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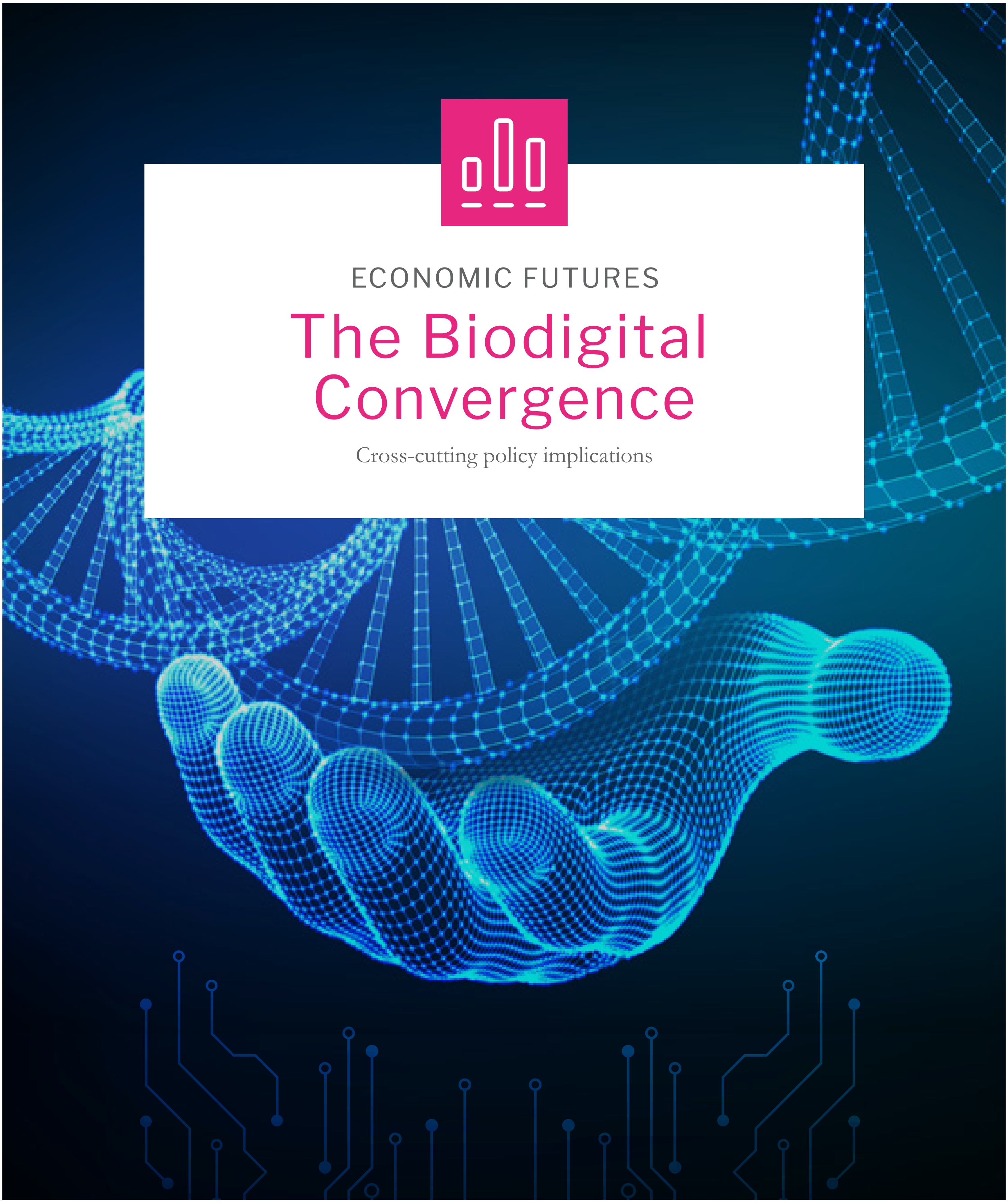
ECONOMIC FUTURES

The Biodigital Convergence

Cross-cutting policy implications



Canada

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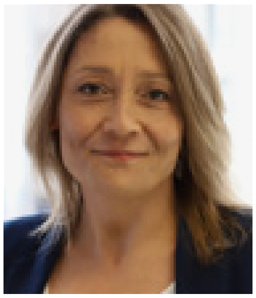
Table of contents

Foreword



Over the past several years, we have seen the biodigital convergence—the merging of biological and digital technologies—mature and give rise to new realities. It is no longer a future concept. It is a present reality that could influence multiple policy areas and demand our immediate attention.

