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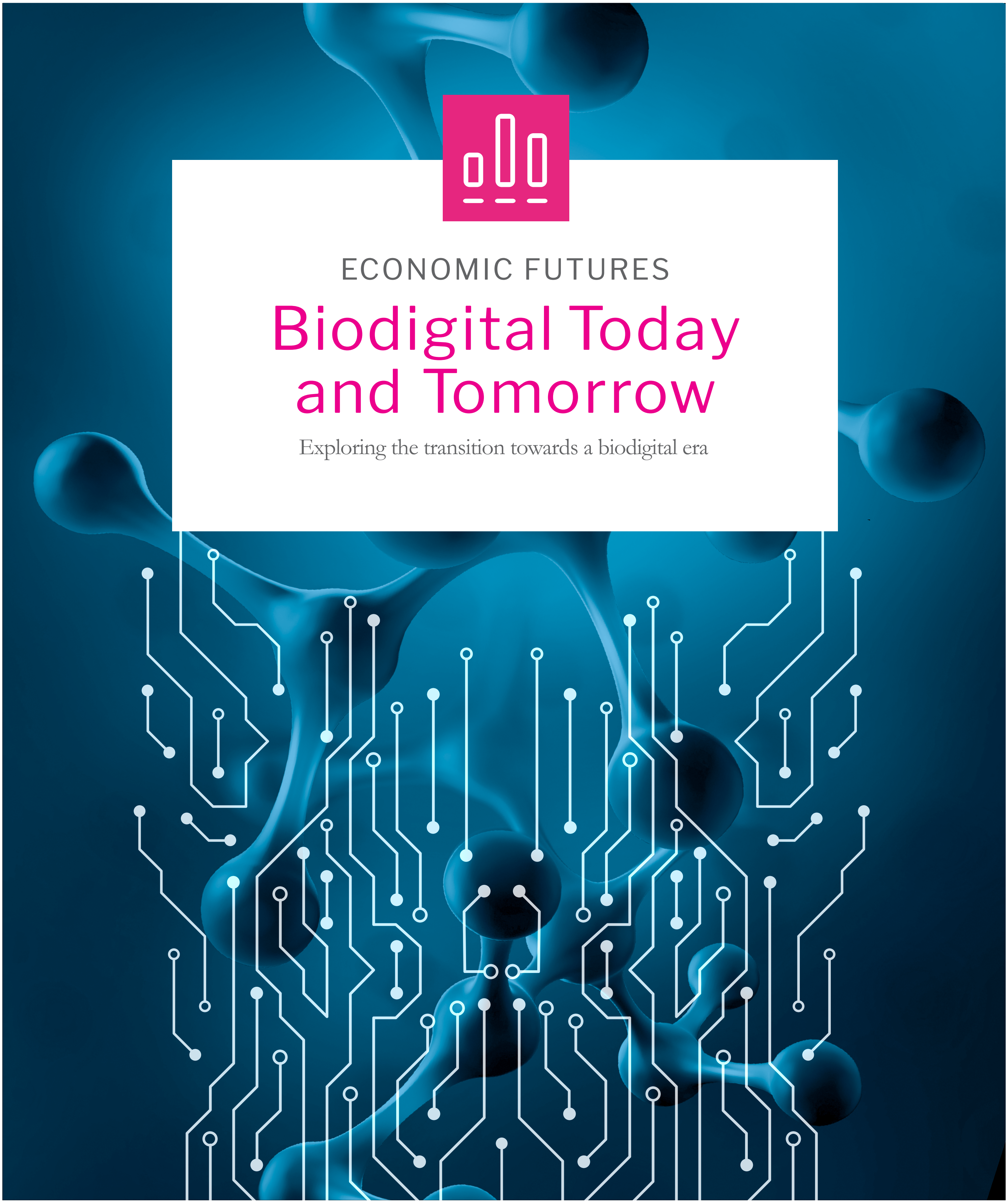
ECONOMIC FUTURES

Biodigital Today and Tomorrow

Exploring the transition towards a biodigital era



Canada

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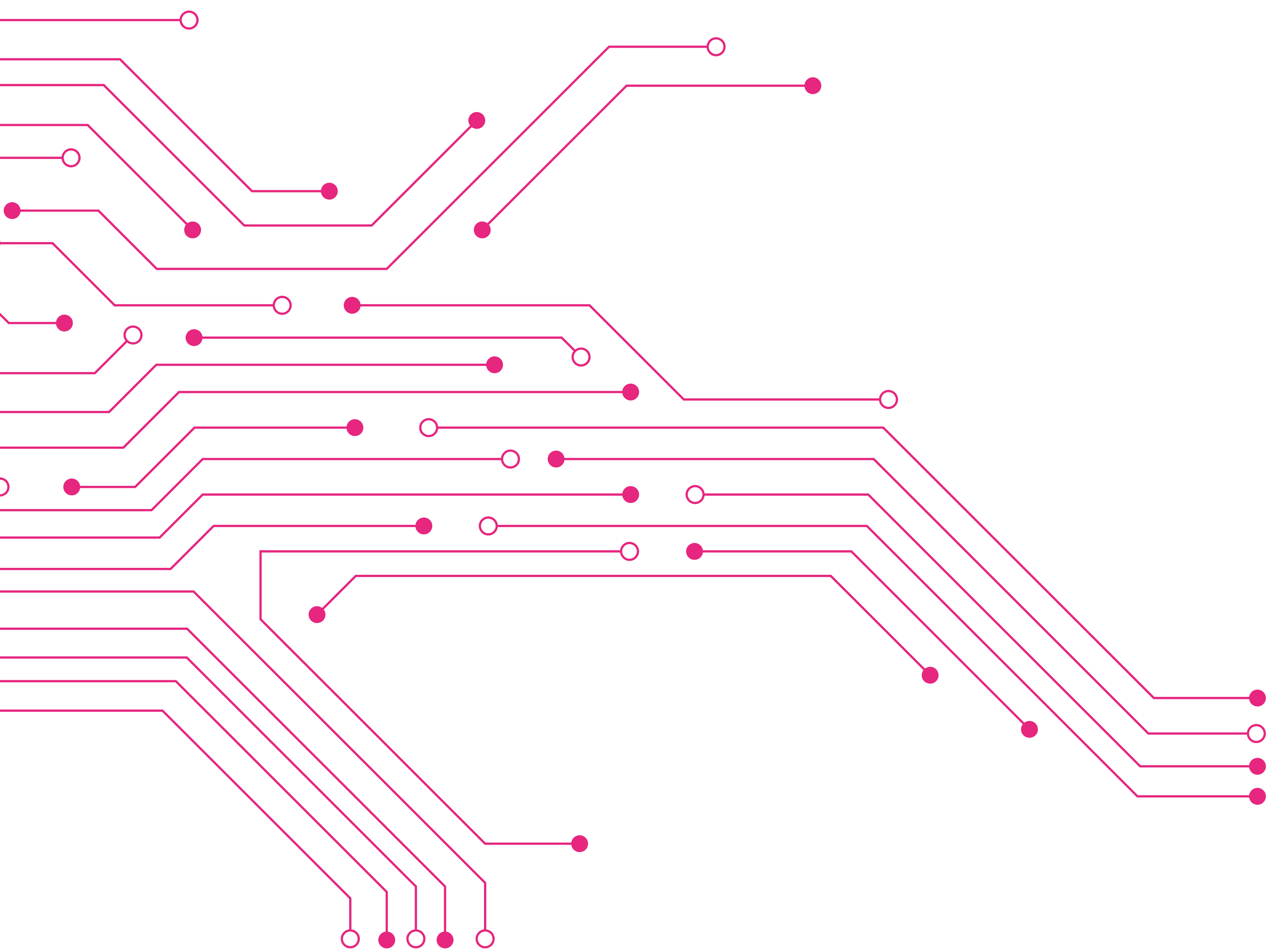

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Foreword

The COVID-19 pandemic is proving to be a powerful driver of change. It is spurring biodigital innovations such as nearly real-time biosurveillance of virus spread and mutations; virus tracking via smartphone; and messenger ribonucleic acid (mRNA) vaccine development at unprecedented speed. Biodigital convergence, the merging of biological systems and digital technologies, is challenging the way we understand ourselves and the world in which we live.

Building on our first report, *Exploring Biodigital Convergence*, this report lays out some of the changes we might see as the biodigital convergence matures and gives rise to new realities. It explores the potential impact of biodigital convergence on sectors such as health, food and agriculture, the environment, manufacturing, and security. It could have implications across many policy areas: global trade, healthcare, the shift to a low-carbon economy, natural resource management, and many more.

Policy Horizons Canada (Policy Horizons) does not provide policy recommendations or advice. Guided by its mandate, it explores what might happen in the future policy landscape, to help the Government of Canada develop future-oriented policy and programs, and to prepare for possible radical and disruptive change.

We hope you will find this report insightful and thought-provoking. By reflecting on what might happen, we can support Canadians and decision makers in considering which futures we want and which ones we want to avoid.

On behalf of Policy Horizons Canada, I would like to thank those who generously shared their time, knowledge, and thoughts with us.

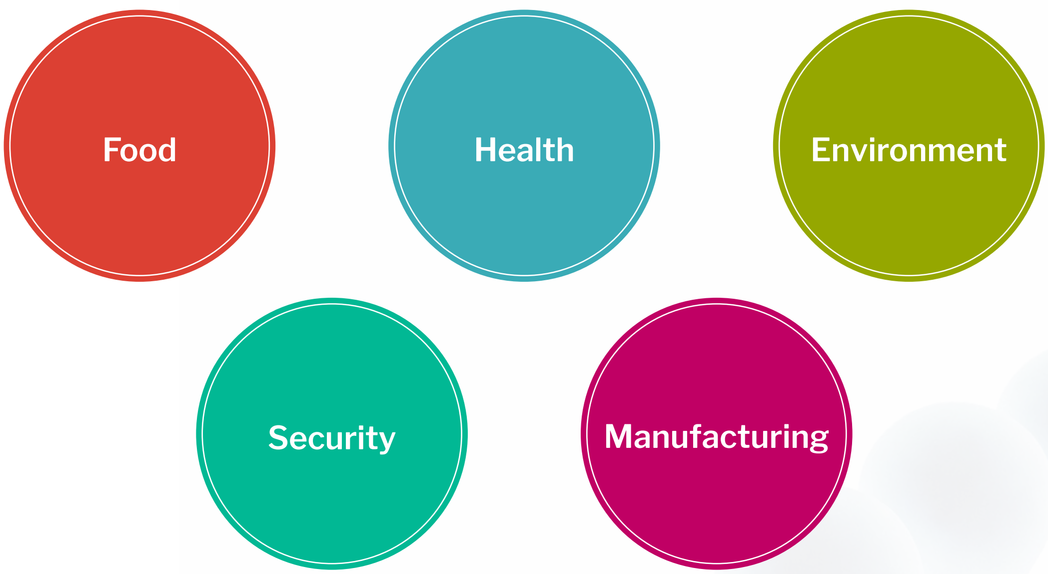
Kristel Van der Elst

Director General,
Policy Horizons Canada

Executive summary

Biological and digital systems are coming together in profound ways, creating a new domain called the biodigital. Digital technology and living things are increasingly able to communicate with each other. We can embed digital technology into living organisms, and incorporate biological components into new technologies. Genetic modification of the natural world for climate change mitigation, environmental remediation, and biodiversity conservation may however raise ethical considerations.

