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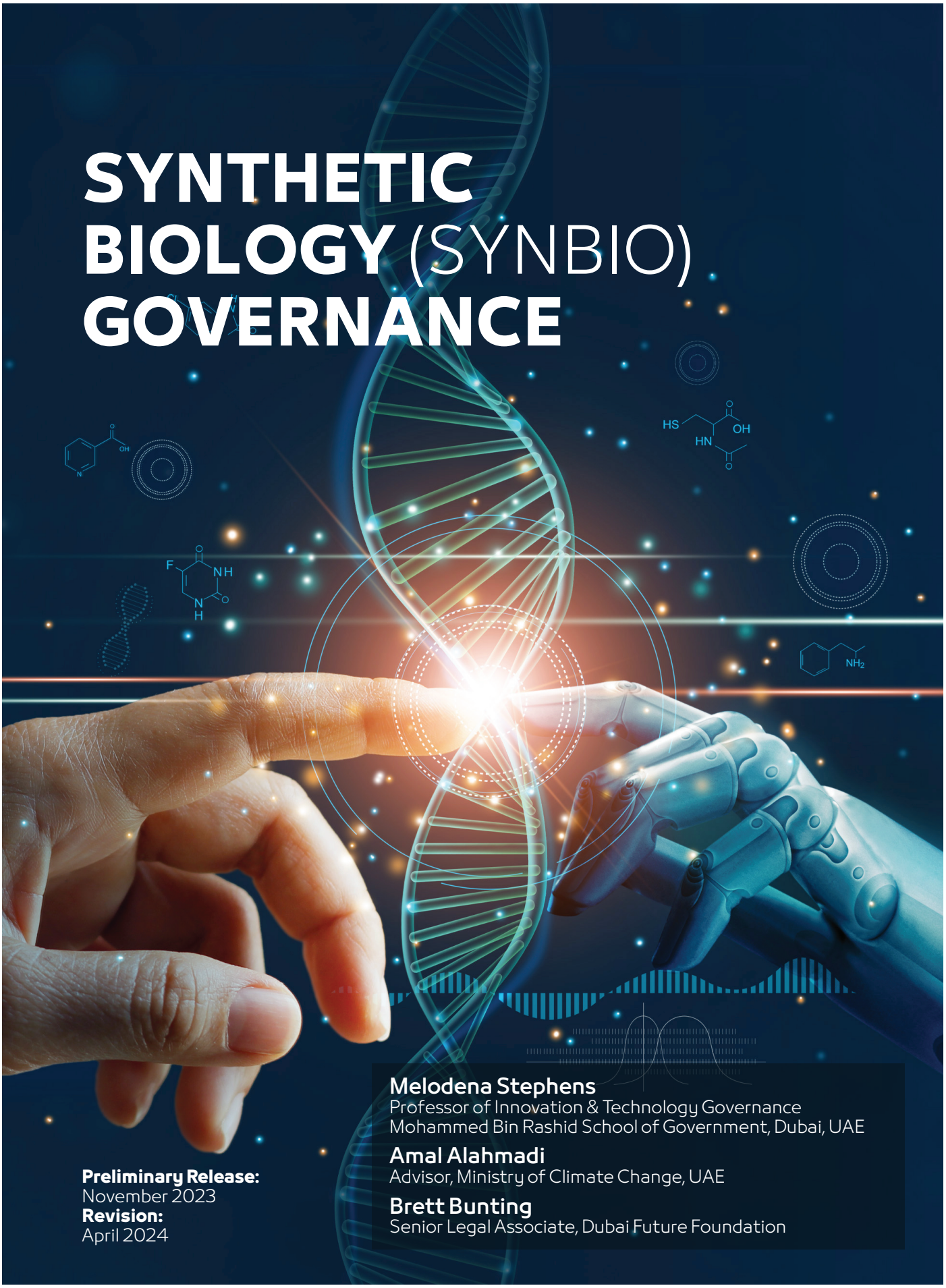
MOHAMMED BIN RASHID SCHOOL OF GOVERNMENT

SYNTHETIC BIOLOGY (SYNBIO) GOVERNANCE



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"The sword of science is double-edged. Its awesome power forces on all of us, including politicians, a new responsibility – more attention to the long-term consequences of technology, a global and transgenerational perspective, an incentive to avoid easy appeals to nationalism and chauvinism. Mistakes are becoming too expensive."

Carl Sagan

Carl Sagan – The Demon-Haunted World: Science as a Candle in the Dark[1]

1. Sagan, C. (2011). The Demon Haunted World: Science as a Candle in the Dark. Ballantine books.

Executive Summary

Synthetic biology (SynBio), in simple terms, refers to artificially developing or imitating a natural process or system. The complexity and novelty of SynBio, however, have together created a level of difficulty in defining SynBio because of the continuously fast-track evolution of the technology and the broadening of its context in the past decade. SynBio's current and potential impact is multidisciplinary, with an estimated applicability and impact of $30 trillion by 2030, which further intensifies the need to understand and govern this exponentially evolving subsector.

SynBio and its regulatory and governance framework have been gaining more traction, especially after several key recent events, such as the fast-track development and adoption of messenger RNA (mRNA) vaccines during the COVID-19 pandemic. This event alone has left many unanswered questions from scientific, legal, governance, ethical, social, and economic perspectives. The fact that we are daily interacting with SynBio knowingly or unknowingly – from food to environment, the development of designer babies, creating a new form of life like artificial intelligence (AI) xenobots from a single cell from a frog, and de-extinction efforts – has made it critical for scientists and policymakers to act immediately. While this sector took years to decode the human genome, it now takes days to design a vaccine against a new deadly virus, at a fraction of the previous cost.

This report delves into several SynBio scenarios through a multidisciplinary lens while surveying the global governance framework and the current and potential risks associated with this sector and its technologies. It does so in the absence of a collective consensus on the legal and ethical frameworks needed, at minimum, to regulate the use and development of SynBio. This report provides an overall perspective of the magnitude and complexity of the sector and the policy options for governing SynBio at national and global levels. These policy recommendations take into consideration continuously evolving and multisectoral technologies, utilising the expertise of geneticists, healthcare providers, researchers, and policy, legal, and pharmaceutical experts.

