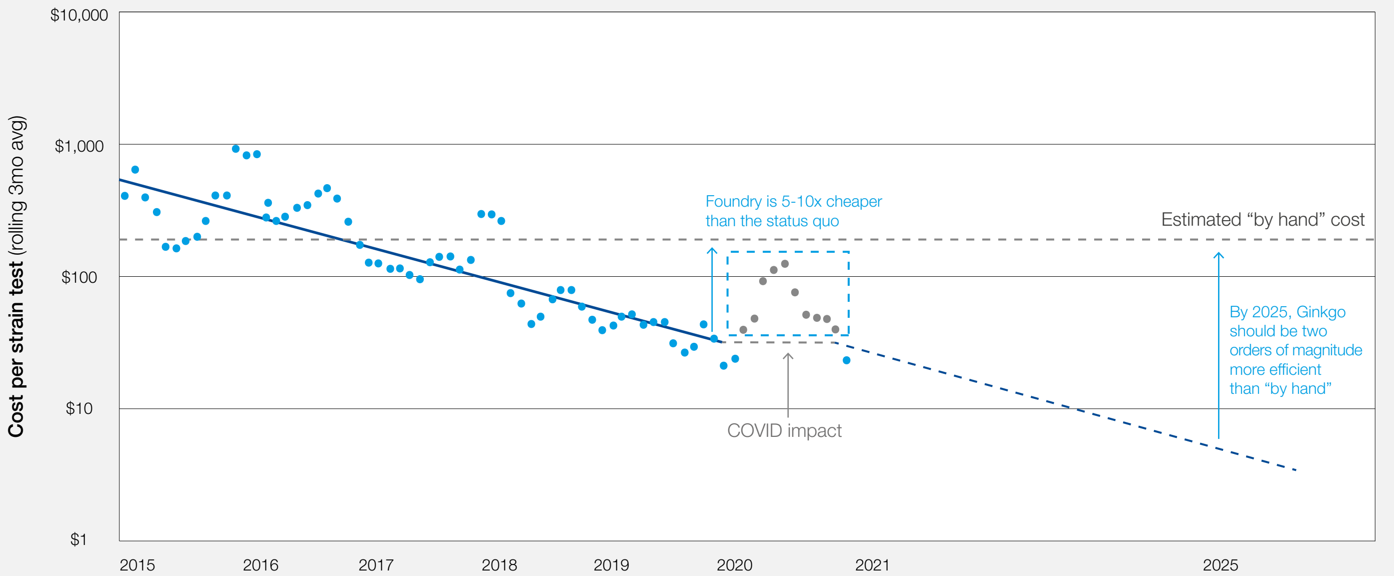
In 2001, the Human Genome Project (HGP) set out to assemble a reference sequence of the human genome, comprising 3 billion base pairs of DNA. Of the HGP's $2.7 billion total budget, the cost to sequence and assemble the complete human genome was estimated to be between $500 million and $1 billion. Over the past two decades, significant advancements have been made in DNA sequencing and synthesizing technologies, bringing the cost to do the equivalent work today to less than $1,000. The US National Human Genome Research Institute plots the cost per human genome over time on their website, overlaid with Moore's law – the phenomenon describing the increase in computer chip performance and a corresponding decrease in cost over time. Comparisons like this have supported an increasingly popular analogy between biology and computers regarding their cost, programmability and scalability (see Figure 2). This intersection between computational principles and biology has been crystallized in synthetic biology.

FIGURE 2 **Cost trends** (2021)

Cost to sequence human genome



Unit costs to program cells have decreased by 50% per year



Sources: National Human Genome Research Institute, *"The cost of sequencing a human genome" (2021)*[2]
Ginkgo Bioworks, *Investor Presentation (2021)*[3]

Furthermore, new synthetic biology "Synbio" startups are appearing with increasing frequency. Through the first three quarters of 2021, Synbio startups have amassed a best-ever $15 billion[4] venture capital investment and pioneers in the bioeconomy space are using increasingly advanced manufacturing solutions and technologies such as automation and advanced analytics to optimize development and enable new applications.