The contours of the coming biodigital era are becoming clearer. This report explores change drivers and how biodigital convergence could transform five economic sectors and areas of life.



It examines some of the changes we could see in each area, how we could experience significant disruption in the future, and what policy considerations might emerge. This report also discusses how the COVID-19 pandemic may be accelerating the transition to a biodigital world.

Food

Traditional agriculture relies on land, water, and a suitable climate. In the future, foods could be manufactured anywhere in labs and indoor vertical farms. This could fundamentally reshape the agricultural sector, international trade, and migration, as well as people's relationships with land, animals, and food.

Health

Biodigital convergence could rapidly advance targeted treatments, and precision medicine based on genomic profiles—leading to improved and targeted preventive care as well as highly efficient treatments for disease. At the same time, biodigital convergence also gives rise to inclusivity and ethical considerations, among others.

Environment

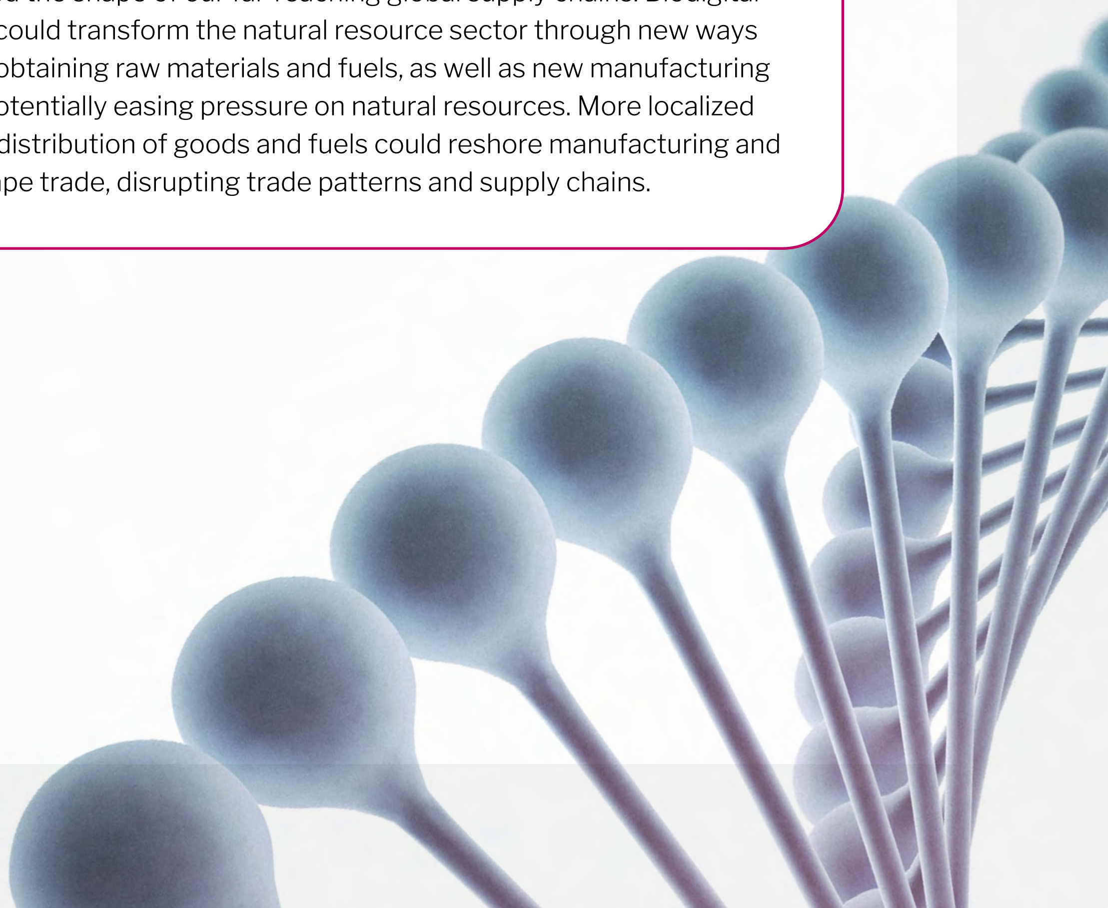
Climate change, pollution, and biodiversity loss are widely recognized as urgent global issues. Today's unsustainable production and consumption modes are endangering long-term socioeconomic wellbeing. Biodigital capabilities could increase our capacity to connect with and monitor the natural world. It could also expand our understanding of the interconnectedness of all living things. Genetic modification of the natural world for climate change mitigation, environmental remediation, and biodiversity conservation may however raise ethical considerations. Furthermore, there may be unintended consequences involved with the release of modified organisms in natural environments.

Security

Emerging biodigital innovations and capabilities are creating both new frontiers and possible concerns in the field of security and defence. With almost five billion people connected to the Internet, digital surveillance and data collection have substantially increased over the last decade. The rise of biodata may add a new layer of complexity in securing potentially valuable personal data. The access to more data may also facilitate criminal investigation and potentially create a more secure society.

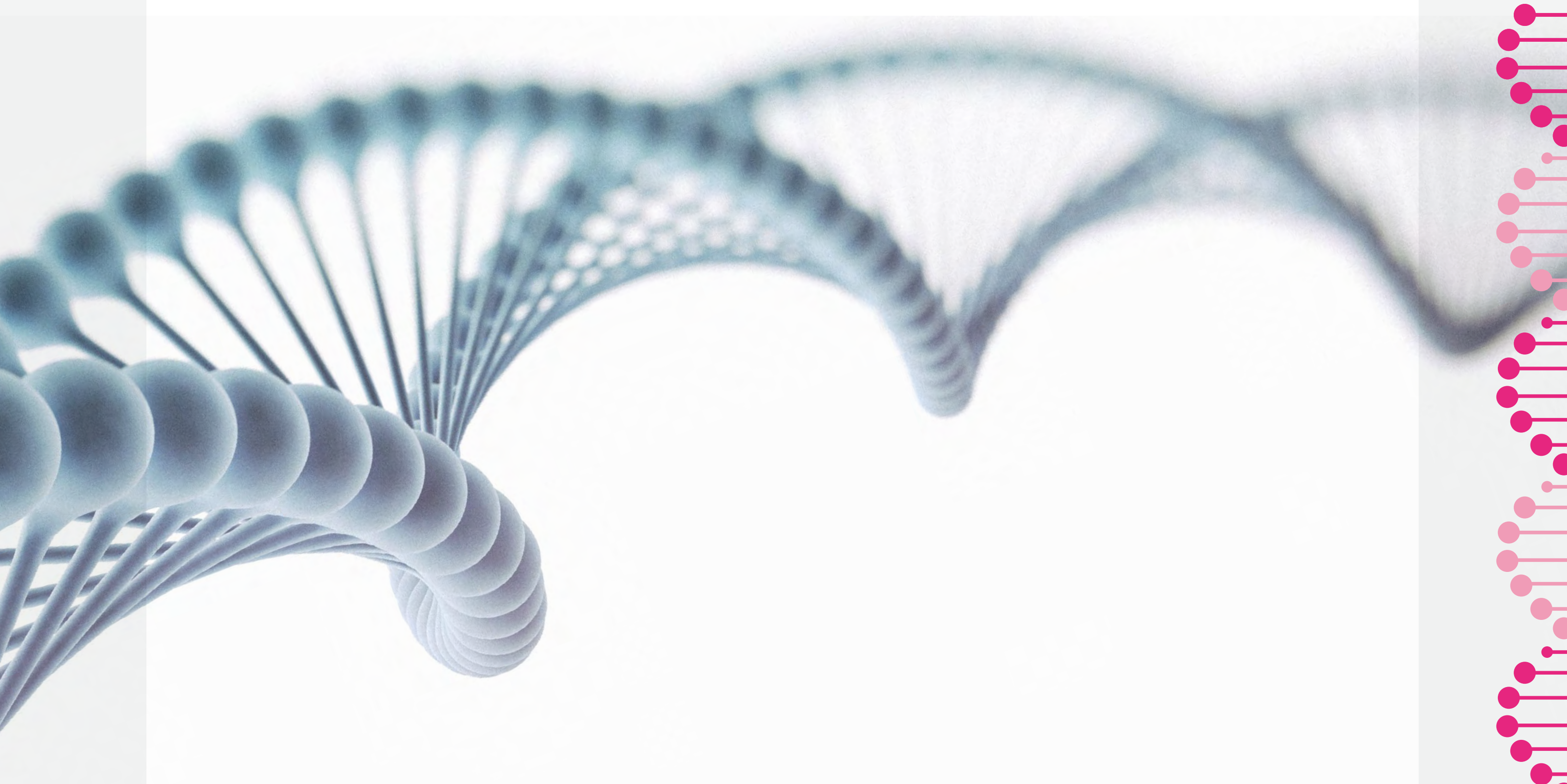
Manufacturing

Manufacturing was historically based on factory workers who transformed natural resources initially extracted from mines, forests, and waters, or grown on farms. Differences in labour costs and the natural distribution of resources have influenced the shape of our far-reaching global supply chains. Biodigital convergence could transform the natural resource sector through new ways of making and obtaining raw materials and fuels, as well as new manufacturing techniques, potentially easing pressure on natural resources. More localized production and distribution of goods and fuels could reshore manufacturing and reshape trade, disrupting trade patterns and supply chains.



The COVID-19 pandemic is acting as a driver of change, accelerating the transition to a biodigital world. It has increased the awareness of biology and its array of uses among people, governments, and industry. It reveals the risks of misinformation and the need for biliteracy. It pushes biodefence capabilities and national self-sufficiency to the forefront of government agendas. And it has forced societies to re-evaluate the balance between biosecurity and personal freedoms.

The speed of biodigital convergence in the coming years will depend not only on technological progress but social acceptance—and the pandemic has shown that unexpected events can trigger rapid shifts in what is widely seen as acceptable or desirable. In the future, we may not see digital technologies and biological systems as separate, but rather woven together, further normalizing the biodigital world that future generations may inherit.