1.0 Purpose

"After millions of centuries during which the evolution or organisms happened naturally, we humans now have the ability to hack the code of life and engineer our own genetic future…. Like any evolutionary trait, this new ability may help the species thrive….Or it may not. Evolution is fickle that way."

Walter Isaacson – The Code Breaker[2] (p. 480-81)

The purpose of this report is to present a brief snapshot of the global state of affairs in SynBio governance and to propose high-level recommendations. Broadly, we can look at SynBio as the use of physical and genetic engineering to create new, modified or enhanced, and, therefore, synthetic, as in 'not naturally found' life forms.[3,4] This report uses a detailed review of policy, literature, and findings from a design thinking workshop. The report is put together by an interdisciplinary team.

Currently, regulations are siloed and SynBio as a field sits at the cusp of several disciplines – technology, biology, chemistry, engineering, materials science, environmental science, and information technology (even using AI) – that have been developing exponentially. Hence, its governance needs cross-sectional experts or at least those with broad enough knowledge to understand how discipline-specific topics overlap. The overlap of these new technologies has implications as they fall under the regulations of various siloed sectors.

Like AI, the scale at which SynBio is being adopted in our daily lives is escalating rapidly and the impact can be potentially generational.[5] The gaps between frontier theoretical research and its transformation into applied research and commercial research are non-linear and usually take decades, but in some cases they are fast-tracked (mRNA vaccines approved on an emergency basis for COVID-19), resulting in a lack of oversight, without inter-agency responsibilities for new technology or detailed oversight of generational impact.[6]

2. Isaacson, W. (2021). The Code Breaker: Jennifer Doudna, Gene Editing, and the Future of the Human Race. Simon and Schuster.
3. Hunter, D. (2013). How to Object to Radically New Technologies on the Basis of Justice: The Case of Synthetic Biology. Bioethics, 27 (8): 426–434.
4. Scientific Committee on Health and Environmental Risks. (2014). Opinion on Synthetic Biology. Definition. Available: https://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_044.pdf
5. Vaidyanathan, P. (2023). IWBDA 2021: An Ongoing Journey to Shape the Future of Synthetic Biology Using Bio-Design Automation. ACS Synth. Biol., 12 (2): 348–349
6. GAO (2018). Science and Technology: Considerations for Maintaining U.S. Competitiveness in Quantum Computing. Synthetic Biology, and Other Potentially Transformational Research Areas. https://www.gao.gov/assets/gao-18-656.pdf

This type of technology, SynBio, is perceived as a dual-use technology or a double-edged sword,[7] raising concerns about how we can develop guard-rails to ensure it is governed well for the greater benefit of humankind and the planet.[8] Hence, we need more oversight of the innovations deployed because they can change humans, their natural evolution, and natural ecosystems. SynBio can do tremendous good, but good governance can make the impact better.

7. Binary weapons are weapons made of organisms or biological products that are inert or non-lethal when alone but deadly when combined. More governance challenges are identified in the following article: Li, J., Zhao, H., Zheng, L., and An, W. (2021). Advances in Synthetic Biology and Biosafety Governance. Front. Bioeng. Biotechnol. Available: https://doi.org/10.3389/fbioe.2021.598087

8. Mandel, G. N. & Marchant, G. E. (2014). The Living Regulatory Challenges of Synthetic Biology. Iowa L. Rev. 100 (1), Available: https://ilr.law.uiowa.edu/print/volume-100-issue-1/the-living-regulatory-challenges-of-synthetic-biology/

2.0 Background

"All of us [on the research team] realized that what had started as a fundamental research question was morphing into a very different kind of project; namely, one with enormous technical potential and also risks and opportunities that we had not appreciated when we started the work."

Jennifer Doudna PhD
2020 Nobel Prize co-winner for developing CRISPR gene-editing technology [9]

2.1 Market Potential and Industry Growth

The SynBio global market size is estimated to reach $30.7 billion by 2026,[10] yet its extended applicability means it may reach $30 trillion by 2030 or one-third of global output (see Table 1 for some SynBio industry sectors).[11] The confluence of AI and genetics spearheaded by, for example, Al Gore's policy in 1991, the High Performance Computing Act of 1991, was adopted to advance computational data science.[12] This policy had significant spillovers into SynBio. The decision by the United Kingdom to be the first country to approve CRISPR gene-editing technology for gene therapy to treat blood disorders will have far-reaching impact.

The use of AI is accelerating the growth of this market. The Defense Advanced Research Projects Agency (DARPA) of the U.S. Department of Defense (responsible for the development of emerging technologies for use by the military) teamed up with the Foundry at the Broad Institute of MIT and Harvard and in 90 days the Foundry was able to identify 6 out of 10 molecules of interest (normally this would take years).[13] This optimism in the technology was further fuelled by the success of the mRNA vaccines used to fight the COVID-19 pandemic.

9. Balch, B. (2021). Making Science Serve Humanity: Jennifer Doudna, PhD, Says CRISPR Gene-Editing Technology Should Be Accessible To All. Available: https://www.aamc.org/news/making-science-serve-humanity-jennifer-doudna-phd-says-crispr-gene-editing-technology-should-be

10. MarketsAndMarkets. (2021). Synthetic Biology Market by Tools (Oligonucleotides, Enzymes, Synthetic Cells), Technology (Gene Synthesis, Genome Engineering), Application (Tissue Regeneration, Biofuel, Consumer Care, Food & Agriculture, Environmental) and Region - Global Forecast to 20. Available: https://www.marketsandmarkets.com/Market-Reports/synthetic-biology-market-889.html?gclid=CjwKCAiAiKuOBhBQEiwAId_sK7v-1tkgmG7tikdUQyW-fOUKEzfl1kjhMnCPCAQuDLLuHv1AGMDmHehoCcP0QAvD_BwE

11. BCG Henderson Institute. (2022). Synthetic Biology Is About to Disrupt Your Industry. Available: https://www.bcg.com/publications/2022/synthetic-biology-is-about-to-disrupt-your-industry

12. This space is being conflated and complicated as the algorithms may be opaque and the ethics and responsibilities of findings and use cases not sufficiently deliberated; hence, when launched at scale, SynBio may not be as inclusive or fair as promised.