Companies like Ginkgo Bioworks are aiming to build economies of scale to systematically reduce engineering costs over time, characterizing this trend in biology as "Knight's Law"[5] (Figure 2), an analogous observation to Moore's law in the world of semiconductors. Just as Moore's Law preceded the ubiquity of the computer revolution, Knight's Law is a signal of the opportunity available in the biomanufacturing revolution to come.

The promise of biomanufacturing

What does a mature bioeconomy look like 10-15 years from now? According to a recent study by the McKinsey Global Institute,[6] there is an annual $4 trillion opportunity in the bioeconomy, with potential growth in multiple segments.

Fostering innovation

Traditionally, cost-prohibitive practices restricted biomanufacturing techniques to either high-cost/low-volume goods such as pharmaceuticals or low-cost/high-volume commodity chemical markets such as bioethanol production. Increasingly, improvements in biomanufacturing capabilities are altering the value proposition for new market segments that span a much broader segment of physical inputs to the economy. In fact, in the same study, it is estimated that as much as 60% of the physical inputs to the global economy could be derived from biomanufacturing. Furthermore, biomanufacturing can enable reductions in the cost of goods sold while also accelerating product innovation/performance, thereby redefining cost targets. Personal care, nutrition, food and materials are all seeing innovations in more efficient production methods and the development of novel and enhanced value chains. Over recent years, major consumer brands like Adidas, Chanel and Tyson Foods have all announced programmes to develop new biomanufacturing applications.

> Scaling partnerships to support faster prototyping and the transition to sustainable and impactful innovation.

Addressing sustainability goals

New biological applications hold the potential to solve some of the major environmental challenges in the next 10 to 20 years. Biological solutions are being developed to treat harmful pollutants from wastewater (bioremediation) and capture dangerous greenhouse gases from the atmosphere (biosequestration), creating solutions for major environmental crises posed by microplastics and climate change. Cultured meat and systematically improved crops adapted to the effects of climate change are poised to revolutionize current agricultural practices.

Enhancing biosecurity

Biological threats to human safety do not respect national borders. In a globalized economy, local diseases quickly transition to worldwide epidemics that cause global suffering, as demonstrated by the virus SARS-CoV-2.

Protecting against the next major pandemic requires a collective global approach and investment to bolster response capabilities everywhere. Ensuring safety for all nations and communities, including the most vulnerable demographics, will ensure a resilient global response. This requires the development of a highly trained local workforce and infrastructure. Biomanufacturing capabilities are becoming an essential element in biosecurity and will continue to be important in future pandemics to enable access to essential treatments.

Accelerating the biomanufacturing revolution

Recognizing these opportunities, the World Economic Forum brought together a community of leaders from business government, academia and civil society to identify the emerging opportunities where biomanufacturing could impact sustainability, economics and/or innovate new product development. With the new wave of development in this industry, the community identified two key strategies needed to accelerate an inclusive, sustainable and innovative future of biomanufacturing:

1. Scaling partnerships to support faster prototyping and the transition to sustainable and impactful innovation

2. Growth of a skilled workforce adopting best practices from recent STEM workforce development in adjacent industries to support continuous education and upskilling

1 Strategic partnerships and investment to accelerate commercial biomanufacturing

New opportunities for the co-development of applications across industries.

1.1 Product development partnerships

Strategic partnerships can be used to significantly accelerate the development and adoption of biomanufacturing approaches. Platform companies like Ginkgo Bioworks, Zymergen and Amyris offer new opportunities for the co-development of applications across industries. Partnering with and engineering on platforms built by these types of companies afford significant scale and cost advantages for new development work. Additionally, building application-focused biomanufacturing startups built on extensive experience in a particular technology area – for example, Impossible Foods, Bolt Threads, Perfect Day and Modern Meadow – can benefit from industry experts to help direct development towards the most important key performance indicators (KPIs) for product success.

Cell development toolkits

Platform companies leverage economies of scale in a particular technology ecosystem that is capable of serving diverse applications. As a proxy, most software applications in computing are developed from a common toolkit on a unique platform and software is decoupled from the application itself. Similarly, as fundamental biological unit operations become increasingly standardized, platform companies are enabling broader access to the bioeconomy.

