GLOBAL TRENDS

APRIL 2021

STRUCTURAL DRIVERS OF THE FUTURE

TECHNOLOGY TRENDS

The Future of Biotech

NIC-2021-02494

Many forecasts during the past 30 years have anticipated amazing advances in biotech—including cures for disease, eradication of hunger, and the means to transition away from petrochemical dependence—but the story of biotech has been one of incremental gains in food and material production, and medical advances. During the next 20 years, however, biotech is likely to transform a broader range of human experiences. A more multidisciplinary, digital, and data-rich approach to life sciences is accelerating the understanding of and ability to predictably manipulate living matter, although market, regulatory, and normative conditions will moderate the pace and focus of progress. Biotechnology probably will improve many aspects of human existence; however, the pursuit and possible application of these technologies may also create social and economic disruptions and raise numerous ethical questions.

This paper was produced by the National Intelligence Council's Strategic Futures Group in consultation with outside experts and Intelligence Community analysts to help inform the integrated Global Trends product, which published in March 2021. However, the analysis does not reflect official US Government policy, the breadth of intelligence sources, or the full range of perspectives within the US Intelligence Community.

BIOSCIENCE POISED TO ACCELERATE

Over centuries, our use and manipulation of life processes in agriculture, medicine, and manufacturing have progressed incrementally, punctuated by leaps in understanding brought about by key discoveries, such as Mendelian genetics, Germ Theory, and DNA. These leaps could not have happened without the development and acceptance of novel tools and algorithms for detecting, imaging, and manipulating biological systems.

During the next 20 years, a more multidisciplinary and data-intensive approach to life sciences will shift our understanding of and ability to manipulate living matter. Scientists are increasingly treating genetic instructions as a form of computational code and incorporating insights and new tools from the rapidly advancing realm of computational science. These disciplines, combined with cognitive science, nanotechnology, physics, and others, are propelling new leaps in our understanding. It is anticipated that the collective application of these diverse technologies to the life sciences—known as bioconvergence—will accelerate *discovery* and *predictability* in biotech design and production. This multidisciplinary approach has made it possible to:

- Visualize, measure, identify, and manipulate biological systems at molecular scales
- Treat genetic instructions in DNA, RNA, and amino acids like a language that can be written, edited, and executed with high precision to synthesize useful materials or organisms
- Collect, digitize, store, and analyze genetic instructions, referred to as genomes, from many thousands of individuals, along with their physical, mental, and health traits to correlate how specific genetic instructions interact with the environment to produce distinct traits
- Combine complex biological and nonbiological processes, such as bioelectronic interfaces for sensing or stimulating biological systems in support of medicine, agriculture, and manufacturing

FACTORS SHAPING BIOTECH'S TRAJECTORY

Economic, social, and political factors are likely to influence the pace and focus of biotech research and the availability of products.

Increased Investment and Decreasing Cost

These economic factors together will be pivotal to future biotech breakthroughs and applications. In 2019, the global bioeconomy, defined as all activity enabled by research and innovation in the life sciences and biotechnology, accounted for about $5 trillion, or nearly 6 percent of global GDP. Based on 10-15 percent annual revenue growth trends, the world bioeconomy could exceed $20 trillion by 2030. A drop in the cost of key enabling technologies could spur application of biotech to a wider set of challenges and potentially democratize aspects of biotech R&D and production, increasing its global accessibility.

Regulatory Restrictions

Such restrictions could prevent or reduce funding, production, or public acceptance of biotech. Bans, restrictions, or modification of standards could emerge in response to accidents, unintended consequences, or public pressure. Greater restrictions could reduce the number of people choosing to enter the field, leading to heightened competition for personnel and shortages of expertise.

International Acceptance

Conversely, international acceptance could increase funding, production, and public acceptance of biotech. Signed treaties or conventions, shared recognition of the need to prevent future pandemics, or biotech advocacy by influential voices on the world stage could encourage global acceptance—a development that probably would motivate more people to pursue formal study in the biosciences.