13. Casini, A., Chang, F. Y., Eluere, R., King, A. M., Young, E. M., Dudley, Q. M., et al. (2018). A Pressure Test to Make 10 Molecules in 90 Days: External Evaluation of Methods to Engineer Biology. J Am Chem Soc. 140, 4302–4316. doi: 10.1021/jacs.7b13292

Table 1. Examples of SynBio industry sectors

Health	Vaccines (e.g. mRNA vaccines for COVID-19, personalised vaccines)
Biofuels	Controlling and enhancing the production of biofuels through engineered crops and the use of microorganisms
Food production	Used in some cases of genetically modified (GM) or functional foods (e.g. animal-free milk, next-generation sweeteners, some Chinese soy sauce and rice wine, 3D printing of synthetic or cultured meat)
Agriculture	Overlaps with GM or functional foods (e.g. new GM seeds, biofertilisation, insect- or disease-resistant crops)
Pest and Disease control	GM mosquitoes (using gene drive technology, i.e. changes can be transmitted to the offspring)
Clean production or waste management	Biomining or bioleaching (extraction of precious metals from feedstock, e-waste), plastic recycling
Cybergenetics	Programming living cells with on/off switches (e.g. monitoring and triggering the release of insulin)
Material Science	Smart clothing, cosmetics, construction, mobility, etc.
AI	DNA as data storage cells

The burgeoning economic potential of SynBio has prompted various governments to publish strategic road maps addressing its governance. Concurrently, investments in emerging start-ups within this domain have experienced a rapid surge, amounting to approximately $6.1 billion since 2015.[14] This heightened interest from both governments and start-ups signifies a paradigm shift away from traditional industrial biotechnology or metabolic engineering towards novel applications in consumer biotechnology and living medicines. Consequently, the advent of the SynBio industry is anticipated to foster a new era in the bioeconomy, characterised by circular green economic models and environmentally conscious investments. This development holds the promise of addressing some of the most pressing global societal challenges, underscoring the transformative potential of the SynBio industry.

14. Freemont, P. S. (2019). Synthetic Biology Industry: Data-Driven Design is Creating New Opportunities in Biotechnology. *Emerg Top Life Sci.* 3 (5): 651–657. doi: https://doi.org/10.1042/ETLS20190040

2.2 Definition

SynBio is a technology that can use unnatural molecules, borrowing from nature to reproduce artificial life or its behaviours or that can take components from natural biology to assemble them into systems that act unnaturally.[15] Often, the terms new or novel[16] are associated with SynBio, creating some challenges in its regulation. At one end of the spectrum, any modified or redesigned biological life form uses some existing genetic material and something new (like an engineered process[17]). Hence, it can be considered modified artificially and, therefore, a form of SynBio.

On the other hand, some legal definitions regarding patentability look at newness as a prerequisite and thus omit some types of genome editing. Processes such as genome editing, which involves minor modifications to an existing genetic code (additions or deletions), may not create something entirely new, even though the process is often the same. So, for example, if the editing of a gene took place using protein reagents rather than nucleic acid, it would not be considered SynBio, even though modifying the gene drive,[18] which is responsible for the hereditary transfer of genetic material to future generations of the species. This narrow viewpoint is a problem as genome editing may often not fall under SynBio regulations, if any exist. The first set of regulatory challenges starts from the fact that there is no internationally agreed definition of SynBio.[19]

The various facets of the definition of SynBio are purpose, method, and process (input andoutput):[20]

15. Benner, S. & Sismour, A. (2005). Synthetic Biology. Nat Rev Genet. 6, 533–543. https://doi.org/10.1038/nrg1637

16. According to the Government of Canada, a new product may be considered 'novel' if it has one of the following: (1) a new trait(s) or characteristic(s); (2) a changed trait(s) or characteristic(s); (3) a new use as a food or livestock feed: https://inspection.canada.ca/plant-varieties/plants-with-novel-traits/general-public/overview/eng/1337827503752/1337827590597

17. National Human Genome research Institute 2023. Synthetic Biology. Available: https://www.genome.gov/about-genomics/policy-issues/Synthetic-Biology [Accesssed 3 August, 2023]

18. Convention on Biological Diversity (2019). CBD/SYNBIO/AHTEG/2019/1/3. Available: https://www.cbd.int/doc/c/b2bb/cf58/b09729bb00be6abf72325a1a/synbio-ahteg-2019-01-03-en.pdf. Article 17, p. 7.

19. Keiper, F., & Atanassova, A. (2020). Regulation of Synthetic Biology: Developments under the Convention on Biological Diversity and its Protocols. Frontiers in Bioengineering and Biotechnology, 310.

20. Ibid; Scientific Committee on Health and Environmental Risks. 2014. Opinion on Synthetic Biology I Definition. Available: https://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_044.pdf; Presidential Commission for the Study of Bioethical Issues. (2010). New Directions: The Ethics of Synthetic Biology and Emerging Technologies. Available: https://bioethicsarchive.georgetown.edu/pcsbi/sites/default/files/PCSBI-Synthetic-Biology-Report-12.16.10_0.pdf; The Royal Society. (2023). Synthetic Biology. Available: https://royalsociety.org/topics-policy/projects/synthetic-biology/; European Environmental Agency. (2021). Synthetic Biology and the Environment. Available: https://www.eea.europa.eu/publications/synthetic-biology-and-the-environment. https://www.eea.europa.eu/publications/synthetic-biology-and-the-environment; CSIRO. (2023). Synthetic Biology Future Science Platform. Understanding Synthetic Biology. Available: https://research.csiro.au/synthetic-biology-fsp/resources-information/understanding-synthetic-biology/

1. Purpose

To solve problems[21] in health, pharmaceuticals, food, manufacturing, chemicals, environment, energy, and defense.[22]

2. Method

New, modified, manipulated, or redesigned engineered process that harnesses the power of nature.

3. Process

Faster and easier processes that can facilitate and accelerate the production of genetic material. Take the example of the COVID-19 virus: China shared the genetic sequence of the virus on January 11, 2020. Moderna used the information to finalize the design of its vaccine for clinical manufacture, using mRNA-1273 by January 13, 2020 (three days).[23]

3.a. Input

The genetic material of living organisms or non-viable, non-reproducing goods and materials generated by or through the use of such living genetically modified organisms; design or construction of novel and artificial pathways or devices.