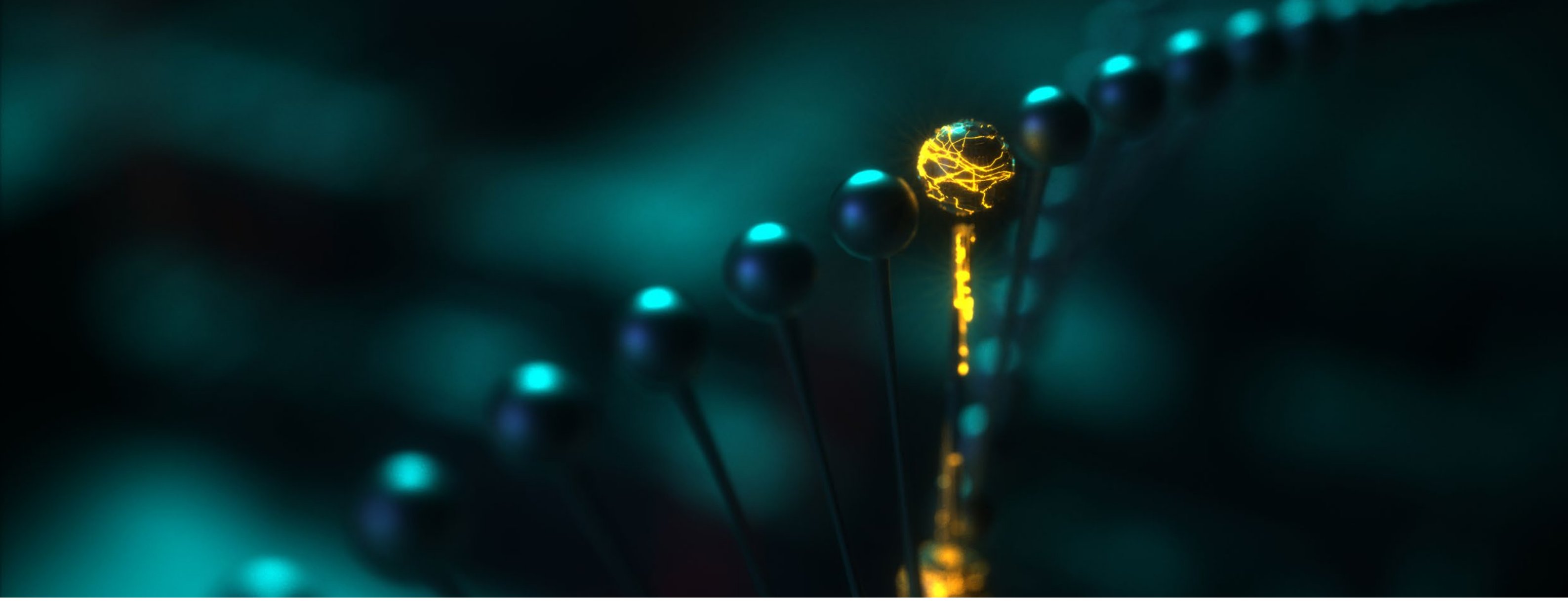
For example, Ginkgo Bioworks is developing a cell programming platform to make biology easier to engineer. Their platform assembles a comprehensive list of the tools, infrastructure and people that companies need to design and develop microbes for new applications, enabling the development of new products in close partnership with product-oriented companies that lack in-house capabilities for large-scale biological engineering.

Ginkgo has introduced a biological equivalent to software development kits, used to develop applications on iOS and Android, for example, by launching Cell Development Kits (CDKs) to lower the barrier to developing new biomanufacturing applications. Cell Development Kits contain everything needed to design a biomanufacturing concept: pre-engineered cells optimized for accepting DNA libraries, tools to design and print new sets of DNA, specialized equipment to build and grow the engineered organisms and the automation, expertise, and infrastructure to characterize and validate bioprocess performance.

Compared to the major financial, time and people investment required for new players in the biomanufacturing space to begin generating material to test new applications, these platforms offer significant cost savings to engage in biomanufacturing. This is especially attractive to technology pioneers to test and expand initial hypotheses without major capital investment. In parallel, larger companies are using these types of tools to explore new biomanufacturing solutions without the burden of developing lab spaces and teams. In addition to cost savings, CDKs are expected to reduce development timelines from years to a matter of months.