Progress in this domain is enabled by three fundamental pillars: data, genomics, and critical systems. These pillars are not just supporting but actively shaping the trajectory of the world in which we live. Together, they could transform the economy, society, the environment, and governance globally.

This report builds on our previous work in this area: Exploring Biodigital Convergence and Biodigital Today and Tomorrow. It delves into the key pillars of the biodigital convergence and aims to provide a comprehensive understanding of the biodigital landscape and what changes could arise in the future.

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

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

On behalf of Policy Horizons, 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

Introduction

Biological and digital systems are coming together in profound ways, creating a new domain called the biodigital convergence. Digital technology and living things are increasingly able to communicate and interact with each other. Digital technology can be embedded into living organisms, and biological components can be incorporated into new technologies.

The biodigital innovation space is changing quickly. Some countries—such as Israel and the United States—started investing substantial public funds into biodigital research and development as well as biomanufacturing sectors, after identifying them as strategically important for sustainable growth and future economic competitiveness. In March 2023, the United States White House Executive Order On Advancing Biotechnology and Biomanufacturing helped establish clear national objectives in areas such as human health, agriculture innovations, and climate change solutions. International organizations such as the International Electrotechnical Commission have been considering whether to standardize options for biodigital innovations. According to their research, the biodigital convergence could contribute to United Nations Sustainable Development Goals like zero hunger, innovation and infrastructure, and climate action.

In addition to offering potential benefits, the biodigital convergence could also impose new challenges and dilemmas. Bioalternatives may disrupt established industries in ways that could affect countries' competitiveness. Human augmentation capabilities may lead to unintentional discrimination and inequality. International alliances could emerge to prevent countries from pursuing genetic engineering experiments, with potential consequences that could cascade across borders.

Our previous reports—*Exploring Biodigital Convergence* (February 2020) and *Biodigital Today and Tomorrow* (May 2022)—investigate possible capabilities and characteristics of the biodigital convergence, how it might disrupt specific sectors, and related policy implications and uncertainties.

The present report builds on this thinking and focuses on three key pillars of the biodigital convergence—data, genomics, and critical systems. These pillars support changes that could influence technological progress, particularly related to the biodigital convergence. This report also explores policy implications that could affect multiple policy areas simultaneously.

We may be approaching a new era in which governance and regulatory frameworks include and target biodigital innovations. Thinking through such a potential transition, evaluating possible risks, and harnessing opportunities from the biodigital convergence could benefit Canada and the world.

Key pillars of the biodigital convergence

Data, genomics, and critical systems are three key pillars that may influence how the biodigital convergence could evolve in the future. Each key pillar depends on the others. Together, they could transform the economy, society, the environment, and governance globally.

The way these key pillars interact may heavily influence technological progress of the biodigital convergence. Recognizing their value might help countries and firms identify the challenges and risks, as well as the strategic assets that they could use to maximize the benefits of the biodigital convergence.