Introduction

This report continues the work of our *Exploring Biodigital Convergence*[1] scoping report, which explored how biological systems and digital technology are converging in ways that could change how we live, understand and make sense of our lives, evolve, and possible capabilities and characteristics of biodigital innovations. We identified three ways in which biodigital convergence is emerging:

1 Full physical integration of biological and digital entities

When digital technology is embedded in organisms, or biological components are incorporated into technologies. Examples include robots with biological brains, digital implants in humans, and neurological control systems in insects. Digital technologies can enhance the natural capabilities of living things.

2 Coevolution of biological and digital technologies

When advancements in one domain enable progress in another, and vice versa. Both digital technology and the natural world provide scaffolding for each other, furthering shared breakthroughs and a coevolution. Examples include new understanding of how brains work, inspiring the development of neural networks; and artificial intelligence (AI) finding patterns in gene sequences that build our understanding of what genes do.

3 Cognitive shift of biological and digital systems

An evolution of perspective, where we begin to normalize the convergence of the natural world and digital technology. We may see the two as an integrated new domain. Advances in our understanding of biological systems and in the creation of new digital capabilities such as AI enables the biodigital conceptual convergence.

In this report, we delve deeper into how biodigital convergence could reshape five areas: food, health, environment, security, and manufacturing. We examine sectors in their current form, how biodigital convergence is changing each sector, what might change these sectors in the future, outline critical uncertainties and future possibilities, as well as policy considerations.

During our work on this report, we lived through the first global emergency of the biodigital era. In the final section, we reflect on the COVID-19 pandemic as a significant accelerator for the biodigital revolution—increasing investment in research, raising public awareness of biological threats, shifting perceptions of what is socially possible, and putting public health at the centre of national governance.

The contours of the coming biodigital era are slowly becoming clearer and the transition to that era will inevitably be disruptive. By thinking now about the possible trajectories of biodigital convergence, we hope to reduce risks, and harness possibilities for Canada and the world.

Food

Traditional agriculture relies on land, water, and a suitable climate. In the future, foods could be manufactured anywhere in labs and indoor vertical farms. This could fundamentally reshape the agricultural sector, international trade, and migration, as well as people's relationships with land, animals, and food.

As the world's population grows[2], demand for and trade[3] in food are expected to rise. Many countries may face food security challenges brought on by climate change, as extreme weather events and diseases affect traditional agricultural production. Regional conflicts may also disrupt global food production and trade. Food systems also have environmental impacts—land use, deforestation, water pollution, and greenhouse gas emissions—while opaque supply chains[4] raise the risk of food-borne illnesses[5].

How is biodigital convergence changing food?

Biodigital innovations have the potential to modify how we produce food, integrate new types of food onto the market, and disrupt existing supply chains.

What follows are some of the ways biodigital is changing how we produce, grow, manufacture, and understand human nutrition and food.

Lab-grown food. Cellular agriculture creates bioidentical animal products—such as seafood, meat, and dairy—in a lab. This involves culturing animal cells in a bioreactor and growing them into fat and muscle tissue. Lab-grown meat and plant-based meat alternatives can also be three-dimensionally printed (3D-printed)[6].

Lab-grown beef burgers are approaching cost parity[7] with traditional burgers, especially when meat cells are combined with plant protein. In 2020, the world's first restaurant serving lab-grown meat[8] opened in Tel Aviv[9], and Kentucky Fried Chicken announced plans to sell 3D-printed nuggets[10]. Companies are working on lab-grown salmon[11], tuna[12], shrimp[13], dairy products[14], pet food[15] and even human breast milk[16]—a potential alternative to infant formula. Scaling bioreactors remains the main technological challenge[17], but Chinese[18] and Israeli[19] organizations are investing heavily.

Individualized diets based on DNA profiling. Advances in nutrigenomics[20]—the study of relationships between genes, nutrition, and health—could allow people to make health, diet, and lifestyle choices based on their genetic profile.

Start-ups are offering personalized dietary advice[21] based on DNA, lifestyle information, and gut microbiome analysis. A restaurant in Tokyo is using analysis of customers' saliva, urine, and feces to evaluate their nutritional requirements and 3D print biome-based bespoke sushi[22]. Nestlé[23] is investing in microbiome research and AI that can create personalized care plans. People can buy vitamin pills tailored[24] to their genome, and one day may 3D print these types of supplements at home. The decreasing[25] cost of genome sequencing will make personalized diets and lifestyle choices more widely accessible.

Precision and smart farming. A combination of technologies could influence or alter how agriculture industries function—and how and where we grow food. Agricultural productivity[26] could become more precise with technology—from robots inspecting individual plants[27], identifying pests and diseases[28], or herding farm animals[29], to data[30]-optimizing fertilizer inputs, to blockchain-enabled origin tracing[31]. Indoor vertical farms in which AI[32] controls light and temperature can grow hundreds of times as much food per acre as traditional agriculture, while using far less water.

Singapore has launched a campaign[33] to produce 30% of its food supply by 2030 through lab-grown food and vertical farming[34]. Companies from the U.S. to China[35] are exploring how Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) technology might customize crops to particular conditions and improve resilience[36] against climate change impacts.

What might change in food systems in the future?

As the biodigital convergence advances and matures, it could reshape food systems in significant ways:

Grow anything, anywhere, anytime. Agriculture has always depended on the availability of land mass, water, and specific climatic and geographic conditions. It is limited by the growing seasons and vulnerable to variables beyond a farmer's control—from weather to pests and diseases.

With new biodigital innovations, these constraints may no longer shape agricultural productivity in the future. Lab-grown meat technology[37] could be located anywhere, as can vertical farming where artificial intelligence (AI) oversees[38] gene-edited crops grown in precisely controlled environments.

Nations pursue self-sufficiency. Trade could change as nations pursue food self-sufficiency. Food-importing countries may opt to produce more food[39] within their own borders, rather than importing it from areas with good natural growing conditions, to reduce their vulnerability to trade disputes[40] or supply disruptions.

As more than 75%[41] of agricultural land is used for livestock farming, low-yield lands could become stranded assets and be replaced by cellular agriculture alternatives. We could increasingly produce food on demand and near consumers, potentially in small-scale home bioreactors. This could substantially reduce the demand for food transportation or distribution.

Diet merges into preventive healthcare. Better understanding of the human genome and biome may transform nutrition and influence healthcare, giving people increasingly detailed information to highly individualize their diets and maximize their health.

Increasing the amount of genome and biome data that is being collected and studied could advance our understanding of the human body as an intricate system and could facilitate preventative medicine. A database of consumers' genomes may become a competitive advantage for some firms.

Food for thought

Our connection with the environment. Biodigital convergence could profoundly change people's relationship with land and animals. Over the centuries, conditions for agriculture shaped where people settled. Our growing ability to produce food independent of climatic conditions could shift what people value in land, as well as patterns of human settlement.

Local food production technology opens up opportunities for remote communities to be self-sufficient, and produce traditional foods in new ways. More land could be rewilded, while growing fish in labs could allow the oceans to replenish. Affordable lab-grown meat could lead to a shift in attitudes towards the ethics of factory farming and in our relationships with animals more generally. It could change the role of culture and ceremony in food production and consumption—how we grow, harvest, connect with, and experience food.

The experience of food transforms. Biodigital convergence could transform how we think of and associate with food. While lab-grown food currently aims to mimic foods familiar to us, it opens up possibilities to create entirely new kinds of edible products with new tastes, textures, and nutrients. People could make "programmable" foods to fit their own tastes and needs. Biodigital technologies could potentially allow people to biohack their own taste buds to alter which tastes they find pleasing, orient them towards healthy food, and create new food cultures.

Critical uncertainties and future possibilities

Various factors could affect the scale and nature of acceptance or rejection of biodigital innovations. The following outlines some possible uncertainties that may lead to different future scenarios.

Societal acceptance: Will there be a societal consensus on adopting new technologies?

- Consumers may increasingly want to buy healthy[42], environmentally friendly, ethically produced foods. Given that vertical farms need less land, water, and pesticides—and that lab-cultured meat does not involve the methane emissions of farmed animals, or the ethical or health issues associated with factory farming—could we see an uptake in new food production methods?
- Could negative early experiences of CRISPR-modified crops and cultured meat affect public acceptance? Will CRISPR plant editing be more or less publicly accepted[43] than previous means of genetically modifying organisms?
- How might we benchmark ethical considerations and values alongside biodigital economic possibilities?

Business ecosystem: How could existing players reshape their business models? How might related sectors evolve, and what new players could emerge?

- Will the existing big agricultural companies adapt and maintain their position? Or will new entrants from other sectors, like pharmaceuticals and big techs, overtake them?
- Could technology's increased role enable a dominant position for large tech companies in the agriculture industry[44]? If so, how could this affect food supply chains and consumer choices?

Labour market readiness: Will there be sufficient talent to develop new markets and activities? Where will biodigital talent reside?

- How will labour markets adapt if digitalization of food production makes certain agricultural jobs obsolete while creating demand for new skills?
- How readily will education programs for agricultural science and food science incorporate biodigital technologies like vertical farming, AI, robotics, or lab-grown food?

Policy considerations

The rise of the biodigital convergence could affect many policy areas. The following are not policy recommendations, but rather considerations, questions, and thought-provoking ideas.

Food safety regulations and nutrition guidance

- New types of food production, manufacturing, and supply chains could lead to new packaging, storage, transportation, cooling, handling, preparation, cooking, and sanitizing procedures. Actors could also use blockchain technology to ensure traceability and make the supply chain more transparent. Blockchain could also help consumers access information on ingredients.

- New categories of plant-based and animal-based foods could emerge from using biodigital production modes and biodata to produce new types of personalized food. This could affect what we consider healthy food, current nutrition guides like the Canada Food Guide, as well as lead to new nutrition facts on labels.

International trade, food sovereignty, and supply chains

- Biodigital food technologies may help countries that heavily rely on food imports to improve their food sovereignty. This could reduce food trade at the global level and have economic impacts on the largest-producing countries of agricultural commodities. The export-import potential of biodigital food products could also lead trade partners to rethink food labeling.

- Biodigital food production modes could disrupt existing supply chains at the national and global level. Increased local biodigital food production could also reduce the need for food distribution and transportation.

- The rising digitalization and automation of food production processes and ingredients via emerging biodigital innovations, such as 3D food printers and online platforms, could substantially increase personal and commercial food production capacity. Home biodigital food production could require new safety measures. Countries that have relied on arable land and rural agriculture economies may need to examine the economic sustainability of traditional food production in the face of new food production possibilities.

Intellectual property & privacy

- Digital technologies like AI and big data analysis could increase the number of patents for customized[45] flavors[46] and recipes[47].

- Secured genomic databanks could become increasingly common. People may be concerned about privacy implications and sharing genome data with food supply chain actors.

- Global compensation and protection systems may help prevent biodigital food-cloning practices. For example, sequencing appellation[48] food goods for local production or growing Kobe beef in a lab.

Environmental footprint and spatial development

- Agricultural land may be stranded and repurposed as we produce more food in vertical farming facilities or through cellular agriculture.