Sustainable product performance

The pace of upstream biomanufacturing progress (i.e. the biological production or fermentation of a molecule) is not currently matched by the pace of application testing and product development needed to bring a product to market. Synbio technology pioneers often bring deep technical experience to the production of a class of molecules, although they are not always the best suited to direct the downstream



processes to purify, isolate and manufacture a finished product from that molecule. Strategic partnerships with mature product companies offer a significant opportunity for technology pioneers to obtain the necessary feedback on core upstream KPIs for successful deployment while giving traditional manufacturers the opportunity to rapidly adopt a biomanufacturing strategy.

In 2020, Lululemon and Genomatica announced a partnership to develop a sustainable bio-nylon. Globally, nylon is a $10 billion/year industry derived from a petrochemical derivative, caprolactam.[7] Together, Genomatica and Lululemon are partnering to ferment plant sugars in a microorganism to produce caprolactam sustainably, creating an opportunity to eliminate the 60 million tonnes of nitrous oxide, a harmful greenhouse gas typically produced by petrochemical production. Genomatica has significant experience in biomaterials development and will probably accelerate further deployment of sustainable biomaterials while benefiting from product expertise from experienced manufacturers like Lululemon.

In addition to the significant reduction in greenhouse gases, bio-nylon also requires significantly less water and energy to manufacture, creating a competitive sustainability advantage over the petrochemical alternative. Even without enhanced material performance, the inherent sustainability of the bio-nylon production process becomes a "performance" metric that holds retail value for the consumers of Lululemon's luxury products. Capitalizing on the sustainability advantage aimed at consumers of luxury and high-margin markets can be a viable strategy to bridge the initial cost of development and adoption of biomanufactured goods.

Manufacturing technology partnerships

As the cost of biomanufacturing applications continues to decrease, the opportunity to employ sustainable and innovative materials is becoming commercially viable for more industries. Pharmaceuticals are generally produced at smaller scales (<1000-litre tanks) with higher manufacturing costs supported by the high margins associated with these products. At the same time, commodity chemicals such as bioethanol have been able to achieve positive economics at massive scales (>200-kilolitre tanks) where the manufacturing costs are distributed across larger batch sizes. Many potential biomanufacturing applications struggle to balance the high cost to produce at relatively smaller volumes until a market is established enough to support scaled-up production. Biomanufacturing costs are expected to continue to fall as advances in biological sciences improve the efficiency of these biotransformations. While partnerships with product companies can help accelerate market adoption for certain applications, partnerships with manufacturing technology partners can also create impactful synergies.

For instance, partnerships merging breakthroughs in synthetic biology with existing manufacturing processes are essential to accelerate the product development and testing needed to bring these challenging applications like biomaterials to market. Modern Meadow is a synthetic biology start-up platform based on the design and engineering of proteins for the biofabrication of sustainable performance materials. Today, Modern Meadow has focused their technology on developing a proprietary application platform – Bio-Alloy – comprising a blend of engineered proteins and biopolymers. The Bio-Alloy technology offers a variety of mechanical and thermal advantages while reducing greenhouse gas production by 60-85% relative to traditional leather, enabling a compelling entry into the materials market. This year, Modern Meadow launched a joint venture partnership, BioFabbrica, with world-renowned Italian textile and materials supplier Limonta to further accelerate the deployment and adoption of the new wave of performance biomaterials. By combining Modern Meadow's patented Bio-Alloy Application Platform with Limonta's extensive experience in cutting-edge materials manufacturing processes, BioFabbrica is poised to deliver sustainable biofabricated material solutions that meet brands' unique performance and design expectations.

1.2 Scaling the deployment of new solutions

Scaling partnerships offers an opportunity to expand the biomanufacturing ecosystem and aggregate synergistic expertise and technologies to increase the rate of commercial biomanufacturing successes.

Much of today's biomanufacturing capacity is pharma-oriented and presents a challenging cost structure for new low-cost biomanufacturing applications. Downstream capabilities to chemically and physically isolate targets for applications in alternative biomanufacturing arenas are not as sophisticated as the infrastructure developed for pharmaceutical applications. As a general principle, early prototyping is essential in commercializing biomanufactured goods to ensure equivalence and/or compatibility with the intended application. This would allow for additional upstream engineering cycles if needed. The lack of this early prototyping becomes a major pitfall in bioengineering campaigns for technology pioneers.