Large-Scale Collaboration and Cooperation

Whether endorsed by the international community or arising from commercial or grassroots initiatives, large-scale collaboration could significantly accelerate biotech R&D. Open, normatively, and legally guided collaboration would be likely to increase the diffusion and accessibility of technologies and expertise, accelerating the resolution of health and environmental challenges. Less visible collaboration among researchers, startups, and hobbyists—focused on cosmetic, covert, or norm-challenging advances—could also drive breakthroughs, even if a political or regulatory support regime were absent. In such cases, breakthroughs probably would outpace the bounds of extant policy and law.

Changes in Consumer Demand

In response to a health crisis such as COVID-19 or food shortages, consumer demand could quickly shift in favor of biotechnology alternatives; consumer interest in cheaper, more nutritious, less environmentally damaging, and animal-free foods would spur biotechnology-derived alternatives. Genetically modified organisms (GMOs) are likely to become more accepted, and therefore, more prevalent, displacing some traditional agricultural sources. It is anticipated that culture grown alternatives to meats and fish will also become common, with similar effects on livestock industries.

Responses to Environmental Change

Biotech is likely to receive increasing attention and support in the coming years as a way to sustain sufficient production in the face of changes in global norms and policies related to land and water usage or carbon emissions. The emergence of policies that give preference to environmentally constrained or carbon-neutral technologies could endow some biotech solutions with global or regional regulatory, normative, or market advantages. Some environmental changes could create situations in which the most effective way to sustain local production of traditional food sources might be through genetically engineered surrogates.

BIOTECH APPLICATIONS AND POTENTIAL IMPLICATIONS

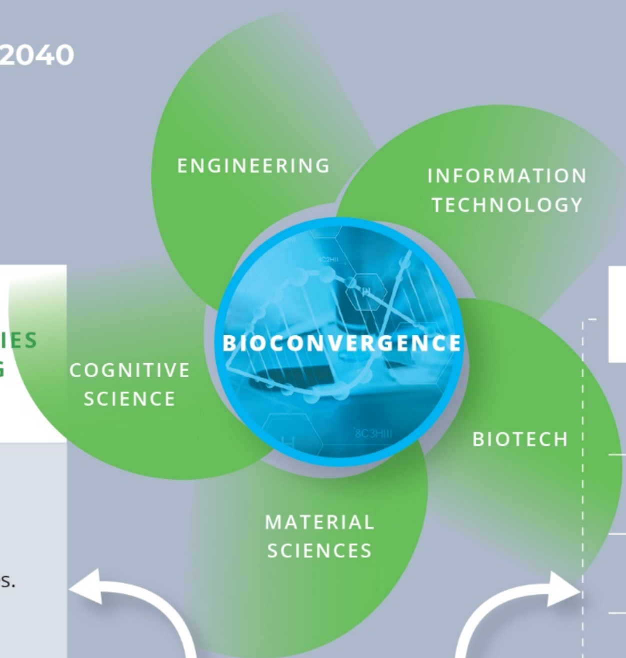
During the next two decades, we anticipate that biotechnology may deliver any or all of the following eleven outcomes. These applications hold promise for improving health and living conditions; however, they are accompanied by potential societal disruptions, ethical concerns, or security challenges. Each application might require a combination of technological advancement and human decisionmaking regarding application or consumption.

Digital Healthcare and Precision Medicine

Medical professionals, medical diagnostics, and personal Internet of Things (IoT) devices are already collecting an increasing volume of health data. This information is being fused with other personal information, digitally recorded behaviors, and cyber indicators to radically improve prediction of new diseases, as well as treatment outcomes. Even so, this data merging could erode physical and digital anonymity, allowing governments, corporations, or individuals to target or discriminate against persons based their biosignatures, assessed or forecasted health status, or inferred genetic traits. Regulations in some countries limit the potential for this capability to create or amplify social inequality, whereas in other countries, practices such as the creation of “social credit” scores could easily incorporate genetic criteria.