- Gene-edited crops and smart farming (sensors, robots) could reduce fertilizer, pesticide, and herbicide use.

- The environmental footprint of emerging biodigital food production and consumption, such as cellular agriculture, gene-edited crops, vertical farming, and smart agriculture may be different from that of the current food system. New innovations may aid climate change goals. However, transitions can be costly and could increase the demand for electricity.

Health

Biodigital convergence could rapidly advance targeted treatments, and precision medicine based on genomic profiles—leading to improved and targeted preventive care as well as highly efficient treatments for disease. At the same time, biodigital convergence also gives rise to inclusivity and ethical considerations, among others.

Healthcare costs are projected to continue increasing over the next 15 years due to factors such as population growth, reproductive problems[49], ageing, degenerative diseases, and rising use of expensive, newly patented medicines[50]. The sector's labour shortage[51] is expected to continue as demand for home care grows, and healthcare worker burnout continues as a result of the COVID-19 pandemic[52]. On the current trajectory, hospitals and healthcare systems will continue to be overburdened, the scope of public health may grow, and emerging innovations may fall within the scope of health mandates, inflicting more pressure on public health systems.

How is biodigital convergence changing health?

Technological innovations in the biodigital space will continue to mature and combine. The following section outlines some innovations that could affect the integrated and complex future of human health.

Synthetic organs and digital implants. Customized body parts and implants could offer new transplant options. In 2019, over 4000 Canadians[53] were on a waiting list for an organ transplant. Human organs can now be 3D-printed[54], or grown in genetically modified pigs[55]. EU regulators approved[56] the first totally artificial heart in 2020. Artificial blood vessels[57] could help treat cardiovascular disease. Artificial skin, made from stretchable electronics[58] that can sense heat and pressure, could improve prosthetics and skin grafts. Such technologies could enable people not only to fix medical problems, but to obtain customized body parts with enhanced capabilities.

Brain implants that can be recharged wirelessly[59] could transform the treatment of neurological diseases. Implanted chips are already being used to monitor health and unlock smartphones. Implants such as Neuralink[60] could expand the human senses, allowing us to "feel"[61] bionic limbs, or interact with virtual spaces in new ways. They may also lead to new treatments for mental illnesses like depression[62]. Brain-computer interfaces allow us to communicate with AI-enabled devices: for example, it can enable blind people to perceive images[63] through an artificial eye. These technologies could help repair or enhance the human body.

The CRISPRization of humans. As a research tool[64], CRISPR gene editing helps us understand DNA's role in human diseases. Medical researchers are exploring its potential to fight viruses[65], destroy cancer[66] cells, overcome immune problems that interfere with potential gene therapy[67], and treat conditions such as acne[68] and blindness[69]. CRISPR-off technology allows us to turn gene expression off[70], effectively stopping a person from getting a disease to which they are genetically predisposed, such as Alzheimer's. Further, it may be possible to turn off epigenetic markers while leaving the DNA strand intact.

CRISPR may increasingly give people the ability to code their own DNA, and that of their children. Some parents may wish to give their children resistance to diseases, enhanced intelligence, and other abilities.

Public opinion research[71] finds a high level of support for using the technology to prevent rare genetic illnesses in babies, but opposition to using it to improve a baby's intelligence. Support or rejection of gene editing depends in part on one's nationality, gender, demographics, religion, and education. Varying levels[72] of ethical consideration and debate exist surrounding genetically altering offspring. There are currently widespread international bans on human use of the technology, but the World Health Organization has an advisory committee[73] looking at global standards, including oversight and ethical considerations for human genome editing.

Tracking human health in real time. The health tech market is actively innovating to find solutions that can support preventative health actions. Wearables that monitor physical health can increasingly track and compile more health data in real time. AI can track moods and mental health[74] by analyzing our voices and facial expressions. Researchers are developing DNA testing kits that plug into smartphones[75] and could help track disease.

Machine learning[76] could potentially process data in the cloud that is automatically collected from nano-scale sensors, monitors, and implants in a patient's body. Increasing knowledge about the human microbiome—the tens of trillions[77] of microorganisms that live inside the human body—is leading to more treatments[78], research, and lifestyle prescriptions.

What might change in healthcare systems in the future?

As the biodigital convergence advances and matures, it could reshape health systems in significant ways:

Regenerative medicine. We can observe the ability to regrow lost limbs or repair damaged organs in some animals like lizards and amphibians. The same cellular signaling pathways we find in animals capable of regeneration are also present in humans[79], and modifications may lead to tissue growth rather than scarring. Stem cell research is also on its way to growing whole organs—starting with smaller organoids[80] that can currently perform some function of the larger organs.

Biodatabases. DNA databases could become a source of income and health security. In the coming years, it could be possible and relatively simple to collect DNA information using a smartphone. As biodata becomes more ubiquitous, questions surrounding who collects, uses, retains, and discloses it will become pivotal. Applications (apps), smartwatches, and phones are already collecting biodata outside the traditional healthcare sector; an extension of this data collection would be commercial and consumer engagement with biomic or genomic data. DNA data marketplaces[81] based on blockchains[82] could emerge, allowing individuals—or designated data trusts—to share genomic information with corporations, academic researchers, and even governments in exchange for benefits or payment.

DNA databases could provide new insights into the complex links between genes and disease. Genomic data could be a source of power or economic advantage in future economies, as health and healthcare continue to increase in priority. Open biodata or platform-gathering big data from individuals could support the development of new therapies, but may also create privacy[83] and accountability risks. Opportunities to collaborate and share data for greater medical efficacy and care could face challenges in individual data protection and trust in the system. Genome data could enable detection[84] before the manifestation of disease, furthering long-term preventative cost savings in healthcare systems.

The pharmaceutical industry may begin shifting away[85] from chemical substances as a source of new drugs, and explore manipulation of living organisms' DNA as treatment[86]. DNA databases[87] could become a strategic asset and input for the development of new drugs and therapies.

Remote healthcare services. Canadians could access more healthcare services remotely. COVID-19 has brought telemedicine and digital health tools into the mainstream, making patients more comfortable using technology to manage their health needs. In the next 10 to 15 years, technological development and the increased proportion of digitally competent people could dramatically accelerate remote healthcare provision.

Implanted sensors could monitor individuals' health around the clock, sending data to the cloud to be analyzed for diagnosis and advice—along with other data, such as from air quality sensors in the workspace, or mental health analysis based on online behaviour.

People take control of their evolution. Germline editing—that is, editing genes that can be passed on to the next generation—is currently banned in most jurisdictions[88]. However, this could change over time as this technology more safely eliminates or improves resilience to diseases, which could improve wellbeing and reduce healthcare costs. In addition, emerging low-cost biodigital devices and services could allow individuals to experience at-home[89] germline editing.

As a first step, using CRISPR to edit out genetic predispositions to disease could be seen as an extension of the current pre-implantation screening practice in in vitro fertilization. A next step could be to insert preferred physical or psychological traits with high precision, by editing the parent's germline before conception rather than the embryo. In some countries, governments could seek to incentivize citizens to have healthier babies; over time, this may lead to a cognitive shift, where people consider procreating "naturally" to be reckless.

How we want to evolve as a species and what consequences could emerge may become important ethical considerations. Could eugenics[90]—the process of eliminating undesired genes from a population—re-emerge as a moral dilemma?

Healthy choices?

Do-it-yourself biology. Biodigital convergence may open up new possibilities, allowing people to choose who they want to be by hacking their own bodies and minds[91]. The growing availability and affordability of CRISPR kits, online open-source resources, and affordable devices opens up new prospects for DIY bio to treat, alter, or enhance physical or mental capabilities.

This could pose a major threat to public health, biosafety, and biosecurity. Unwise or inexpert gene edits could damage experimenters and, if they modify their germline[92], their future children. If it becomes possible to select children's traits and combine DNA inputs from multiple people, traditional motives and selection models for procreation could shift. Recreational implants that activate the pleasure centre of the brain may lead to a new form of addiction. People could choose to shape not only the health but the personality of children, to embody belief systems. When exploring the DIY movement, ethical considerations and the possibilities of procedural errors could lead to unintended consequences[93].

In the longer term, gene edits that successfully enhance human capabilities could lead to technologies that create a new "superclass" of humans, vastly widening societal and possibly equity divides.

Critical uncertainties and future possibilities

Various factors could affect the scale and nature of acceptance or rejection of biodigital innovations. The following outlines some possible uncertainties that may lead to different future scenarios.

Societal acceptance: Will there be a societal consensus on adopting new technologies?

- How concerned might people be about the security and privacy implications[94] of health data access?
- To what extent might lab-grown brains[95] and other lab-created organisms already be or become conscious? What ethical implications could arise in future health sciences—or even art[96]—that uses synthetic biology?
- To what extent might the ability to alter our own genes and brain functions call into question who we are as humans?

Business ecosystem: How might existing players change, how could related sectors evolve, and what new players could emerge?

- To what extent could big tech firms dominate health and healthcare, as Amazon's logistics and Google's machine learning capabilities become increasingly important at the research and development (R&D) and healthcare service level?
- Could individuals monetize their DNA data on an online marketplace? Could DNA marketplaces shift the financial gain of biodata sharing from biodatabase firms to individuals?

Economic rollout: How might policies, standards, and ideologies around the world differ, and what consequences or advantages in industry and socioeconomic status could emerge as a result of these differences?

- Could uneven access to new human augmentation technologies give rise to new forms of economic growth, inequality, and discrimination?
- Could human augmentation contribute to productivity and be considered a competitive advantage? How would international labour and employment agreements respond to the possible uneven global adoption of human augmentation?

Policy considerations

The rise of the biodigital convergence could affect many policy areas. The following are not policy recommendations, but rather considerations, questions, and thought-provoking ideas.

Role of regulation

- Augmentation for work, school, or sports situations could give some people unfair advantages.
- AI outputs from black box machine learning[97] could prove problematic in applying AI-based digital therapeutic

technologies that can continuously learn and self-modify. It may be difficult to trust the outputs without ensuring a lack of bias in a diagnosis.

- Networks of biofoundries around the world could reduce the effectiveness of national regulations. Biodata, automation technology, platforms, and cloud-based labs[98] could make it easier for organizations to offshore some R&D functions to jurisdictions with or without ethical regulations.

Public sector involvement

- Biodigital innovations that have been developed in response to the COVID-19 pandemic—like health data collection and tracking, and bioproduction, including vaccines, treatments, and supply chains—may be applicable to other public health situations.

- The multi-sectoral implications of CRISPR treatments may require further discussions about their ethics and possible uses in healthcare.

Access to new treatments through public healthcare systems

- Affordability could affect the speed of new models of healthcare delivery, options, and treatments.

- Like other digital technologies, biodigital technologies may require ongoing and regular software support to maintain their effectiveness. Governments may be required to step in if private sector suppliers withdraw their support[99].