As an example, access to commercial demonstration scale for non-pharma-related applications is gating to biomanufacturing applications. Producing an initial prototype batch or initial commercial production run, however, poses a significant financial and logistical challenge for early-stage products for biomanufacturing. Although there has been significant success in these types of applications by historical leaders in fermentative manufacturing (e.g. DSM, Cargill), carrying the costs of development and manufacturing scale is a capital-intensive process for technology pioneers bringing new manufacturing concepts to the market. Today, academic labs can perform small-scale process demonstrations but are often limited by diversity in equipment/capabilities. Alternatively, contract manufacturing organizations can offer large-scale solutions, but these organizations are often expensive to partner with and require existing commercial demand. At the same time, improvements in the automation and sophistication of upstream process development technology (e.g. Sartorius' ambr250, Culture Biosciences, Univercell) are reducing the importance of having an in-house manufacturing footprint, enabling more rapid technology transfer across production.

The biomanufacturing co-operative

The current scattered state of pilot and prototyping capabilities for biomanufacturing applications points to the need for pre-competitive bioprocess demonstration facilities designed with the flexibility of applications achievable today. Public-private programmes such as "biomanufacturing co-operatives", where organizations co-invest and co-design, could enable technology pioneers to accelerate prototyping and application testing, increasing the overall success rate for biomanufacturing applications. Many upstream equipment needs are shared among biomanufacturing applications and can enable versatility across market segments and biosecurity applications. Downstream capabilities are much more diverse and require thoughtful design and significant investment to span the necessary range of applications but address a major barrier to biomanufacturing prototyping. The following section explores the characteristics of such a model.

Co-operative design needs

Most biomanufacturing opportunities today are derived through culturing microbes in a stirred tank to perform a biotransformation on low-cost feedstock. Today, proteins for meat-free burgers, chemicals like caprolactam for bio-nylon and the plasmid DNA starting material for COVID-19 vaccines all begin with microbial fermentation. Depending on the application, there can be variations in tank size, specific process control needs and regulatory compliance (e.g. oxygen feeds, solvent rating, Good Manufacturing Practice compliance), but the major capital components and capabilities are similar.

While the toolkit for engineering biology is shared across the biomanufacturing ecosystem, each product application requires unique processing constraints to achieve the key performance metrics for product success. The pipeline of upstream bioprocess development to biologically produce desired goods is expanding and accelerating in step with the maturation of biological engineering capabilities. The same cannot broadly be said for the downstream unit operations required to isolate the product and prepare it for product application. Outside of the biological component of biomanufacturing, there is a diverse set of chemical, physical, thermal unit operations needed to extract and process target products from biological systems for a variety of applications, as shown in Figure 3.

FIGURE 3 | **Cost trends** (2021)

It is imperative to initiate downstream development as early as possible in the biomanufacturing development cycle to ensure minimum acceptable performance against core product KPIs and avoid product integration challenges after extensive capital and time investment. Successful integration of biomanufacturing applications depends on the ability to test the newly derived raw input in the product context – stress testing finished biomaterials, sensory testing of flavour and fragrances and nutritional studies of new ingredients. These application testing methods are only possible following the design of all upstream and downstream unit operations to purify and isolate the final product. Overall, these operations have not benefited from the same automation and scaledown as most upstream biological steps, requiring these types of demonstrations to take place at a larger scale, larger than what makes sense for an SME to invest in during development. Many startups waste valuable time and resources accumulating niche production scale before validating the commercial viability of the intended application.

Scaling partnerships offers an opportunity to expand the biomanufacturing ecosystem and aggregate synergistic expertise and technologies to increase the rate of commercial biomanufacturing successes. Joint programmes, such as those described in this section, would aggregate the necessary resources and expertise to bolster biomanufacturing product deployment capabilities. Investment in the creation of cutting-edge, collaborative spaces and manufacturing resources will break down a major barrier to the commercialization of new biomanufacturing applications by tech pioneers and accelerate bioeconomic growth.

2 Workforce transformation

Fostering lifelong learning and upskilling.

In addition to technological advancements and strategic partnerships, urgent action is vital to accelerate the growth and breadth of the future workforce to power the biomanufacturing revolution. The evolution of traditional manufacturing into biomanufacturing will create the need for entirely new skill sets in various workforce segments, creating synergies with recent skill developments in automation and digitalization.