1 Data

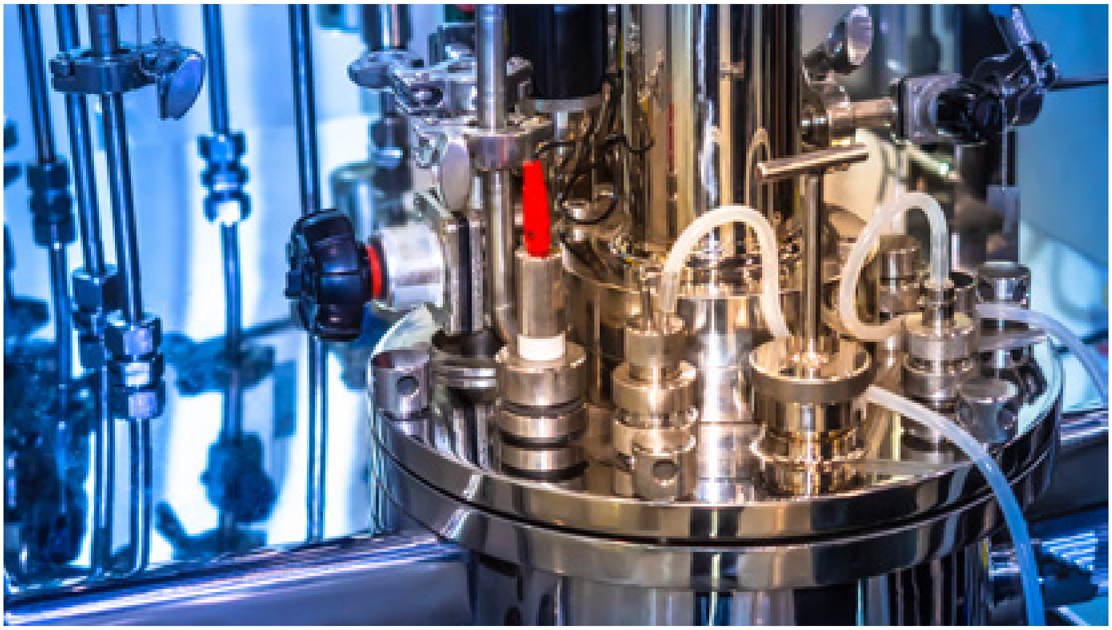
Data is the raw material fueling the digital economy and may have the same impact on the bioeconomy. Data such as biometrics—including states of health and physiology—and genome sequences may create value in sectors like healthcare, food, biodiversity conservation, and security. For example, biometric data could improve virtual healthcare services and provide ecologists with vital biodiversity-tracking databases for conservation efforts. Biometric data may also transform personal or organizational decision making by identifying issues or trends.

Technological advances and the ongoing reductions in genome sequencing cost may speed up the digitization of biology and create a large amount of data from living organisms. It may accelerate the growth of the data economy as more people, animals, plants, and microorganisms could have their genome sequenced, stored, and shared in databases. Much like data collected by digital platforms such as search engines or social media websites, biological and biometric data are raising concerns in terms of privacy, access, collection, storage, sharing, assessment, and protection.

2 Genomics

Genomics is the study of gene structure in organisms. It aims to uncover the structure and function of genes and related products like proteins. Genomics is a vast scientific field that goes beyond the human genome to include plants, animals, and microorganisms.