Equitable healthcare access for remote areas

- Telemedicine, remote biosensing, and local bioproduction could offer different possibilities for diagnosis and treatment. In Canada, these medical services may benefit remote or rural areas. Remote collection of biodata in areas with limited access to reliable Internet may be a challenge to universal accessibility.

R&D, data sharing, and privacy

- International agreements and collaboration on the future of health data could result in alliances and disputes.

- Open-source science[100] may challenge existing intellectual property frameworks related to diagnostics, therapies, treatments, and manufacturing.

- The value of biodata may increase with the growing use of AI in drug discovery that relies on that data to generate products.

- There may be international implementation of agreements, such as access and benefit-sharing systems[101] under the Convention on Biological Diversity[102] for example, that affect access to genetic resources from biodiversity that may be used for new drugs and therapeutics.

- The digital nature of people's biodata, and the ability to easily transfer or access it via online platforms could drive discussions about biodata sharing, storage, access, and privacy.

Environment

Climate change, pollution, and biodiversity loss are widely recognized as urgent global issues. Today's unsustainable production and consumption modes are endangering long-term socioeconomic wellbeing. Biodigital capabilities could increase our capacity to connect with and monitor the natural world. It could also expand our understanding of the interconnectedness of all living things. Genetic modification of the natural world for climate change mitigation, environmental remediation, and biodiversity conservation may however raise ethical considerations. Furthermore, there may be unintended consequences involved with the release of modified organisms in natural environments.

Few countries are on course to reach their carbon emission reduction targets. The cost of extreme weather events[103] caused by climate change[104]—such as fires, droughts, floods, and hurricanes—may continue to rise. Other environmental crises may also intensify, from plastic pollution to biodiversity loss, to pollution of air, soil, and water. Despite a trend towards voluntary corporate disclosures[105] and private sector investment against climate change, public policy remains key to environmental protection.

How is biodigital convergence changing the environment?

Biodigital innovations will continue to mature and combine. The following section outlines some innovations that could affect the future of ecosystems, biodiversity, and climate change.

Hybrid biodiversity. People may augment natural ecosystems and biodiversity to increase resilience. Gene editing[106] is enabling the creation of new forms of biodiversity, from plants that glow in the dark[107] to nanobionic sensors that monitor arsenic levels[108] in soil. Researchers are using CRISPR gene editing for projects such as improving the resilience of forest ecosystems[109], and bringing the woolly mammoth[110] back from extinction.

Gene drives[111] allow people to introduce certain genetic traits into an animal or insect population. This could help control invasive species[112], restore coral reefs[113], or prevent insect-borne diseases. For example, Florida released 750 million genetically engineered mosquitoes[114] as an alternative to using insecticide. These interventions are not without risk, as it may be difficult to stop their spread once modified genes are released into nature.

Environmental clean-ups through synthetic biology. Scientists are developing jellyfish[115] that can detoxify contaminated ocean; bacteria- and yeast[116]-based smart materials that can sense environmental contaminants; and microbes that can destroy[117] pollutants in soil and water, recover rare earth metals[118] from polluted land, and clean up oil spills[119].

Carbon dioxide can be extracted from the atmosphere by genetically engineered weeds[120] and fast-growing algae[121], cultivated into biomass in specially designed bioreactors, and then harvested as fuel, fertilizers, oils, and plastics.

Internet of Living Things. Although in its early stages, it is possible to discern the beginnings of an “Internet of Living Things” (IoLT) similar to the current Internet of Things (IoT). Plants’ sensitivity to chemicals, combined with technology, opens up new capabilities. For instance, spinach can send an email to warn about landmines[122]. If its roots detect a specific explosive chemical, the plant emits a signal that is picked up by a sensor, triggering an email to researchers.

CRISPR has been used to edit genes to store binary information—the kind used in computers—in DNA form, allowing researchers to encode the phrase “hello world” into an E. coli cell[123]. Microsoft is exploring the future potential to store data[124] in biochemical systems; theoretically, a gram of DNA could hold 215,000 terabytes[125] of data, which people could read using portable DNA sequencers[126].

What might change in the environment in the future?

As the biodigital convergence advances and matures, it could reshape the environment, biodiversity, and ecosystems in significant ways:

Modifying the environment. Biodigital interventions could increase the value of ecosystem services. The value of ecosystem services[127]—the benefits we gain from a functioning natural environment, from clean water to flood protection—has an estimated worth of 1.5 times more than the global GDP.

Artificial biodiversity could add even more value, from microorganisms that break down plastic pollutants[128] and oil[129], to glow-in-the-dark trees[130] that replace street lights, to soils that absorb more water[131] to mitigate flooding, and trees that are more resistant to forest fires. Technologically enhanced biodiversity could transform ecosystems that are currently uninhabitable to humans, and provide alternatives to geoengineering[132] for tackling climate change.

Environmental biosensors and data collection. Better data could transform environmental monitoring and governance. Environmental protection laws have historically legalized environmental harms from human activity by setting pollution emission caps. Genetically modified plants could monitor anti-pollution laws, detecting pollutants and triggering alerts to the relevant authorities. Biodigital sensors, drones, robotics, and sequencing of DNA fragments in the environment[133] could help monitor air, water, and soil quality more widely and in greater detail, including at remote extraction sites. Releasing smart biodigital living entities into ecosystems could share real-time signals with authorities, identifying harmful substances, microbes, or pollutants. This could potentially replace or support pollution emission standards and lead to personalized, real-time environmental legislation.

Additionally, emerging fields of study like imageomics[134]—where machine learning is used to extract biological traits from wildlife images of living organisms captured by drones or uploaded on platforms such as eBird[135] and iNaturalist[136]—could rapidly improve our understanding of biological processes and detect early signs of harm to biodiversity.

Environmental DNA[137] (eDNA) can identify species in an area without directly observing them. This could allow for better understanding of the environmental impacts of proposed projects and policies[138], as well as environmental monitoring[139] of ongoing human activities. It could also lead to new ways of determining the economic value of living things, illustrating the value of ecosystem services. Moreover, it could help track how species[140] move in response to climate change and facilitate early detection of invasive species. Collecting eDNA in seafood markets may improve wildlife crime investigation[141] techniques by detecting the sale of endangered and protected fish species. The emergence of eDNA might call for reflections on who controls that data and what uses are ethical.

Deeper green

Redefining the concepts of natural and artificial. That nature exists and evolves more as an art than a science is a prevailing assumption. However, our understanding of the mechanisms that govern life has reached a point where we can modify biological instructions, to program organisms to perform specific tasks. There are signs of a cognitive shift[142] in which society increasingly values biological entities. There is an emerging philosophy, based on new development of living robots[143], that organisms act as "hardware," and DNA and cellular communication (via electric gradients[144]) are the "software" that dictates the hardware's function.

The ability to reshape ecosystems by eliminating or reviving[145] certain species, or directing how they evolve, raises ethical[146] questions about the rights of species and ecosystems, and the risk of unintended consequences if our ability to reshape ecosystems outpaces our capacity to understand them. As people are still trying to map and understand the intricacies of ecosystems, our understanding may be limited and ever-evolving, even with the help of technology. There may be a risk of harming nature when influencing or manipulating the intricacies of the natural world.

Indigenous perspectives could offer deeper insight into and awareness of the potential ramifications of new biotechnologies. Acknowledging and thinking about implications seven generations into the future, as many traditional Indigenous teachings suggest, could guide ethical considerations of biodigital innovations.

Critical uncertainties and future possibilities

Various factors could affect the scale and nature of acceptance or rejection of biodigital innovations. The following outlines some possible uncertainties that may lead to different future scenarios.

Societal acceptance: Will there be a societal consensus on adopting new technologies?

- As the next generation of children grows up familiar with digital and biological technologies, will public consciousness shift towards a realization that humans are an integral part of larger ecological systems? Could there be a wider recognition of the importance of safeguarding ecosystems for their socioeconomic value?
- Might there be backlash to greater modification of the environment? By whom, and what form could it take?
- If it becomes feasible[147] to store data cost-effectively in the DNA of living organisms, could some plants play a new market-based role in the digital economy?
- Would we want to establish new forms of sensing and connecting with nature?
- If portable sequencers become accessible and cheap, would people use them to assess the state of biodiversity or discover new pathogens?

Environmental ecosystem: How might the environment be affected and how might it react? Should the precautionary principle be applied?

- How great are the risks of unforeseen consequences? For example, new artificial microorganisms could disrupt the food chain, create new forms of pollution, cause new allergies, or themselves become a form of waste.

Policy considerations

The rise of the biodigital convergence could affect many policy areas. The following are not policy recommendations, but rather considerations, questions, and thought-provoking ideas.

Economic development

- Environmental sequencing could reveal causality between economic activities and their impacts on biodiversity and ecosystems.
- Land could become a key tool for companies to mitigate their environmental footprint with artificial biodiversity, using it to compensate for the environmental impacts of economic activity.
- An IoLT system could be deployed at large scale and be dominated, like the Internet, by a small number of powerful companies.

Intellectual property

- Current intellectual property rights may have to shift to encompass entities in nature, raising questions about whether to consider new organisms a private or a public good.
- With better sequencing technologies available, governments may have to clarify at the international level rules regarding the access, ownership, and benefit sharing of digital sequence information[148], and its legal status[149] under the Convention on Biological Diversity.

Environmental regulation & enforcement

- New regulatory frameworks at various levels may affect the introduction of new genetically modified organisms. Rules on reproduction of new modified species could vary.
- Migration of genetically modified species could be difficult to control across jurisdictional borders.
- Emerging digital and biosensors could act as tools to monitor environmental quality and biodiversity loss. Creating communication channels with the help of digital technologies between living organisms and regulators could facilitate rule enforcement.

Security

Emerging biodigital innovations and capabilities are creating both new frontiers and possible concerns in the field of security and defence. With almost five billion people connected to the Internet, digital surveillance and data collection have substantially increased over the last decade. The rise of biodata may add a new layer of complexity in securing potentially valuable personal data. The access to more data may also facilitate criminal investigation and potentially create a more secure society.

The IoT is being deployed around the world in smart cities, which allow authorities and private actors to monitor citizen movements. These technologies have led to privacy issues and much controversy[150]. Combined with the rapidly declining cost of DNA sequencing, a large amount of biodata could be generated over the next decade, facilitating biosurveillance in the future. Moreover, the rise of DIY bio-capabilities and the access to emerging biotechnologies could facilitate new forms of biowarfare and bioterrorism.

How is biodigital convergence changing security?

Biodigital innovations will continue to mature and combine. The following section outlines some innovations that could affect the future of security.