GRAPHIC 1

BIOCONVERGENCE 2040



RAPIDLY EVOLVING TECHNICAL CAPABILITIES ARE NOW ENABLING RESEARCHERS TO:

- Visualize, measure, identify, and manipulate biological systems at increasingly smaller scales.
- Read, write, edit and execute DNA, RNA and amino acids sequences with high precision to synthesize useful organisms and materials.
- Collect, digitize, analyze and store population scale volumes of biological, behavioral and environmental data to learn and predict how genes, environment and lifestyle work together.
- Create and merge biological and non-biological materials with novel properties.

FACTORS SHAPING BIOTECH

- *Investment*
- *Regulation*
- *Acceptance*
- *Collaboration and cooperation*
- *Demand*
- *Responses to environmental changes*
- *Geopolitical competition*

EMERGING APPLICATIONS

- *Digital / Personalized healthcare*
- *Bioprinting / Xenotransplantation*
- *Reproductive Engineering*
- *Biosystems / Ecological Engineering*
- *Computer-Human Interfaces*
- *Biomanufacturing*
- *DNA storage*
- *Eradication of major diseases*
- *On demand medicines*
- *Synthetic organisms*
- *Transformation of agriculture and food production*

Bioprinting of Organs and Other Individualized Therapies

Therapies that use genetic-based medicine and cellular engineering specific to an individual person, otherwise known as bespoke medical therapies, are already available to treat some conditions—albeit at a high cost. During the next 20 years, the range of conditions and treatments these techniques will be able to address is likely to grow, including printing of tissues and the creation of genetically tailored animals to produce human organs compatible for transplantation. Although these treatments are expensive, they may be less costly than decades of treatment for chronic diseases, such as diabetes. However, this more tailored approach to medicine may not be within reach of most people during the next 20 years, and disparity of access to the most advanced techniques could make equal access to health care an even more fraught topic of public debate.

Reproductive Engineering to Enhance Human Traits and Performance

Technology now exists to enable screening and selection or rejection of fertilized human embryos based on desired genetic traits, and genetic modification of human life in these embryonic stages is increasingly possible. Near-term practices in this field are likely to focus on avoidance of adverse health outcomes and the selection of desirable physical traits. As costs for these procedures fall and reliability increases, a growing number of people and societies may be tempted to pursue trait selection as a means to protect or advantage their children, or to alter the health and productivity dynamics of entire populations. Before 2030, practices may include selection or modification for more well understood cosmetic features, such as height and eye or hair color, and may even progress to include traits such as intelligence or personality as confidence in the safety of the techniques grow. These practices may intersect with significant cultural and moral fault lines and probably will not be available to large segments of the global population, or possibly be mandated in others, raising the potential for inequality within and between states.

Ecological Engineering

Plants, animals, and microorganisms could be selected and modified to stabilize an environment, reduce human impact, or improve productivity. Ecosystems could be engineered to enable production of food, materials, and even energy in ways that consume less fresh water, require less arable land, and enable productivity in formerly unproductive or inefficient settings—potentially ranging from depleted farm fields to the surface of Mars. Genetic modifications are already enabling crop productivity in areas where saltwater incursion is occurring or farming has never been possible.

Harmful applications of genetic modification are certainly possible; however, this application of biotech has already exhibited great potential to address needs and reduce conflict. Future risks include greater pressure on fragile ecosystems as they become more readily exploitable by humans, the displacement of native plant and animal species, and unintended second-order consequences on consumers' health. Industrial-scale actors able to overcome regulatory, technical, and market challenges are more likely to advance this outcome, raising the possibility that costs and benefits will accrue unevenly, advantaging specific countries, communities, or firms.

Computer-Human Interfaces

The fusion of machine and human capability occurs in various forms and at different levels of integration. Noninvasive or virtual augmentation of physical, visual, tactile, and auditory senses through gloves, glasses, and headsets is common in gaming, learning, and telework. Electroencephalographs and electrical or magnetic transmitters worn on the head enable similar uses through stimulation and detection of brain activities. This form of manipulation has been shown to marginally enhance perception, memory, and attention. Invasive neural interfaces that directly connect brain or nervous tissue to computers are commonly used to correct neurological conditions, but all the current forms of brain-computer interaction occur at very low data-transfer rates.