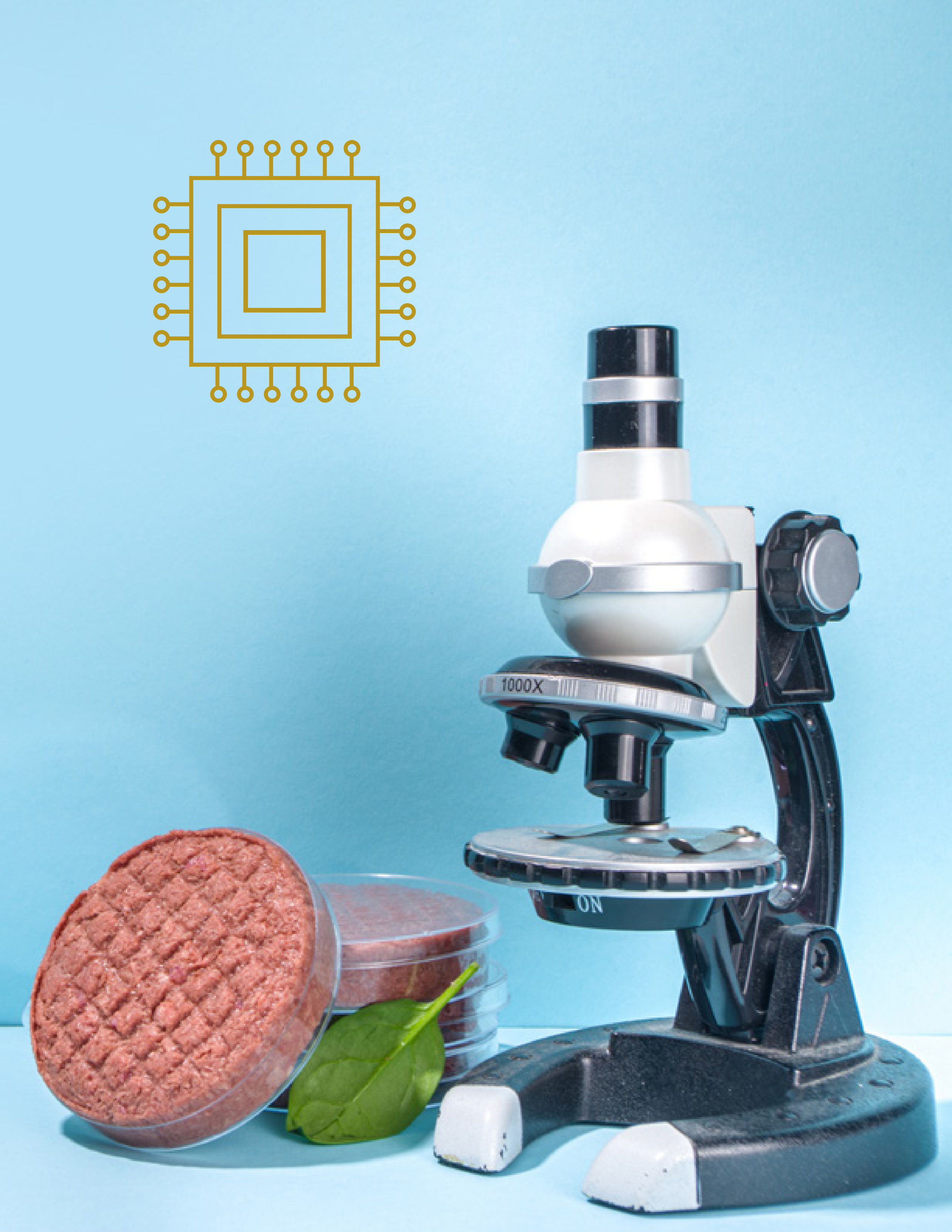
Genomics supported by artificial intelligence (AI) and big data analysis could accelerate our understanding of how complex biological systems naturally evolve and modify an organism's deoxyribonucleic acid (DNA). Genomics could also help us understand how gene-editing technologies might modify an organism's DNA. The broad spectrum of genomics of all living beings is raising questions about how to use scientific knowledge. It is also raising questions about research and development collaboration and partnerships that could emerge at the international level.



3 Critical systems

Critical systems such as biofoundries and biomanufacturing facilities are essential in supporting research and development as well as production capacity related to the biodigitial convergence. Biofoundries are multidisciplinary research labs used to craft specialized genetically modified organisms (GMOs) for industrial bioprocesses. They bring together big data analysis, AI, robotics, bioengineering software, 3D printers, and genomics expertise. Biomanufacturing facilities use specialized GMOs and precision fermentation to produce high-value proteins, enzymes, and even animal cells in large bioreactors or fermenters.

The use of digital technologies has accelerated over recent years, increasing the capabilities of synthetic biology. For example, despite limited industrial scaling capacity for biomanufacturing, innovative biomaterials made from synthetic biology and 3D printing provide alternatives to existing resources produced by mining, petrochemical, forestry, and agriculture. Over the coming years, the biodigital convergence may transform production methods and supply chains.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Cross-cutting policy implications

Emerging biodigital technologies could disrupt current production and consumption methods, cause ethical debates, and transform the regulatory landscape of many sectors. The rapid pace of biodigital innovation is pushing some governments around the world to develop policy frameworks that lay out their goals for the future bioeconomy. These frameworks include three key pillars of the biodigital convergence—data, genomics, and critical systems.

Each pillar has its own regulatory frame-work. The effectiveness of those frameworks may reduce uncertainty around biodigital goods and services development, and affect public perception of biodigital innovations. The way these pillars interact may also lead to opportunities for governments and industries.