3.b. Output

Design, manufacture, and/or modification of genetic material *in vivo* (inside cells) or *ex vivo* (in test tubes or other non-cellular environments), leading to a *living modified organism*.

Most definitions do not look at the system of SynBio, choosing to focus either on one type of method or process and are regulated across silos based on purpose. We suggest looking at the definition as a *SynBio system*.

21. National Academies of Sciences, Engineering, and Medicine (2018). Biodefense in the Age of Synthetic Biology. Washington (DC): National Academies Press. https://doi.org/10.17226/24890

22. Ibid.

23. Moderna's Work on our COVID-19 Vaccine. Timeline: https://www.modernatx.com/modernas-work-potential-vaccine-against-covid-19; It relies on transformational changes and the reengineering of natural and artificial components to achieve biological gains (see: Cameron, D. E., Bashor, C. J., & Collins, J. J. (2014). A Brief History of Synthetic Biology. Nature Reviews Microbiology, 12(5), 381-390)

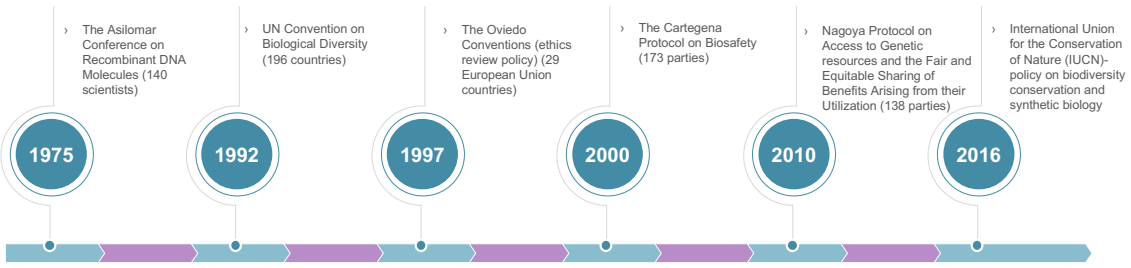
2.3 Brief History of SynBio Governance

The dawn of SynBio can be traced to the discovery of the DNA structure in 1953. This was followed in 1973, 20 years later, by the first attempt to 'cut' genes from DNA from one organism and insert these genes into the DNA of another. In the United Kingdom, the first national strategy for SynBio was released in 2012 and it is estimated that government funding in this sector exceeds £300 million. The countries leading in SynBio development are: the United States (close to 70% of patent filings), followed by China, the United Kingdom, Japan, Korea, and Germany, with other countries having 10% or fewer filings.[24]

There is an important debate about whether SynBio is a new field or an evolving field as there are existing policies for governance in some of the older fields, such as biotechnology, molecular biology, and metabolic and genetic engineering, and, for now, patents do not distinguish SynBio as a separate field. However, from 1995 onward, the patent numbers have exponentially increased.

Governance of SynBio at the international level has been largely driven by conventions, the key one being the Conference of the Parties (COP) and, within it, the United Nations Convention on Biological Diversity (CBD) (see Figure 1 for more details). Sadly, many issues are being left out of discussions. Key subsidiary agreements currently focus on the biosafety of living modified organisms (Cartagena Protocol on Biosafety to the CBD) and access to, and the benefit sharing of, genetic resources (Nagoya Protocol to the CBD).

Figure 1. History of SynBio governance (condensed)



24. This does not include European Patent Office and Patent Cooperation Treaty filings, and data were based on the following 2018 article: Oldham, P., & Hall, S. (2018). Synthetic Biology-Mapping The Patent Landscape. bioRxiv, 483826.

In 2010, COP Decision XI/11 noted 'the need to consider the potential positive and negative impacts of components, organisms and products resulting from synthetic biology techniques on the conservation and sustainable use of biodiversity'.[25] In 2015, it published a technical series on SynBio. The most recent report in 2022[26] states, 'However, the current regulatory landscape at the international level is fragmented, creating a complex situation with the potential for regulatory gaps and overlaps, as well as the development of potential synergies and convergence. While enhanced regulatory oversight and/or coordination to address potential gaps and areas of convergence has the potential to strengthen the governance of synthetic biology, there is also a risk of creating an overly complex or stringent environment that slows development in the field.' In 2022, in Decision 15/31, COP states that its Ad Hoc Technical Expert Group on Synthetic Biology had challenges and the studies 'have been inconclusive in determining whether synthetic biology is a new and emerging issue or not and decides not to require further analysis on whether synthetic biology is a new and emerging issue'.[27]

There are four challenges associated with governing SynBio. The first challenge is that the definition is ambiguous – would the current regulations for existing technologies be enough or would SynBio fall between the cracks? There is no uniform definition of SynBio.[28] Existing laws, to some extent, regulate genetic material, GM food, biosecurity, or environmental protection, but there are no overarching regulations.[29] The gap arises as scientists and industry often argue that the process of DNA editing is just an acceleration of what is there in nature. Some legal definitions justify that new regulations are not required as when they look at patentability, newness is a prerequisite, which omits some types of genome editing. Hence, things like genome editing, which involves minor modifications to an existing genetic code, may not involve creating something entirely new. But should a legal definition get conflated with the need for regulations, which is for the public good?

Second, is there political will to make changes (see Box 1)? SynBio, like AI, can contribute to national competitiveness, so the countries pushing the SynBio agenda may not want more regulations that could curtail their economic and technological progress. In 2012, in the United States, the Office of Science and Technology Policy released a report on the potential for bioeconomy, and a decade later, in 2022, the National Biotechnology and Biomanufacturing Executive Order was signed.[30] The United Kingdom produced a strategic road map on SynBio as early as 2012, which was followed by the UK Synthetic Biology Strategic Plan 2016. In November 2023, the United Kingdom became the first country to

25. COP (2010). Decision XI/11. Available: https://www.cbd.int/doc/decisions/cop-11/cop-11-dec-11-en.pdf
26. CBD (2022). Synthetic Biology. Available: https://www.cbd.int/doc/publications/cbd-ts-100-en.pdf
27. COP (2022). Decision 15/31. Available: https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-31-en.pdf
28. Keiper, F., & Atanassova, A. (2020). Op. cit.
29. See, for example, this detailed study on GM crops: Turnbull, C., Lillemo, M., & Hvoslef-Eide, T. A. (2021). Global Regulation of Genetically Modified Crops Amid The Gene Edited Crop Boom–A Review. Frontiers in Plant Science, 12, 630396.
30. White House (2022). National Biotechnology and Biomanufacturing Executive Order. Available: https://www.whitehouse.gov/briefing-room/presidential-actions/2022/09/12/executive-order-on-advancing-biotechnology-and-biomanufacturing-innovation-for-a-sustainable-safe-and-secure-american-bioeconomy/

approve personalised medicine using CRISPR genome editing. In the United States, this frontier market has evolved largely unregulated, backed by commercial promise.