Historically, the perception of the workforce opportunity in the biomanufacturing space has been centred on highly technical, high salaried positions requiring extensive higher education. In addition, these types of jobs have been localized in urban/metropolitan centres near elite academic and technology institutions. As biomanufacturing expands, workforce opportunities are expanding across the manufacturing value chain and geographies.

2.1 Emerging opportunities

The biomanufacturing revolution is changing the traditional hierarchy of the biotechnology workforce. The development and deployment of a biomanufacturing process from upstream biological engineering, through manufacturing and down to product integration and marketing, require a diverse set of interdisciplinary, cross-functional skill sets. This ecosystem will continue to require a postgraduate-trained workforce for a subset of upstream bioengineering roles. However, biomanufacturing is creating additional opportunities in automation and software engineering, chemical and materials engineering, skilled-labour manufacturing and cross-functional roles that bridge gaps and support product integration.

“ The biomanufacturing revolution is changing the traditional hierarchy of the biotechnology workforce.

Biomanufacturing requires the development of a new segment of “cyan-collar” manufacturing jobs – the intersection between sustainable green technologies and traditional “blue-collar” manufacturing.[8] Today, many of these positions are accessible with a four-year undergraduate degree. Automation and digitalization are standardizing skill sets across manufacturing technologies, enabling the development of targeted trade certificate programmes and creating opportunities to reskill existing manufacturing workforce segments that biomanufacturing may disrupt. It is important to note that the growth of these cyan-collared jobs is particularly relevant in rural areas. Many low-cost feedstocks for common biomanufacturing applications are agriculturally derived close to fermentation facilities, creating the opportunity to grow skilled jobs outside major cities.

Similarities are evident in the ICT industry. The computer revolution led to the creation of the software developer, which today accounts for approximately 24 million accessible, high-paying jobs worldwide. Software developers are the backbone of the digital economy and are essential for nearly any business engaging in a digital strategy. Similarly, this segment of the biomanufacturing workforce that will design and develop applications on increasingly automated and digitalized platforms is expected to expand significantly with entry opportunities for those with a two- or four-year degree.

Nevertheless, technical innovation in biological engineering/capabilities will still be largely driven by PhD-level scientists and academia, a workforce segment that will continue to grow. There will also be a new class of entrepreneurs growing apps on biological platforms that will not necessarily require biological sciences expertise but rather soft skills such as vision and creativity to design with biology.

2.2 Workforce strategy

Over the past two decades, there has been significant growth in the science, technology, engineering and manufacturing (STEM) workforce driven by the success of ICT and the chemical, energy and pharmaceutical industries, leading to a growth of high-income skilled-labour positions. For example, ICT specialists accounted for 7% of the total employment in Canada in 2020.[9] The biomanufacturing workforce of the future will share many of the underlying skills in automation and digitalization shared across the broader STEM community today, creating an opportunity for workforce mobility as well as shared best practices for workforce development. A recent study by the International Labour Organization (ILO) of the ICT sector in seven countries – Canada, China, Germany, India, Indonesia, Singapore and Thailand – yielded 10 possible policy recommendations to foster workforce development (see Figure 4).

FIGURE 4 **ILO labour study key findings and possible policy responses for an ICT workforce**

Ten possible policy responses that could help inform dialogue among governments and employer and workers' organizations and facilitate the formulation of effective policies to advance equitable work opportunities for more people in the digital economy:

1. Invest in a skill anticipation system to enhance understanding of current and future skills needs.
2. Increase investment in post-secondary education institutions and teaching staff.
3. Encourage more women to study science, technology, engineering and mathematics (the so-called STEM subjects) and pursue careers in the field of ICT.
4. Tackle the skills gaps between the skills acquired at universities or vocational training institutions and the skills demanded by industry.
5. Increase the focus of education and training on soft skills.
6. Promote interdisciplinary approaches to skills development.
7. Invest in effective lifelong learning systems and continuous training in the field of ICT.
8. Facilitate better recognition of formal foreign qualifications and work experience.
9. Simplify visa application processes and provide support for migrant ICT specialists to facilitate their integration into their new working and living environments.
10. Promote coordination among relevant ministries and authorities and strengthen social dialogue.