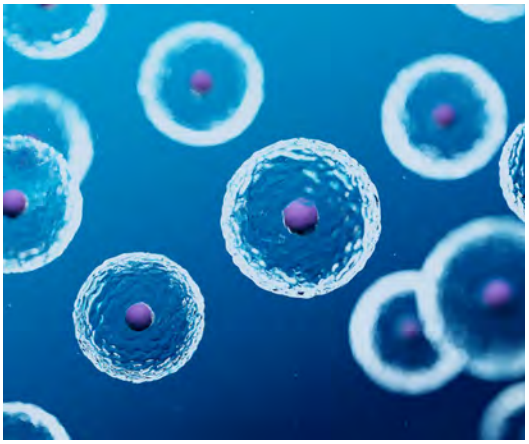
The rise of biodatabases. The adoption of biodatabases and DNA biodata by private or public entities may have privacy and national defence risks. Because of its nature and the type of information it contains, biodata could lead to new tiers of threat. Consent, access, and nefarious use could pose severe risks for individuals, and for security and defence operations to manage. The cost of gene sequencing is rapidly declining: in 2020, a Chinese firm claimed it could sequence a full genome for $100[151]. Some governments have established DNA databases: the U.S. has accumulated around 14 million[152] samples on criminal suspects, with an overrepresentation of black men; and China routinely[153] collects DNA from male citizens for predictive policing. Researchers are working on using DNA to predict[154] how a person's face will look, so DNA databases can inform surveillance through facial recognition software.

Many people voluntarily give their DNA in exchange for information on their health or ancestry, or to support medical research, such as the FinnGen study[155]. While some human genetic-testing companies have comprehensive[156] privacy policies, many others do not[157]. Some judges have ordered[158] companies to share customers' DNA with law enforcement agencies, and nearly half of Americans support police access to private DNA databases. Biodatabases can be a useful tool for forensics. Cold cases over a decade old may be reopened[159] as DNA data is more abundant and easier to access. Theoretically, bad actors may be able to hack[160] into and identify individuals in open-source databases[161], to which people upload their DNA in search of relatives or medical studies.

International entities trade surveillance technology abroad without similar regulations as arms dealing, even though many consider the impacts of technology to pose similar dangers. Many are calling for DNA databases and facial recognition technology to be classified as weapons[162] in an attempt to regulate this global trade and monitor their use by authoritarian regimes.

The race between biothreats and biodefence. Much like the Internet, biodigital convergence is seeing a new and continuing struggle between attack and defence. The U.S. has classified gene editing as a potential weapon of mass destruction[163] and the FBI has a biocrime department. New technologies can indicate when a person is becoming ill[164], and enable early detection[165] of which virus or bacteria they may have. The U.S. Army is looking at wearable[166] biosensors for soldiers to detect biothreats. While it can be difficult to differentiate natural from artificially engineered pathogens, the technology is improving[167].

It is increasingly feasible for individuals to sequence and synthesize DNA, with DIY gene-editing kits retailing online[168] for as little as US$169. Aims of the DIY bio movement include making insulin and other medicines more affordable[169]. However, DIY bio also increases the risk of either deliberately or accidentally releasing DIY pathogens[170]. California has become the first U.S. state to pass a law[171] specifically to restrict the use of CRISPR, but regulations differ from place to place.



What might change in security in the future?

As the biodigital convergence advances and matures, it could reshape security and defence systems in significant ways:

Modern biothreats. Weaponization of biotechnology could lead to a rise in threats to society. While only organizations with significant resources and expertise can hope to develop a nuclear weapon, it may be increasingly feasible for individuals or small groups to develop potentially devastating bioweapons, such as a version of the Ebola virus modified to spread more easily. It is harder to anticipate the potential for scale and collateral damage of new bioweapons compared to more traditional weapons.

Adverse actors with a long-term agenda could invest in or infiltrate start-ups in the biotech field, while cyberattacks on biological research institutes[172] could allow access to knowledge that can be weaponized using readily available technologies and materials. Vaccine researchers, for example, routinely create synthetic viruses to test strategies. The recent reproduction of the extinct horsepox virus[173] raised concerns that smallpox could be synthesized and weaponized. Similarly, research into neurotoxins such as tetrodotoxin[174]—produced by pufferfish—could inform the development of bioweapons.

Terrorist groups and rogue nations could also target a nation's food supply with bioweapons: agroterrorism[175] could involve pathogens that affect cultivated crops or forests[176].

The rise of biosurveillance. Biological threats require new ways of thinking about monitoring and border control. With a significant increase in international trade, we may need to implement intelligent biodetection systems to monitor and give timely warnings about new viruses, bacteria, or other genetically engineered pathogens. New biosensing technology could be deployed at borders in an attempt to protect them against biological threats. Synthetic biology techniques and raw materials are dual-use, raising questions about regulation of international trade in resources such as yeast cultures and algae strains. Raw biomaterials may need new types of border oversight and tracking, as their end products could vary.

Biological threats may impact national defence priorities, as nations pivot to create biopreparedness. However, biothreats cross many policy domains, including environment, health, national security, and border control.

Identity crises

The ethics of DNA sequencing. Genomic data could have far-reaching consequences for economic competitiveness, and questions of identity, equity, and discrimination. It is becoming financially feasible for businesses to create DNA databases of their customers and enable business models in which consumers trade their DNA data for free services. Firms currently track digital data to create consumer or even electoral profiles[177]. Tracking biodata profiles could be an extension of this. With advances in genomic analytics, firms could access a bioprofile of who you are[178] and gain a broader understanding of your identity. Moreover, genomic data could become a new form of digital authentication.

Security and surveillance could bleed into equity practices and ethical domains. Sharing individuals' genetic identity could create new challenges to equity, if access to education or employment opportunities depended on whether DNA tests suggest suitability for a given career. Similarly, access to healthcare, insurance, or immigration opportunities could depend on DNA tests for susceptibility to expensive-to-treat diseases. Ethno-nationalist movements could discriminate based on DNA or create communities rooted in shared ancestry, leading to geopolitical divergence, social unrest, or new types of inequity and discrimination.

As an individual's DNA gains importance, a black market in fake DNA evidence[179] could emerge. People could avoid tracking by using CRISPR technologies to alter their DNA. More institutions may use biodata as a means of authorization, which could open up a new avenue for identity theft.

Critical uncertainties and future possibilities

Various factors could affect the scale and nature of acceptance or rejection of biodigital innovations. The following outlines some possible uncertainties that may lead to different future scenarios.

Societal acceptance: Will there be a societal consensus on adopting new technologies and supporting this industry?

- Could their potential for use in bioweapons sway the public against potentially beneficial uses of synthetic biology and gene-editing technologies?
- Could attitudes towards justice and predictive policing[180] change if it becomes possible to use genetic profiling[181] to predict future criminal behaviour with a high degree of confidence from an individual's DNA?
- Might concerns about biohazards lead more people to move to isolated areas or seek to make their properties more biosecure[182]?
- How might differing cultural attitudes[183] shape responses to biothreats in different countries?

Business ecosystem: What might be the shape of businesses in this space, how might related sectors evolve, what new players could emerge, and how might they evolve over time?

- Might the nature of biothreats require international standards[184], or will countries develop their own parameters and regulations on capturing, storing, and sharing biodata?
- Could large companies monopolize synthetic biology, since smaller entities may not have the resources to meet the biosafety requirements for high-risk activities?
- How might firms, organizations, and governments reach an appropriate balance between innovation and regulations, bans[185], and moratoriums?

- How would bioinnovation organizations address a higher risk of industrial espionage[186] and cyber attacks[187]?

Labour market readiness: Will there be sufficient talent[188] to develop new markets and activities? Where will biodigital talent reside?

- Could we see national defence departments and security firms employ a growing number of "bio" experts?

Economic rollout: How can policies adapt and stay ahead of transitions?

- What new protocols and regulations are needed to securely trade biodata?
- What safety standards and regulations, such as government-issued licenses, might be required to conduct DIY biology?

Policy considerations

The rise of the biodigital convergence could affect many policy areas. The following are not policy recommendations, but rather considerations, questions, and thought-provoking ideas.

Biosecurity and biothreats

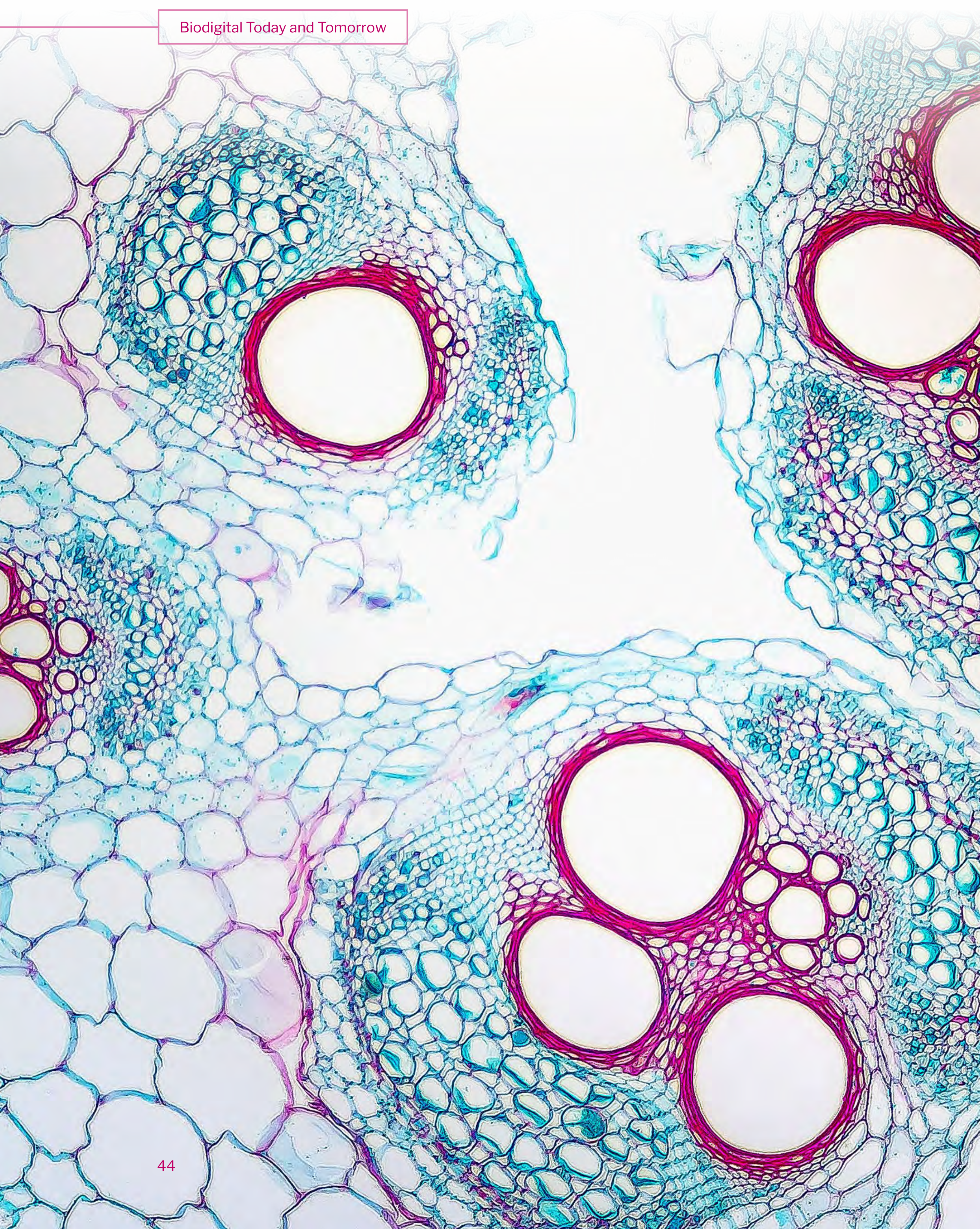
- Nefarious actors could learn from failures to detect, mitigate, and respond to the COVID-19 pandemic[189], and the underlying socioeconomic impacts, increasing the likelihood of future biological weapon attacks.
- The digital components of wearable or implanted devices could be hacked, leading to biological harm to the user.
- Open-source science and international sharing of research data could lead to international surveillance and authentication.
- Biodigital convergence could enable individuals to develop low-cost biothreats.
- Some countries might create, redesign, and invest in new infrastructure to prevent or mitigate potential biothreats.