Third, there is a need to better understand the trade-off between the good that SynBio could do and the risks. How would you audit and determine those? A deeper level of governance (as in good manufacturing practice (GMP), conformity evaluation, trials, etc.) is needed as it is currently very underdeveloped. As an example, the European Medicines Agency is just now developing a GMP framework for mRNA vaccine manufacturing (comments were closed on 30 September 2023), while over a few billion doses have already been administered globally. SynBio is developing faster than the regulatory apparatus is able to cope. We need a better policy mindset to manage frontier or advanced technologies.

Another challenge is the possible exploitation of these technologies. The fact that many countries are profiling their population's DNAs (for greater health benefits) might expose large groups of people to security risks. Genetic profiles may not be stored securely in the home country or may be shared with third-party providers, perhaps in other countries, for research or commercial reasons. Who has the responsibility for ensuring these technologies and the data harvested are limited to the original purpose.

Another trade-off is found by looking at the need for experimentation at the research stage, its translation into commercialisation, and the ethicality of the process. For example, Germany has a strong research foundation in the field with professorships being developed in 2009 and the formation of MaxSynBio (a collaboration between the Max Planck Society and the German Federal Ministry of Education and Research). Will the current ethics and research guidelines in academia be enough when new products are commercialised?

Fourth, and last, through what lens should we look at SynBio? It has been insidiously integrating itself across all industries; could it, therefore, require a separate focus like AI, which cut across several sectors and industries? For example, some lawyers argue that SynBio can be viewed as a device rather than a drug[31] (which would require a different regulatory approval with less oversight). This narrow viewpoint is a problem as genome editing may often not fall under SynBio regulations, if any exist.

31. Fatehi, L. & Hall, R. F. (2015). Synthetic Biology in the FDA Realm: Toward Productive Oversight Assessment, 70 Food & Drug L. J. 339, 349, supra note 7, at 360

Box 1: Political will

The largest market for GM crop seeds is the Americas, which accounts for 90% share of the global seed market,[32] with two corporations (Bayer, previously Monsanto Corveta, previously DuPont) controlling 40% of the seed market.[33] The Bill & Melinda Gates Foundation has invested in Monsanto and Cargill, another key player in the GMO market, which has raised some criticism.[34] The challenge is that GMOs may evade regulations and raise lots of questions: field testing, how these GMOs interact with other plant species, impact on the food chain (and humans) long-term, and using existing regulations may not be enough.[35]

In 2016, DARPA had research program called "Safe Genes" to prevent pests from carrying diseases for up to 20 generations.[36] One key area of focus has been malaria and hence mosquitoes. Mosquitoes with modified gene drives have been touted as a viable solution for the reduction of malaria. Engineering bacteria (BTI, Wolbachia) to fight mosquitoes carries the risk of fast and uncontrolled spread since those bacteria can, by definition, be spread by the mosquitoes outside of the treatment area. It›s okay as long as they only affect mosquitoes, and we do not end up with a Wolbachia strain capable of infecting most pollinators. Another company, (Forest Innovation)[37] is using RNA to sterilize mosquitoes– and there seems to be no direct risks here, but this illustrates how unorthodox SynBio approaches can be.

In 2018, a Chinese scientist said he created designer babies in by editing gene embryos.[38] Gain-of-function research (GoF research or GoFR), like that associated with the Wuhan lab, is an example of dual-use research of concern (DURC) and was stopped in 2012 for eight months due to its controversial nature. The space of SynBio governance is complex and messy.

32. Fortune (nd). Genetically Modified Seed Market Size, Share, and Industry Analysis. Available: https://www.fortunebusinessinsights.com/industry-reports/genetically-modified-seeds-market-100389

33. Food & Power (2022). GMOs & Seeds. Available: https://www.foodandpower.net/gmos-seeds#:~:text=In%202020%2C%20the%20top%20four,Corteva%20alone%20claiming%20roughly%2040%25.

34. The Guardian (2010). Why is the Gates Foundation Investing in GM Giant Monsanto? Available: https://www.theguardian.com/global-development/poverty-matters/2010/sep/29/gates-foundation-gm-monsanto

35. Suppan, S. (2015). From GMO to SMO. How Synthetic Biology Evades Regulations. Available: https://www.iatp.org/sites/default/files/2014_07_18_Synbio_SS_0.pdf

36. Garthwaite, J. (2016). How US Military Preps for Gene Drives Runs Amok. Available: https://www.scientificamerican.com/article/u-s-military-preps-for-gene-drives-run-amok/

37. See more on the company: https://www.forrestinnovations.com

38. Science. (2019). Chinese Scientist Who Produced Genetically Altered Babies Sentenced to Three Years in Jail. Available: https://www.science.org/content/article/chinese-scientist-who-produced-genetically-altered-babies-sentenced-3-years-jail

3.0 SynBio Risks

"Many of the traditional approaches to biological and chemical defense preparedness will be relevant to synthetic biology, but synthetic biology will also present new challenges."

Biodefense in the Age of Synthetic Biology[39]
National Academies of Science: USA (p. 7)

SynBio risks are typically categorised as a) biosafety risks and b) biosecurity risks. Biosafety is concerned with the health and safety of people and the environment in relation to the potential risks associated with accidental or unintentional exposure to synthetic organisms. Biosecurity on the other hand relates to those risks arising from the intentional or nefarious use of synthetically modified organisms as bioweapons. A third risk category exists – namely bioethics – concerned with the unethical direction of research in SynBio. While the bulk of commentary on the risks associated with SynBio focuses on biosafety and biosecurity, it is essential that any regulatory framework addresses bioethics in equal measure. In an ever-increasingly unequal society, SynBio has the very real potential to bifurcate human development, leading to the 'haves' and the 'have-nots', not just in terms of wealth and resources, to which we are accustomed, but also in terms of biological superiority/inferiority.