Human-machine networks currently in development may be able to overcome these limitations, radically increasing the rate of data transfer, expanding the range and depth of human perception and cognitive capabilities. Although initial uses of these hybrid systems may be for medical treatments to overcome neurological conditions, nonmedical uses are already being explored. These uses are likely to include new forms of social interaction, entertainment, and tools giving competitive advantage to “power users,” who are able to use the systems to solve hard problems or gain market advantage. Unintended consequences may include leaps in the adverse consequences of cyber attacks and technically enabled influence operations. As the divide between enhanced interface “haves” and “have-nots” grows, it may fuel new cultural, social, and workforce tensions.

Biomanufacturing of Materials and Devices

Automation and data-driven processes are increasingly being incorporated into biotechnology, and anticipated to radically improve the predictability and reproducibility of research and manufacturing outcomes by 2040. Automated molecular assembly techniques with DNA and other biomolecules probably will push engineering and design capabilities further into the nanoscale application space, hastening the convergence of biological and digital technologies. In some current industrial processes, such as the creation of chemical feedstock, fermentation, enzymatic processing, and medicine production, automation has already become routine. Also routine are genetically modified organisms (GMOs) used in industry and agriculture that are consumed as foods, albeit often with labeling or regulatory restrictions. Most developed nations have instituted policies that mandate identification of GMO products, but not all, suggesting that global polices regulating GMO’s are still evolving.

Just as genetic modification may enable production with less fresh water or land, it may also enhance or tailor output in fertile environments, bypass traditional hydrocarbon input sources, reduce reliance on chemical fertilizers and pesticides, or enable new production paths that create less atmospheric greenhouse gases. For example, biologically altered plants or fungi may be used as sources of nonanimal protein for human consumption or to grow carbon-negative structural materials. Such applications are likely to emerge gradually, possibly in response to new policies that penalize water, pesticide, or carbon-intensive legacy processes, or because economies of scale develop around biotech alternatives, making them more economically attractive.

DNA-Based Data Storage

Use of DNA to encode and store data is already technically feasible and being demonstrated in laboratories, and DNA or similar chemical polymers probably will be used to store data for archival purposes within the next 20 years. With an orders-of-magnitude greater storage capacity than most current technologies, synthetic DNA might become a preferred medium for applications that place a premium on data volume and longevity, and, low power. In an increasingly instrumented and hyperconnected world, the ability to store vast quantities of data for long, perhaps indefinite periods could enable new forms of long-term social monitoring, engendering capabilities that could be used to control as well as protect.

Cures or Eradication of Many Diseases

Eradication of most common diseases may be possible within the next 20 years, spurred on by a range of biotech advances, including disease vector control and the development of new medical treatments and preventive medicines. However, real-world execution is unlikely to match the theoretical health potential because of uneven global access to these technologies within this period. Instead, there probably will be debate over which diseases to prioritize for elimination and significant variability in access to treatment, driven primarily by market forces.

Global efforts to address contagious and deadly maladies, such as malaria or tuberculosis, could offer significant improvements in productivity, quality of human life, and longevity. In such cases, inequality and conflict would be less likely as first-order consequences but could still arise in response to rapid shifts in labor forces or more gradual demographic changes. For example, eliminating malaria would relieve vast suffering but, over time, could also local communities with generations of young people they cannot employ.

On-Demand Medicine Production

The ability to rapidly produce new treatments and vaccines at scale could prove to be a critical factor in a country or region's ability to respond successfully to natural or artificial pandemics. The COVID-19 pandemic created a global shock that increased investment in medical technology. Such capabilities could contribute to inequality or drive conflict if a large-scale public health crisis produced different outcomes between groups with and without access to the technology.