These interactions could lead to cross-cutting policy implications under different economic, geopolitical, and social conditions. Considering these potential implications could help decision makers minimize the risks of the biodigital convergence and identify strategic assets that could be used to maximize the benefits.

The possible policy implications presented below were selected for the range of futures they offer as well as their relevance to policy making. They are not predictions, and do not represent expected or desired futures—nor is this list exhaustive.

Local production and supply chains

Biodigital technologies could increase bioproduction capacity and transform local supply chains, strengthening vulnerable global supply chains that face disruption and trade wars.

Increased bioproduction capacity could facilitate scaling local production of goods such as food, pharmaceuticals, and materials. At a sub-national or national scale, there could be opportunities to use technologies like lab-grown meat using cultured cells and precision fermentation to improve food resilience. This could present opportunities to shorten supply chains, protect against shocks from extreme weather events or geopolitics, and improve preparedness for crises such as pandemics.

On the other hand, there is a risk that biotechnological substitutes could shift economic value away from countries and regions that earn wealth from natural resource extraction. This could decrease their competitiveness and revenue. A shift in food production to urban farms, for example, could negatively affect rural areas. More widely available bioalternatives in areas such as forestry, fisheries, agriculture, and mining may harm Canada's natural resources sector.

Biodigital threats

The dual-use nature of biodigital innovations, like gene editing and DNA synthesis, together with AI could put both individuals' safety and national security at risk.

New biomanufacturing techniques and the greater integration of biological and digital systems may give rise to concerns about product safety, contamination, or pollution.

Increasingly, concerns may not be limited to large-scale laboratories with highly qualified personnel. Innovation could come from small-scale local labs and amateurs. It may be difficult to know when a biodigital innovation—such as a medical device or an organism—has the potential to be weaponized. Law enforcement agencies may lack the capacity to monitor what is happening.

Biodiversity can be monitored using technologies such as environmental DNA (eDNA) that collect DNA from air, soil, or water in natural environments. While this could be used to detect and track animal populations or dangerous pathogens, the same technologies could also collect human DNA in urban environments. This might raise consent and privacy issues. Automated and remote biosurveillance of human populations that monitor biological threats to public health could lead to backlash from the public at large.

The growth in wearables and implants that monitor physical and mental health could make users more vulnerable to cyberattacks that target the devices themselves or the companies providing digital services through the devices. Military technologies developed to enhance human capabilities, such as gene editing, implants, or prosthetics, may find their way into consumer markets and into the hands of civilians. This could follow a similar path to the Internet, which was once a closed system and is now available to everyone. Some of these devices could be hard to detect and put public safety at risk.

Intellectual property and open-source innovations

Intellectual property (IP) systems may be vulnerable to open-source innovation and biomanufacturing that can replicate traditional products and materials at low cost.

IP is a key component of biodigital innovation. For example, it is integral to the development of hardware like bioreactors and 3D printers, and of products like genetically modified yeasts that produce specific substances through fermentation. However, not all IP is proprietary. Open-source initiatives are also emerging and leading to the development of low-cost tools that facilitate access to technologies and drive innovation.

It may be difficult to reach global consensus on how models of IP and open science can coexist. There may be uncertainty about the ability to patent living organisms produced using open source biodigital technologies, techniques, or data. Similarly, it may be challenging to patent products created by generative AI, where human intervention is minimal.

Commercial products could be developed using bioprospecting—the search for genetic information from species. This practice could lead to issues when only DNA sequence data, rather than physical samples, are needed to enable an organism native to one country to be economically exploited in others.

Privacy-protected access to data

Biological data is increasingly digitized. Combined with digital technology's ability to capture human biometric data, this could speed up the transition to personalized medicine while risking individual privacy.

Data is the key to unlocking biodigital innovations and advances that could transform life for the better, such as finding new cancer therapies. But the more important biological data becomes, the greater the risk of policy dilemmas. For example, there may be a need to allow service providers access to data to enable research and development, while also protecting people's privacy.