3.1. Biosafety: Human Direct and Indirect Impact

The direct impact on humans comes from treatments that use SynBio, such as personalised medicine or vaccines, or gene modification or therapy (see Box 2). According to the National Human Genome Research Institute, 'Gene therapy is a technique that uses a gene(s) to treat, prevent or cure a disease or medical disorder. Often, gene therapy works by adding new copies of a gene that is broken, or by replacing a defective or missing gene in a patient's cells with a healthy version of that gene.' [40] The long-term effects are unknown for the individual and for society. Is there enough oversight? At what point would gene therapy be detrimental and lead to greater inequality between those that can afford the technology and those that cannot?

39.: National Academies (2018). Biodefense in the Age of Synthetic Biology. Available: https://nap.nationalacademies.org/catalog/24890/biodefense-in-the-age-of-synthetic-biology

40. National Human Genome Research Institute (2023). Gene Therapy. Available: https://www.genome.gov/genetics-glossary/Gene-Therapy#:~:text=Gene%20therapy%20is%20a%20technique,healthy%20version%20of%20that%20gene.

Box 2: Gene Therapy

Gene therapy is often one aspect of personalized medicine, with a predicted market size of US$ 17.2 billion by 2027.[41] Here, we assume we know enough about the role of genes and have the technology to influence, modify, or replace them for health reasons. Ideally, there should be a difference between treatment when you use gene therapy to identify and then cure the disease and enhancement when you use genetic therapy to create better humans.[42] All gene therapy is genetic engineering.[43] Take the example of gene therapies that use adeno-associated virus (AAV) or other vector-based gene therapies. As of now, most therapies require a large viral load, leading to immunity to this type of vector (e.g., AAV5), meaning it can only be used once and may render other therapies based on the same vector ineffective in the same patient.[44]

There is work on vectors that do not induce immunity, but it›s not there yet. The reality is that we are still learning about human genetic material and the human genome. The human genome contains genetic material like genes and the non-coding DNA, mitochondrial DNA (16,569 nucleotides), chloroplast DNA and line genes. It is currently estimated that we have around 23,000 genes in our genetic code. Genes are parts of DNA, they have the instructions to produce a molecule (mostly a protein with specific functions like colour of the eyes, a liver cell, etc.). DNA is made up of complex molecules called nucleotides and human DNA has about 3 billion individual DNA molecules called nucleotides. Each human DNA is looped into a structure called chromosome.

Each human has 46 chromosomes where one pair (23 chromosomes) comes from each parent. Each individual, except pairs of identical twins, has their own sequence of genomes. If written in a normal type font, the entire length of this sequence would be 5,000 kilometers.[45]There are 13,000 genes whose functions are not yet known; of the ones we know – 38.2% are responsible for functions like immunological proteins, biochemical transport processes and protein folding, and structural protein, 23.3% are expression, replication, and maintenance of the genome, 21.1% for signal transduction and 17.5% for biochemical functions of cells.[46]

41. MarketsAndMarkets. (2023). Gene Therapy Market. Available: https://www.marketsandmarkets.com/Market-Reports/gene-therapy-market-122857962.html?gclid=Cj0KCQjw3JanBhCPARIsAJpXTx4BbDS2YDv_LkyAKAGJsEPWO7-

42. This was a topic of discourse in 1999; See https://www.cancernetwork.com/view/scientists-warn-about-potential-misuse-gene-therapy

43. Metzl, J. (2020). Hacking Darwin: Genetic Engineering and the Future of Humanity. Illinois: Sourcebooks, p. 103.

44. Stivers, N. (2023). Introduction to AAV Gene Therapies. TheScientist. Available: https://www.the-scientist.com/sponsored-article/introduction-to-aav-gene-therapies-71193

45. Brown, T. A. (2002). Genomes. 2nd edition. Oxford: Wiley-Liss; Chapter 1, The Human Genome. Available from: https://www.ncbi.nlm.nih.gov/books/NBK21134/

46. Brown (2002) Op. cit.; Venter, J.C., Adams, M.D., Myers, E.W., et al. (2001). The Sequence of the Human Genome. Science, 291:1304–1351.

It is important to remember, "One thing that the gene catalog cannot tell us, and will not be able to tell us even when it is complete, is what makes a human being… More detailed studies of how the human genome functions may reveal key features that underlie some of the special attributes of human beings, but genomics will never explain why a human was able to compose Mozart's 40th symphony, or indeed why it was composed by Mozart and not by an ordinary human."[47]

Another example of indirect impact could be the food humans consume (see Box 3). In the CBD, there is still no consensus on whether modification of gene drives is SynBio. The challenge seems to be a lack of control or the inability to predict future impact on evolving systems. Take the example of a GM crop. The term GMO is commonly used to refer to genetically engineered crops that result in higher yields (so are geared for large-scale farming), are more resistant to disease or have higher nutritional content. GM crops may be cheaper but they allow higher doses and frequency of pesticide use. There are added dilemmas regarding engineered crops being unable to reproduce (keeping the genetic traits) or cross with other varieties (leading to gene contamination, common in the United States and Mexico, especially with corn), thus increasing the costs for farmers who now cannot use their own crops for the next planting season (this is primarily a legal issue with soy and corn in the United States). Health dilemmas are compounded by having to consider environmental safety versus preserving biodiversity and the self-sustainability of farmers.

GM crops now dominate our food chain and are eroding more nutritious indigenous species, affecting biodiversity and Indigenous Peoples. Because they are grown as monocultures (single-crop farming, such as corn, wheat, and rice), they leave the food chain more susceptible to disease outbreaks. In the United States, more than 87% of corn is GM.[48] At this point, the way risk is categorised is not uniform, with different tolerance limits for GM ingredients, labelling requirements (voluntary/optional; categories), and trade requirements (e.g. bans).[49]

47. Brown (2002). Op. cit.

48. Waddell, M. (2023). The GMO High-Risk List: Corn. NonGMO Project. Available: https://www.nongmoproject.org/blog/the-gmo-high-risk-list-corn/#:~:text=More%20than%2087%25%20of%20corn,Non%2DGMO%20Project%20was%20created

49. Garcia-Yi, J., Lapikanonth, T., Vionita, H. et al. (2014). What Are the Socio-Economic Impacts of Genetically Modified Crops Worldwide? A Systematic Map Protocol. Environ Evid, 3, 24.