Synthetic Organisms

The creation of living reproducing organisms based on an expanded genetic code and amino acid repertoire could be common in research settings and some parts of industry within the next 20 years. The ability to do this routinely would mark a milestone in the human understanding of living processes and represent an inflection point in the pace of biotech discovery and application. Creation of synthetic organisms is likely to catalyze greater investment in biotech and amplify debates about the direction and goals of bioscience. The creation of never-before-seen organisms, materials or therapeutics, even if designed solely for beneficial purposes, is likely to spark concerns about broad availability to the global population and debates about benefits and potentially dangerous uses.

Transformed Agriculture and Food Production

Within the next 20 years, new food production and preparation processes may be increasingly conducted in highly automated, environmentally controlled conditions that use genetically altered organisms, potentially displacing conventional agricultural practices as the major form of food output. Present day forerunners of these technologies are used in large-scale controlled environment farms, and in the factory cultivation of gene-altered fish, staple crops, and meat substitutes.

Impacts on communities and the environment will vary depending on the species, process, and location. These future farming techniques–while unlikely to create conflict between nations–have the potential to create both healthy and harmful effects on communities and ecosystems. For example, some experts assess that integration of modern technologies into rural farming in Africa has both raised output and created incentives for aspiring "high-tech" youth to remain engaged in local communities. In contrast, sporadic illness in US factory-farmed fish and the supposed damaging health effects of herbicide tolerant GMOs have led to public opposition; Automation of labor-intensive harvesting practices is displacing labor, and further tilting agricultural production in favor of corporate-scale actors.

BROADER SOCIETAL IMPLICATIONS

Biotech offers the possibility of improving and making more sustainable human health, the environment, agriculture, and modes of production. Conversely, biotech and the growth of the bioeconomy may also create disruptions and compound existing challenges, including expanding inequality, aggravating international competition, and intensifying ethical debates about what it means to be human.

Unequal Access and Benefit

During the next 20 years, biotech advancements, particularly expensive, tailored technologies, are likely to be unevenly distributed within and between countries. Although some of the emerging biodevelopment models prioritize widespread collective benefit, biotech will remain an R&D-intensive, profit-driven, and largely commercial undertaking. Consequently, the leading edge of what it can offer probably will remain out of reach, at least initially, for many people, even as many biotech products become commoditized and commonplace.

Geopolitical Competition

Biotech has historically been concentrated in a limited set of countries because it depends on clusters of innovation that harness extant academic and technological communities, but countries are looking to lure both firms and talent to catapult their domestic industry.

- Biotech expertise is global and similar to artificial intelligence and other advanced technologies; firms in the United States, China, and other countries are increasingly competing for the best biotech talent.
- Although access to visionary human talent is critical to biotech *research*, the coming era of automation may see biotech *manufacturing* shift to places with access to key production resources and inexpensive labor, or regulatory permissiveness.
- Biotech can be a driver of local innovation as industries with convergent capabilities collocate in response to favorable government policies that encourage biotech development. Countries with focused policy support and an agile regulatory regime may be better able to harness biotech to advance national economic, health, or security objectives.

Evolution or Devolution?

As the ability to alter human traits and capabilities both before and after birth increases, we probably will see debate, or even conflict, about the limits and implications of manipulating human biology. Biotech may offer greater control and predictability of human form and behavior, allowing for specialization to impart compatibility with machine interfaces, for personal reproductive or performance advantage, or to effect scaled social change. The promise of improved health and longevity is likely to increase support for its implementation, while at the same time raise concerns about how societies should prepare to manage a much healthier, longer-living population. Biotech alteration of humans also holds the potential to create medical dependence, nonmedical advantage, or inequality between those who are, and are not, altered.

We anticipate that some people and societies will embrace these challenges, and some will seek to control the availability of these options to advantage or protect themselves and their allies. Some individuals will reject the new orthodoxies by abstaining from human engineering—becoming rebels or even refugees from the prevailing bionormative regimes. The differences that arise from the application of these technologies are likely to pose social, legal, and cultural challenges. Even if human engineering is not widely permitted or practiced, it could join other risky medical tourism practices, such as stem cell treatments offered in countries without clinical protections or enforced regulations. During the next 20 years, biotech could become a factor in divisive identity politics as different communities or countries grapple with foundational questions about human evolution and the environment.