Growing demand for genetic testing could create new markets for the analysis of biological data. Companies that have access to genomic data about potential customers could gain a competitive advantage in terms of goods and services. Without adequate governance to protect privacy, issues could arise over the right to use biological data in different circumstances. Risks include accidentally sharing the DNA information of close genetic relatives, such as siblings and children, with third-party actors without these relatives' consent. An organization that collects DNA information could create a genetic profile not just of the person who voluntarily shared, but also their relatives.

Future advances in genomics could allow DNA database services to draw new conclusions from DNA sequenced in the past. This could be problematic if users have not consented to their DNA being used to generate new insights when they signed up for a particular DNA testing service. The digitization of biological data such as DNA and their use on online platforms could result in ongoing privacy issues over a lifetime, and for many generations.

Ecosystem wellbeing

A global shift to biomanufacturing could reduce the need for natural resources and create opportunities to repurpose land, restoring and protecting ecosystems and making them more resilient.

New biodigital technologies could boost the restoration of ecosystems. Technologies such as eDNA and AI could improve capacity to measure and track biodiversity and the value of ecosystem services, as well as predict the impacts of proposed development on nature. This could improve the environmental assessment process and reduce the impact of human activities on the environment.

Biodigital innovations and products that use advanced carbon-storing methods could support climate change mitigation and adaptation. Biodigital innovations used for bioremediation could create new ways to decontaminate brownfields.

However, some innovations—such as gene drives that allow actors to introduce highly inheritable genetic traits into animal or insect populations—could also pose threats to ecosystems. Once genetically modified living beings are released in an area, there may not be a clear method of reversing that act. Concerned communities that may be affected by genetic modifications to the ecosystem could help identify ways to minimize or mitigate these risks. They may hold valuable knowledge of their ecosystem and may share concerns on the impact to their environment.

Cross-border governance

Biodigital technologies may not be developed or used at the same rate, or follow the same standards across the globe. Inconsistencies in the governance of biodigital technologies may lead to cross-border conflicts and limit collaboration in innovation.

Even if a country puts measures in place to monitor bioinnovations, it may also need to monitor the innovations that cross its borders from other countries that may have different controls. Potential risks include GMOs spreading in nature, or biological data held in offshore data centres that are exploited by foreign actors.

Different approaches to sharing information and coordinating limits on research across jurisdictions may be considered. Unless there is consensus on what is and is not allowed, medical tourism may rise—for example, some people could travel to jurisdictions with different rules, hoping to boost their capabilities through gene-editing technology. People travelling overseas to access experimental procedures or to obtain medical devices could return with issues that could create pressure on local healthcare systems.

Bias and inequality

Genetics could act as a basis for discrimination, whether intentional or unintentional, creating new forms of inequality.

Countries could use genetics to discriminate. For example, greater use of DNA profiling in areas like immigration and law enforcement could raise new risks of human rights violations. Private companies such as insurers and employers could discriminate in new ways based on DNA data. New identity-based movements related to genetics may emerge and spread racism and other forms of prejudice.

Genetic discrimination could also be unintended. Biological data that does not represent population diversity could skew the innovation process. This could create new forms of inequality and exclusion. For example, just as AI trained on biased data maintains bias, if a portion of the population is more likely than others to have their DNA sequenced, innovation based on that DNA could disproportionately benefit that group.

Trust

Unethical research and development, conspiracy theories, mis- and disinformation, and unsupported excitement about biodigital innovations could weaken trust in biodigital technologies, and lead to an unequal distribution of associated benefits and risks.

Trust in biodigital technologies may be difficult to earn or maintain, given their novelty, potential for dual use, historical considerations, and the ethical concerns they are raising.

Trust may be challenged in many areas, such as: the use of AI diagnostics instead of human doctors; medical technologies like nanobots delivering medicine inside the body; new services to alter the human genome; and biological data collection by public or private actors with a questionable track record.

Good intentions behind research and development are not enough to ensure the general public's adoption and acceptance of biodigital innovations. The public's trust in the actors who provide goods and services is also important. For example, much like controversies in the nuclear energy or petrochemical industry affected trust in entire sectors in the past, the reputation and regulation of the actors proposing gene drives could heavily influence whether these new technologies are accepted. The public's trust in biodigital innovations and services could greatly depend on the governance framework meant to protect public interest, encourage social cohesion, and curb market failure.