Source: ILO, "The Future of Work in ICT" project (2020)

The analogy between the computer revolution and the ongoing biological revolution goes beyond the parallels in technical and economic trends but also shares similarities in the strategies needed to grow and support a highly technical workforce for a rapidly changing industry. Industry leaders like Johnson & Johnson are exemplifying several of these principles, orienting internal workforce development programmes to foster continuous interdisciplinary development (see Figure 5). Expansion and standardization of these types of programmes across the industry will be essential in developing and maintaining the future workforce as this industry continues to evolve.

FIGURE 5

Johnson & Johnson's support of lifelong workforce development

Building the learning journey		
Define critical capabilities needed for the future	How should future capabilities change?	What underlying skills link to each critical capability (by role)?

Workforce solutions	
Digital primers: Online training modules tailoring skills and skill level to target workforce segments along individual learning journeys	Janssen Digital Badges: A gamification program designed to track accomplishment of individual and leader-led challenges leveraging digital tools within the Janssen Genius ecosystem

Source: Johnson & Johnson, Community Insights (2021)

Focusing on workforce transformation to expand the diversity of opportunities in the bioworkforce and leverage best practices for continued education and upskilling will be essential to unlocking the biomanufacturing revolution. A diverse and agile bioworkforce is needed to power industry growth and establish local biosecurity, securing the human expertise essential to manufacturing critical pharmaceutical applications in response to potential pandemics.

2.3 Taking action to accelerate the biomanufacturing revolution

Leaders in the biotechnology space today are already taking action, focused on the two enablers described in the previous sections. Specifically, organizations are taking steps to:

- Encourage collaboration and innovation through investment in pre-competitive access to cutting-edge manufacturing technologies and spaces
- Develop academic-industry partnerships to identify workforce needs and fill skill gaps

As an example, Singapore has been encouraging a domestic biopharma sector. Since 2000, the country has made significant investments in partnership with industry leaders to bolster infrastructure and workforce development to enable a local ecosystem of biopharma innovators that can contribute to the growing Asian and global markets (see Figure 6).

FIGURE 6 **Singapore biopharma development**

	Approach	Impact
Infrastructure	Establishment of ready-built facilities such as the JTC Space at Tuas Biomedical Park.	– AnT continues to be a robust pipeline of skilled workers with more than 170 training places filled to date. – Since 2000, Singapore's pharma sector manufacturing output has increased more than 3X, producing more than $16 billion worth of products for global markets. – The skilled workforce has more than doubled. – Today, 8 of the top 10 pharmaceutical companies have facilities in Singapore, where they manufacture 4 of the top 10 drugs by global revenue.
Investment	$4 billion in public sector research funding committed to health and biomedical sciences.	
Workforce development	Attach and Train (AnT) Programme in partnership with leading pharmaceutical companies such as Lonza and Amgen, where graduates undergo on-the-job training to ensure that graduates from local universities possess the most relevant skill sets.	

Source: Singapore Economic Development Board, *Overview of the Singapore PharmBio Sector* (2018); *Pharmaceuticals & Biotechnology* (n.d.)

Community call to action

Consultations and workshops conducted with the World Economic Forum's Accelerating the Biomanufacturing Revolution initiative have provided best practices and validated the importance of strategic partnerships and investment to enable commercialization across the value chain and workforce development to accelerate the opportunities for green skilled labour. Companies that engage in this ecosystem today, deploying the first wave of biomanufacturing concepts, will be the champions of this journey and consistently have the greatest impact on innovation as well as society and the environment. This is a natural effect of assembling diverse stakeholders, internally and across value chains, to address cross-functional challenges in this space.

Almost all manufacturing companies have the opportunity to reap benefits from the biomanufacturing revolution, but no company is poised to achieve this future in a vacuum. Because of the constantly evolving technology and practices, companies need to continuously innovate and share key insights.

In future, the World Economic Forum will continue to identify best practices and recognize those who pioneer and lead the journey towards deploying impactful and sustainable biomanufacturing processes. The Forum will also further support the incubation of new pilot projects, the scaling up of cross-company and public-private collaborations and bringing existing initiatives and coalitions together. These are critical steps towards accelerating the biomanufacturing revolution, a world of sustainable and innovative inputs to the global economy, creating new economic opportunities and technological solutions to the major societal and environmental challenges ahead.

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Endnotes

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