Box 3: Genetically modified crops

Often, new strains of crops are introduced before we can fully access possible side effects, as was the case with the LY038 variety of corn, which was withdrawn from the European market because it was producing the neurotoxin acrylamide.[50] This was also a focus for GM potatoes, which had lower levels of the chemical.[51] Acrylamide is produced at high temperatures and linked to cancer,[52] and focus on it began t1hrough global collaboration with agencies such as the Food and Agriculture Organization of the United Nations and the World Health Organization (WHO).[53] The issue seems to be that standard tests developed for regulatory approval do not identify unintended effects of the chemical (so the tests are confirmatory rather than questioning safety). Acrylamide causes bruising in potatoes, for example, and if the potato is modified to remove bruising, the consumer may not know that the chemical exists. While GM products are regularly withdrawn from the market, there is not enough awareness of why. For example, BASF withdrew from the GM potato market in 2013. An article from National Geographic states 'Genetically modified (GM) food plants are often transgenic—that is, they contain inserted gene sequences from wildly unrelated organisms, among them bacteria, jellyfish, rats, mice, spiders, and scorpions."[54] This technique uses RNA interference (acts like an on and off switch). Should consumers be aware of what they eat?

SynBio presents a promising avenue for addressing challenges in food security and agricultural sustainability by facilitating the development of disease-resistant crops capable of mitigating the impact of pathogens, parasites, and insect vectors. As this innovative approach enables the modification of natural systems, the implications for crops (and also livestock) are contingent upon various factors, including intellectual property (IP) policies, technology regulatory frameworks, and the balance of funding between public and private sectors.[55] These considerations are crucial in ensuring equitable access to the advantages conferred by genetically engineered crops and livestock to society in a safe and sustainable manner.

50. TestBiotech (2009). Approval Procedure for Genetically Engineered Maize LY038 Stopped for Safety Reasons? Available: https://www.testbiotech.org/en/press-release/approval-procedure-genetically-engineered-maize-ly038-stopped-safety-reasons

51. Halterman, D., Guenthner, J., Collinge, S. et al. (2016). Biotech Potatoes in the 21st Century: 20 Years Since the First Biotech Potato. Am. J. Potato Res. 93, 1–20. https://doi.org/10.1007/s12230-015-9485-1

52. Raffan S, & Halford NG (2019). Acrylamide in food: Progress in and prospects for genetic and agronomic solutions. Ann Appl Biol. 175(3):259-281.

53. Raffan S, & Halford NG (2019). Acrylamide in food: Progress in and prospects for genetic and agronomic solutions. Ann Appl Biol. 175(3):259-281.

54. Rupp, R. (2015). New Commercial Potato Bruises Less, Could Reduce Food Waste. National Geographic. Available: https://www.nationalgeographic.com/culture/article/potato-possible-carcinogenic

55. Pixley, K.V., Falck-Zepeda, J. B., Giller, K. E., Glenna, L. L., Gould, F., Mallory-Smith, C. A., Stelly, Jr. D. M., & Stewart, C. N. (2019). Genome Editing, Gene Drives, and Synthetic Biology: Will They Contribute to Disease-Resistant Crops, and Who Will Benefit? Annual Review of Phytopathology, 57:1, 165-188.

3.2. Biosafety: Environmental Impact

SynBio is actively used to manage the environment, for example in farming. Monoculture or single-crop farming leaves plants more susceptible to disease and pests. To avoid this, most corn in the United States is sprayed with neonicotinoid, a synthetic insecticide modified from nicotine, which, for example, leads to the destruction of bee colonies. Another example in which SynBio is used is to engineer bacteria for managing the environment (see Box 4). Mosquitoes are being bred to remove malaria. Over one billion mosquitoes have been released across Brazil, the Cayman Islands, Panama, Florida and Texas in the United States, and India. At this point, the United States Environmental Protection Agency does not think they are a risk.[56] The environment is a complex ecosystem and any interference with it may lead to unintended effects that we may not be ready to deal with. The WHO, only in May 2021, released its guidelines for GM mosquitoes, after the mosquitoes had been released.[57] SynBio is also used in the development of new materials, for example, like DNA-based data storage, fertilizers, bioleather, surfactants and biofuels.[58] Biofuels have been linked the inflation of sugar commodity markets.[59] Mushrooms, often genetically modified, can be used as a biofertilizer, but could also lead to more greenhouse gases.[60] Another example, which may have an unknown impact on the environment, is the process of de-extinction, which is the effort to revive extinct species (and in some cases predators). The United States and Australia have a $15 million project to revive the Tasmanian tiger.[61]

56. CDC (2023). Genetically Modified Mosquitoes. Available: https://www.cdc.gov/mosquitoes/mosquito-control/community/emerging-methods/genetically-modified-mosquitoes.html#:~:text=GM%20mosquitoes%20are%20mass%2Dproduced,GM%20mosquitoes%20in%20the%20wild

57. WHO (2021). WHO Issues New Guidance for Research on Genetically Modified Mosquitoes to Fight Malaria and Other Vector-Borne Diseases. Available: https://www.who.int/news/item/19-05-2021-who-issues-new-guidance-for-research-on-genetically-modified-mosquitoes-to-fight-malaria-and-other-vector-borne-diseases

58. For example see: Biotechnology Innovation Organization (nd). Available: https://archive.bio.org/articles/current-uses-synthetic-biology

59. See World Sugar Prices here: https://www.ifpri.org/blog/déjà-vu-all-over-again-global-sugar-markets-roiled-el-niño-biofuels-and-trade-policies

60. Joniec, J. et al. (2022). Assessment of the Effects of Soil Fertilization with Spent Mushroom Substrate in the Context of Microbial Nitrogen Transformations and the Potential Risk of Exacerbating the Greenhouse Effect, Agriculture, 12, 1190. https://doi.org/10.3390/agriculture12081190