National security

- Disinformation and fake news about emerging biodigital technologies could contribute to changing social attitudes, behaviour, and subsequently become a national security concern.
- With the rise of low-cost DIY biolabs and easier access to technologies like DNA synthesis, front-line emergency services such as policing, firefighters, and paramedics might need training to detect labs, biohazardous organisms, and potentially human augmentation.
- There may be a rise in human augmentation, which could lead some countries to develop augmentation detection capabilities and regulations.

Military and defence

- Defence departments might consider national and global defensive and offensive solutions to potential biothreats, similar to past nuclear and anti-missile defence programs.



Manufacturing

Manufacturing was historically based on factory workers who transformed natural resources initially extracted from mines, forests, and waters, or grown on farms. Differences in labour costs and the natural distribution of resources have influenced the shape of our far-reaching global supply chains. Biodigital convergence could transform the natural resource sector through new ways of making and obtaining raw materials and fuels, as well as new manufacturing techniques, potentially easing pressure on natural resources. More localized production and distribution of goods and fuels could reshore manufacturing and reshape trade, disrupting trade patterns and supply chains.

Through the industrial age, international trade agreements and the offshoring of manufacturing activities led to complex supply chains[190]. Demand for physical products is expected to increase in the coming years, as the global population grows and standards of living continue to rise. International trade is also expected to increase. Digital technologies[191] such as AI, robotics, cloud computing, 3D printing, and mixed reality are already transforming the manufacturing sector. Although labour costs still affect decisions about production location, the Next Digital Economy[192] is expected to revolutionize global value chains. It may also accelerate the transition towards genetic engineering-based biomanufacturing.

How is biodigital convergence changing manufacturing?

Biodigital tech innovations will continue to mature and combine. The following section outlines some innovations that could affect the integrated and complex future of manufacturing.

Smart biofactories reaching industrial scale. Synthetic biology has historically been labour intensive, with many manual and repetitive tasks—but this is starting to change. Private organizations and research institutions are building smart bioproduction facilities that can reach industrial scale.

Robotic lab assistants can perform experiments 1000 times faster[193] than humans, enabling researchers to focus on the design and creation of genetically modified organisms. Data generated from testing new organisms train and optimize machine learning[194] to predict biological system behaviour and provide recommendations, which could greatly accelerate the development of bioengineering[195]. Costs are decreasing as online DNA marketplaces[196] facilitate price comparisons between synthetic DNA producers.

Synthetic biological materials. Synthetic biological materials are disrupting current methods of manufacturing. Innovative biomaterials include a fabric resembling silk[197] produced by genetically engineered microbes; 3D-printed bio leather[198] and wood; biodegradable bricks made from mushrooms[199]; bacteria mixed with concrete[200] to self-heal and prevent cracking; bacteria that can produce hydrogen[201] fuel on demand; "soft robots[202]" that can move cargo underwater; and 3D-printed gel[203] that changes colour in response to light and can be used for camouflage. AI-designed living machines made from frog skin and muscle cells[204] to fit a novel body plan can move autonomously and perform "programmed" tasks. New concepts and innovations are facilitating the physical integration of biological and digital, as well as furthering the cognitive shift we are seeing. Technology and nature may be more readily integrated than we may have thought. Further, technology could be more intuitive and nature more prescriptive than previously imagined.

Synthetic biomaterials could conceivably offer alternatives to almost every raw material used to produce goods—from plastic to wood, metals, chemicals, and even plant fibres like cotton.

Bioenergy made from genetically modified organisms. Despite significant investments over the last decade, algae biofuel remains expensive—but researchers are using AI[205] to genetically engineer algae that can produce energy at lower cost, as a potential replacement for fossil fuels. Genetically engineered bacteria can produce hydrogen fuel in biosolar cells using only sunlight and water.

What might change in manufacturing in the future?

As the biodigital convergence advances and matures, it could reshape manufacturing, supply chains, production modes, and consumer behaviour in significant ways:

Biologically sourced natural resources. Genetically engineered microorganisms could reduce demand for natural resources. We may no longer need traditional raw materials to manufacture goods. The primary industry sector—including mining, farming, and forestry—could face competition[206] from a range of functional, cost-effective biomaterials. Supported by cloud-based labs, additive manufacturing, computer-aided design software, and automation, biofoundries could provide local genetic engineering services[207] (biomanufacturing as a service) and raw biomaterials respectful of local regulations to manufacturers wishing to reduce their supply chain and production infrastructure costs.

With likely lower carbon footprints[208], bioalternatives could support efforts to mitigate climate change. A dramatic decline in revenues for oil-producing states could also have geoeconomic and geopolitical implications.

Distributed manufacturing with biofoundries. Distributed biomanufacturing facilities could meet local needs for commodities. Combined with 3D bioprinting, biofoundries could accelerate manufacturers' transition from a traditional business-to-business model to a business-to-consumer model by providing local people with niche goods like biomaterials, food, and personalized drugs for rare diseases[209]. In remote areas, biofoundries could produce a range of goods that are currently expensive to import, lowering the cost of living and potentially helping remote communities become more self-sufficient.

If products are increasingly manufactured and transformed locally, the need for extensive physical infrastructure like electrical grids, pipelines, ports, and railways may decrease—and the need for fermentation facilities may increase. This could ease pressure on land and allow goods and services to be more accessible to remote communities. It could also lead to the emergence of new, more local infrastructure to move biomass—such as a beer pipeline[210].

Decreasing cost of bioengineering. More affordable research equipment could lead to an increase in bioalternative innovation. The declining cost of gene sequencing, DNA synthesis, and automation could enable a rise in open-source DIY biomanufacturing research. Individual entrepreneurs could explore an unprecedented number of new possibilities for goods and services, from health to construction, infrastructure, materials, and furniture.

These new bioalternatives could require regulators to review a suite of regulations related to health and safety, environmental protection, intellectual property, climate change mitigation, and social welfare, while aiming to promote economic growth. Bioengineering's high capacity for customization could lead producers to adapt their products to accommodate disparities between countries' regulations.

Recapture, regenerate, recycle

Circular economy and sustainable development. For decades, the production and consumption[211] that drove economic growth on a global level have increased the environmental footprint of materials and led to the depletion of natural resources. From resource extraction to disposal, the linear “take-make-dispose” economy that dominated our development model has threatened the Earth’s carrying capacity to regenerate renewable resources. To achieve sustainable development goals[212], a movement has emerged advocating for a global shift to a circular economy[213], by separating economic activity from the consumption of finite resources, and by designing products made from renewable raw materials while respecting their regenerative cycle.

A biodigital production system could reduce human demand for natural capital by optimizing the use of biomass, and developing genetically engineered alternatives to non-renewable resources like fossil fuel and many minerals.

What if biopackaging with integrated seeds could turn easily into plants? Or if new fungi[214] materials for the construction sector would grow rapidly while capturing carbon? And what if biomaterials would be embedded with specific biosensing capabilities like detecting food spoiling, or air, water, and soil pollution in urban areas? Consumption of bioproducts could lead to the regeneration of ecosystems and biodiversity all over their life cycle, from production until the end of their useful life.

Critical uncertainties and future possibilities

Various factors could affect the scale and nature of acceptance or rejection of biodigital innovations. The following outlines some possible uncertainties that may lead to different future scenarios.

Societal acceptance: Will there be a societal consensus on adopting new technologies?

- Will consumer preferences and the economic movement towards lower-carbon goods accelerate the shift to biomaterials? How readily might the public accept new genetically engineered products? Could divides emerge along generational, cultural, geographic, or religious lines?

Business ecosystem: How might existing players change, how might related sectors evolve, and what new players could emerge?

- Will biomanufacturing be developed by multinationals or by start-ups?
- How could biomanufacturing redesign supply chains within different industries?

Labour market readiness: Will there be sufficient talent to develop new markets and activities? Where will biodigital talent reside?

- Will there be investment for multidisciplinary collaboration between engineers, digital scientists (such as AI, robotics, connectivity), and biologists?

Economic rollout: How rapidly could policies shift and adapt to enable the transitions?

- What is the potential for new biomaterials to pollute ecosystems? What kind of waste might biofoundries producing novel materials generate? Would it be easier to handle than chemical, industrial (packaging, wood, steel), or nuclear waste?
- How could interprovincial and international trade rules prevent or enable biomaterials from moving across borders?

Policy considerations

The rise of the biodigital convergence could affect many policy areas. The following are not policy recommendations, but rather considerations, questions, and thought-provoking ideas.

Innovation systems

- Biofoundry infrastructure could encourage local entrepreneurship and innovation.
- Intellectual property rules surrounding new biomaterials and engineered microorganisms could either incentivize or slow down R&D and innovation.
- Large firms and e-commerce actors may drive bioconsumption globally by adopting bioalternatives and low-carbon materials like bioplastics or edible packaging.

Economic development

- Federal, provincial, and municipal governments could have different positions on biomanufacturing given the impact on various economic sectors such as agriculture, food transformation, construction, oil and gas, petrochemicals, forestry, fisheries, pharmaceuticals, mining, and transportation.
- The value of traditional materials and natural resources could rapidly decline where an alternative exists.

International collaboration

- Biofoundries could enable new international partnerships and collaboration in R&D, and break traditional commercial alliances between countries and regions.
- International standards on biomaterials research and production could emerge.