Labelling regimes

Consumers of biodigitally produced goods and services like food or healthcare may be confused if there is a lack of standardization for their ingredients or processes, leading to different interpretations of certain words or concepts.

Companies and governments could use ambiguous or misleading communication strategies to gain a competitive advantage on global markets. For example, they could use marketing that promotes unproven claims such as the low environmental impact of their food product compared to a conventional one. Such strategies may be deployed to appeal to specific consumer interests or market segments.

New biodigital products and services could be differently regulated at the global level, and some countries could use labelling requirements to discriminate against those products and services as a protectionist measure. Biomanufactured products made via gene editing or synthetic biology could trigger right to know movements demanding more labelling transparency. There may be calls not only to indicate whether a product was genetically engineered, but also what gene-editing technique was used in its production. For example, CRISPR is only one of many gene-editing techniques that itself has several variations, each with specific uses.

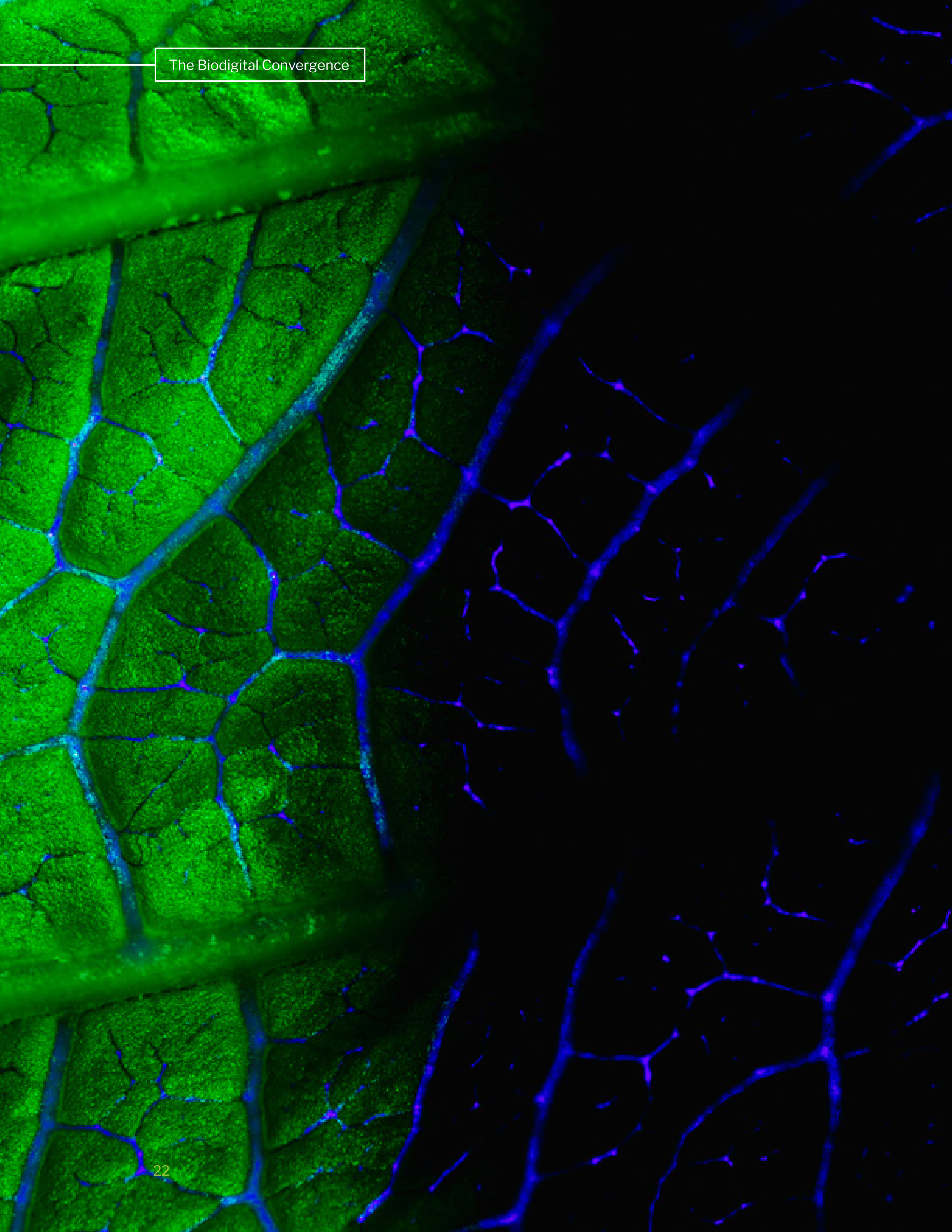
Literacy and training

Biodigital innovations could become more common and the innovation process more accessible, requiring new literacies and research training for the general public.

Finding ways to improve scientific literacy on biodigital matters could reduce the risk of harmful uses of biodigital technologies and help prevent the spread of mis-information and conspiracy theories.

Affordable research equipment combined with open science are supporting the growth of do-it-yourself bio, a social movement in which people with little biology training experiment with genetic engineering research tools. The rise of business models that offer benefits in return for sharing DNA data reveals the importance of fostering better individual decision making through scientific literacy. For example, individuals may not understand the potential risks of misused biological data. They may also not understand how to use information about themselves to improve their health.

Much like a makerspace is a public facility that offers people access to tools like 3D printers and laser cutters, public biofoundries could provide synthetic biology and computer-aided design software. Citizen scientists, having some biodigital knowledge and experimenting in biofoundries, could increase the pool of expertise to support a local and regional bioeconomy.



Biodigital impacts on policy areas

The possible cross-cutting policy implications listed in the previous section may affect some policy areas more than others. Table 1 summarizes these possible impacts.