Regulation and trade

- Emerging biomaterials and genetically engineered microorganisms could prompt new labeling on consumer products and building materials.
- Environmental regulations on waste management, toxic substances, and transportation may need reviewing to assess new biomaterials made from synthetic biology, engineered tissue, or 3D bioprinting. These may also affect import and export activities.
- Governments may consider the ethics surrounding the use and management of genetically engineered organisms.

COVID-19— an unexpected accelerator

The COVID-19 pandemic is acting as a driver of change, accelerating the transition to a biodigital world. It has raised awareness of biology and its array of uses among people, governments, and industry. It reveals the risks of misinformation and the need for bioliteracy. It pushes biodefence capabilities and national self-sufficiency to the forefront of government agendas. And it has forced societies to re-evaluate the balance between biosecurity and personal freedoms.

The speed of biodigital convergence in the coming years will depend not only on technological progress but social acceptance—and the pandemic has shown that unexpected events can trigger rapid shifts in what is widely seen as acceptable or desirable. In the future, we may not see digital technologies and biological systems as separate, but rather woven together, further normalizing the biodigital world that future generations may inherit.

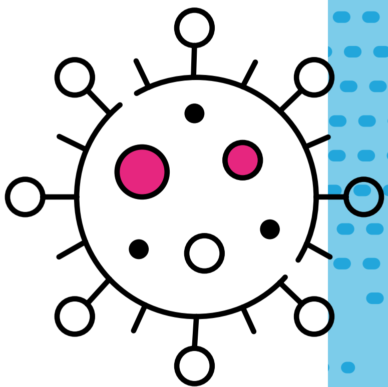
Throughout the COVID-19 pandemic, we have been living through the first global-scale biodigital experience. We are simultaneously encountering the profound evolution of biodigital innovations and witnessing the emergence of a new domain. The biodigital technologies discussed in this report exist today and will continue to evolve. The extent to which they will transform our lives in the future depends in part on whether and how quickly they become more capable and affordable, as well as normalized and integrated into society. In other words, transformation is a function of technological possibility and social acceptance.

Often, social acceptance is gradual, as new generations grow up with different attitudes and experiences. Sometimes, events can trigger unexpectedly rapid shifts in what is widely seen as normal. The change in airport security procedures after 9/11 is one example of a security and travel protocol shift as a result of a profound event. The COVID-19 pandemic has prompted many rapid changes as a result of the circumstances we face; from the digital transformation[215] of businesses to increased video meetings[216], online shopping[217], food delivery apps[218], telemedicine[219], and surveillance[220]. Advancements were made in mRNA vaccine deployment[221], real-time sequencing[222], and the global cooperation[223] that led to the rapid production of vaccines due to pressures on the biotechnology sector.

COVID-19 may be ushering in a new era of biothreats in which rapid change becomes more normal. This pandemic is unlikely to be a once-in-a-century occurrence[224], as many factors such as climate change and population growth may contribute to more—and possibly more severe—zoonotic viruses in the future. The global risk of biothreats may rise and experts may increase efforts to understand the variables that lead to the emergence of pandemics.

So what might COVID-19 mean for biodigital convergence?

A rise in bioliteracy



People, governments, scientists[225], and industry are talking about biology like never before. From the R number to mutations in the spike protein, concepts that were niche in early 2020 have become part of mainstream conversation. This rise in bioliteracy could facilitate discussing, explaining, and understanding emerging biodigital technologies like those explored in this report. Similarly, a rise in bioliteracy has contributed to environmental conversations and climate change initiatives, which have also risen in tandem with the pandemic.

More attention and funding for biodigital technologies

COVID-19 has accelerated interest and investment in research in various biological and biodigital innovations, from mRNA vaccines and alternative immunization methods such as nasal sprays[226], to biosurveillance, sensors, genomic therapies[227], and increased understanding of the microbiome[228], toxic stressors[229], and the human immune system. COVID-19 has accelerated the use of biodigital innovations like telemedicine and health apps, and could prompt discussions about biosurveillance or environmental biosensors in the future.

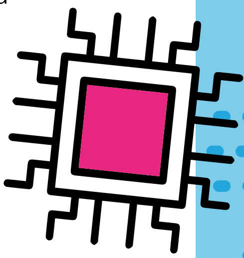
Health and biodefence as a cross-cutting issue for public institutions

People have become acutely aware of the powerful and far-reaching effects of microorganisms. Public health has become central to every aspect of government, from the economy to the environment. Pandemic preparedness is now being considered by some as a national security[230] issue, given the general acceptance that it is only a matter of time before another significant biothreat emerges.

A new era of misinformation risks

COVID-19 demonstrates how conspiracy theories[231] can gain traction while scientists are racing to understand the nature of a new threat. Examples include harmful theories that COVID-19 is caused by 5G[232] and vaccines contain microchips controlled by Bill Gates[233], and fake cures and health advice like injecting yourself with bleach.

People have to decipher mass amounts of information and make sense of the world through new information channels. “Viral disinformation and conspiracy theories pollute our information environment. They shape the way a growing number of Canadians make sense of the world, which in turn influences their social, economic, and political decisions[234].” Sense-making drives what people think they know and how they make decisions. Misinformation bears the risks of backlash that could slow down or speed up the adoption of biodigital innovations. How we make sense of emerging biodigital innovations will affect the way the biodigital era unfolds.



A wider quest for national self-sufficiency

The early weeks of the pandemic demonstrated how commercial contracts can break down in a global emergency, as national governments intervened[235] to prevent exports of personal protection equipment (PPE), medical supplies, and grains[236]. The pandemic also affected many supply chains, including semiconductors and meat[237]. As a result, governments may increase domestic capacity to manufacture essential supplies in a range of essential sectors. In response to the COVID-19 pandemic, Singapore has advanced[238] its 2019 goal[239] to produce 30% of its own food by 2030 using cellular agriculture and vertical farming. In 2021, Canada proposed a $2.2-billion investment[240] in the biomanufacturing and life sciences sector, to strengthen vaccine production capabilities and healthcare innovations. We are seeing a similar focus on healthcare innovation and bioproduction around the world, France[241] being one of many countries investing heavily in this rapidly growing field.

Public involvement in the pharmaceutical industry

Countries that invested in COVID-19 vaccine development and manufacturing infrastructure enjoyed earlier access[242] to vaccines than those that took a more transactional approach to procurement—and disparities in early access quickly led to threats of export bans. Some countries may explore strategic bioinfrastructure and biomanufacturing capacity to better prepare for future biothreat emergencies and national security.

This could call into question the accepted dominant role of private enterprise in pharmaceutical development and manufacturing, as reflected in recent encouragement of public participation[243] in biomanufacturing and pharmaceutical production.

Governments may especially value the domestic capability to pivot quickly and manufacture any new vaccine, treatment, or diagnostic test in the face of a new threat.

International vaccine distribution and contracts to secure supplies brought to light the inequality[244] in access to prevention and treatments. The nature of global biothreats may require new strategies to allow more equal distribution of treatments.

A shifting balance between privacy, right to health, biosecurity, and biodefence

Testing and isolation emerged as key strategies early on for countries that were able to keep the pandemic under control. Some countries, such as South Korea[245], did so especially effectively and compromised individual privacy[246] to an extent currently unacceptable in Western culture—though this might change given a sufficiently serious threat. While still rife with ethical concerns, there is a growing sense that acceptance[247] of biosurveillance tools is increasing, as we deal with a global pandemic. Interestingly, some islands and remote areas, such as New Zealand[248] and Prince Edward Island[249], administered stringent protocols controlling entry and responding to threats early, and have been praised and recognized for effective pandemic mitigation.

Many governments and scientists may want to improve[250] their capacity to predict and detect[251] the next pandemic virus despite uncertainties[252]. Diagnostic technologies that require personal biodata are developing quickly. Researchers are working on portable diagnostic devices using gene editing to detect any pathogen, processing hundreds of tests within 15 minutes; and sensors injected under the skin[253] to detect an infection that may be contagious but not yet symptomatic. COVID-19 vaccine passports[254] could herald a world in which many activities are accessible only with willingness to share one's current state of health. The access and availability of healthcare services have been strained by the pandemic, leading jurisdictions to consider difficult measures such as vaccine mandates[255] and health contributions[256], or refusing healthcare services[257] for the unvaccinated. There may be debate on whether healthcare is a right or a privilege. Some jurisdictions[258] have deployed wastewater surveillance systems[259] to better understand how COVID-19 spreads in a community.

Systemic shifts in science & technology during the COVID-19 pandemic

COVID-19 brought dramatic changes to some aspects of how science itself is conducted. Whether these changes become entrenched or fade away with the threat of the pandemic remains unknown.

- Clinical trial and approval processes for new mRNA vaccines were accelerated[260] to an unprecedented degree.
- Synthetic biology companies and biofoundries have demonstrated their ability to rapidly switch their production capacity to raw materials[261] for new tests and vaccines.
- Scientists around the world shared data[262] on the sequencing of the COVID-19 genome and new variants.
- Academic journals prioritized[263] speed of publication over thoroughness of the peer review process.
- Platforms such as Crowdfight[264] emerged, enabling scientists to exchange ideas and enlist volunteer help.
- People volunteered their data to enable real-time science, such as through the UK's Zoe symptom-tracking app[265].

Conclusion

We are at the cusp of the biodigital convergence era. We use technology in biology today, but biology in itself is also a form of technology—it is programmable, codable, and alterable. The future of biology as technology could include programmable digital components. Digital technologies and biological systems are combining and merging in ways that could be profoundly disruptive to our assumptions about society, the economy, and our bodies.

Five sectors are set to transform with the onset of the biodigital convergence: food, health, the environment, security, and manufacturing.

Beyond the transformation we might see in those sectors, exploring the impact of the biodigital convergence on specific sectors may reveal more systemic opportunities, challenges, and dilemmas society will face.

Biodigital convergence opens up new perspectives on how biological entities affect economies; how the natural world interconnects with sectors; how technology advances and enables new biological innovations; what makes for an ideal location for human settlement; what are our ethical responsibilities to the natural world; and other challenges and opportunities that may arise in our evolution as a species.

Biodigital convergence also imposes new challenges and dilemmas: how should we coordinate international regulation approaches, to avoid countries embarking on experiments with potential consequences that could cascade across borders? What might be the economic implications on different industries, and how might it affect the competitiveness of countries? What implications might new human augmentation possibilities have on equity and discrimination? To what extent should we prioritize preserving traditional ways of life? We may be approaching a new era in which governance and regulatory frameworks include and target biodigital innovations.

Thinking through a transition, broadly evaluating possible risks, and harnessing opportunities could enable a better future for Canada and the world.

Acknowledgements

Policy Horizons is spearheading an area of foresight called the biodigital convergence. This report examines five sectors where possible disruptions may occur and explores how these systems may change as a result of the biodigital convergence. As this new domain emerges, we will continue to examine plausible future scenarios for biodigital convergence.

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We look forward to collaborating with partners and stakeholders on the study of biodigital convergence.

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