Table 1. The policy areas most affected by the biodigital convergence

IMPLICATIONS OF THE BIODIGITAL CONVERGENCE	POLICY AREAS
Local production and supply chains	• Agri-food production and consumption • Food security • Trade competitiveness and protectionism
Biodigital threats	• Food security • Public health emergency preparedness • National security and defense
Intellectual property and open-source innovations	• Biomanufacturing • Research and Development (R&D) • Trade competitiveness and protectionism

IMPLICATIONS OF THE BIODIGITAL CONVERGENCE	POLICY AREAS
Ecosystem wellbeing	• Climate change adaptation and resilience • Biodiversity conservation
Cross-border governance	• Biodiversity conservation • National security and defense • Trade competitiveness and protectionism
Trust	• Public health emergency preparedness • Mis- and disinformation • Privacy
Labelling regimes	• Agri-food production and consumption • Health and safety risks of consumer products
Literacy and training	• Biomanufacturing • Mis- and disinformation • R&D

Conclusion

The biodigital convergence may bring many opportunities to solve a range of challenges, such as those stemming from climate change, food security, supply chains, biodiversity loss, and disease. Several governments around the world have already created policy frameworks and adopted strategies to grow biomanufacturing capacity and be competitive in the new bioeconomy.

The three key pillars of the biodigital convergence—data, genomics, and critical systems—may interact and substantially influence technological progress. Thinking about these pillars may help identify strategic assets; and using those assets could help maximize the benefits and identify risks of the biodigital convergence.

As the biodigital convergence continues, biodigital production methods and services may accelerate. While this may have the potential to solve important global challenges, it could also create risks. Accelerated data collection may threaten privacy, consent, and human rights. Bias embedded in biodigital products and services may lead to discrimination, whether intentional or not. Synthetic biology may result in irreversible changes to ecosystems and threaten traditional ways of living. Finally, the dual use of biodigital production methods may endanger national security.

Exploring the links between seemingly unrelated policy implications could provide an opportunity for multidisciplinary collaboration to address these issues. Conversations that involve various stakeholder groups could enable a careful balance between economic and societal wellbeing while navigating the possible risks and opportunities of the biodigital convergence. This may help pave the way to a sustainable, prosperous, and safe future for Canada.

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