61. Orf, D. (2023). The Tasmanian Tiger Has Been Extinct for 87 Years. It's About to Return From the Dead. Popular Mechanics. Available: https://www.popularmechanics.com/science/animals/a45264805/tasmanian-tiger-extinct-rna-resurrection/

Box 4: Bioleaching

The mining industry has a negative effect on the environment. To counter this, SynBio is used to modify microbes (fungi, bacteria, and archaea) to extract or decompose toxic material in run-off or to extract metals. Currently, it is often used in copper mines for retrieval of copper, gold, or uranium.[62] It could also be used to recover rare metals from e-waste.[63] Challenges include whether the designed 'kill switches' will work if the genetically engineered microbe escapes from its containment.[64]

3.3. BioSecurity/Weaponisation

SynBio can be used for weaponisation for biological warfare (biowars) and bioterrorism. The JASON group, a team of scientists advising the government of the United States, identified the threat in 1997, with the former Soviet Union having a clandestine biological weapons programme.[65] The U.S. Naval Institute identified the threat to national populations through the illegal collection and storage of national DNA data by foreign powers through, for example, gathering data from disease testing.[66] While there is a Biological Weapons Convention from 1975, it may be outdated and difficult to enforce in the current context. On the other hand, SynBio research for the security of a country can also be classified as a dual-use concern.[67] An example of this is 'Insect Allies', a DARPA project to secure food chains. This programme looked at modification of plant and insect genetic material for more resilient crops.[68] Box 5 gives examples of the security concerns that can arise in an open-source, global, and poorly regulated industry.

62. Saldaña, M.; Jeldres, M.; Galleguillos Madrid, F.M.; Gallegos, S.; Salazar, I.; Robles, P.; & Toro, N. (2023). Bioleaching Modeling—A Review. Materials, 16, 3812. https://doi.org/10.3390/ma16103812

63. Anaya-Garzon, J., Hubau, A., Joulian, C., & Guezennec, A. G. (2021). Bioleaching of E-waste: Influence of Printed Circuit Boards on the Activity of Acidophilic Iron-Oxidizing Bacteria. Frontiers in Microbiology, 12, 669738.

64. Giachino, A., Focarelli, F., Marles-Wright, J., & Waldron, K. J. (2021). Synthetic Biology Approaches to Copper Remediation: Bioleaching, Accumulation and Recycling. FEMS Microbiology Ecology, 97, 2: fiaa249, https://doi.org/10.1093/femsec/fiaa249

65. Wickiser, J. K. et al. (2020). Engineered Pathogens and Unnatural Biological Weapons: The Future Threat of Synthetic Biology. Available: https://ctc.westpoint.edu/engineered-pathogens-and-unnatural-biological-weapons-the-future-threat-of-synthetic-biology/

66. Knutzen, M. (2021). Synthetic Bioweapons Are Coming. US Naval Institute. Available: https://www.usni.org/magazines/proceedings/2021/june/synthetic-bioweapons-are-coming#:~:text=Unlike%20traditional%20bioweapons%2C%20which%20most,effects%2C%20mechanisms%2C%20or%20processes

67. Keiper, F., & Atanassova, A. (2020). Op. cit.

68. DARPA. (2018). Insect Allies. Available: https://www.darpa.mil/program/insect-allies

Box 5: Mail order CRISPR and biosafety

The cost of decoding a gene has fallen from $1 million in 2007 to $200 in 2023 and is expected to cost only $100 in a few years.[69] Biohackers are able to access material and equipment that was once unaffordable and dabble with them at home. A DIY CRISPR kit for bacterial gene engineering can cost $85–179.[70] You do not need to be a researcher or a scientist to access such material.71 Biohackers are selling these kits online (e.g. on Indiegogo and The ODIN).

Gain-of-function research involves enhancing some characteristics of DNA that may lead to more virulent strains of viruses or bacteria with the potential to cause pandemics, while *loss-of-function* research diminishes certain characteristics. The United States banned gain-of-function research from 2014 to 2017 and the conditions for restarting required robust biosafety.[72] More policies are needed around this with regular and timely inspections. However, research crosses borders and ensuring standards are met in other countries may be a challenge.

DNA printers are feasible and will soon be available (as of now, for the United States, regulatory screening for access is voluntary).[73] Within the next 5–10 years, the length of the DNA sequence that can be printed may increase from 200–700 base pairs to 10,000 base pairs (similar to the size of the smallest viral genome).[74] Worldwide, more than 100 companies sell DNA sequences. For example, a French company, DNA Script, 3D prints long oligonucleotides (oligos). A small amount of material can be used for explosives, chemical nerve agents, or to create a viable virus/organism that is self-replicating. How will control over newly synthesised oligos be handled in such a decentralised system?

69. 3billion (2022). Whole Genome Sequencing Cost 2023. Available: https://3billion.io/blog/whole-genome-sequencing-cost-2023; Regalado, A. (2020). China's BGI Says It can Sequence a Genome for Just $100. MIT Technology Review. Available: https://www.technologyreview.com/2020/02/26/905658/china-bgi-100-dollar-genome/

70. Odin site: https://www.the-odin.com/diy-crispr-kit/

71. Sneed, A. (2017). Mail-Order CRISPR Kits Allow Absolutely Anyone to Hack DNA. Scientific American. Available: https://www.scientificamerican.com/article/mail-order-crispr-kits-allow-absolutely-anyone-to-hack-dna/

72. Willingham, E. (2021). Why Scientists Tweak Lab Viruses to Make Them More Contagious. Scientific American. Available: https://www.scientificamerican.com/article/why-scientists-tweak-lab-viruses-to-make-them-more-contagious1/

73. Service, R. F. (2023). Benchtop DNA printers are coming soon—and biosecurity experts are worried. Science, Available: https://www.science.org/content/article/benchtop-dna-printers-are-coming-soon-and-biosecurity-experts-are-worried

74. NTI (2023). Benchtop DNA Synthesis Devices: Capabilities, Biosecurity Implications, and Governance. Available: https://www.nti.org/analysis/articles/benchtop-dna-synthesis-devices-capabilities-biosecurity-implications-and-governance/

3.4. BioEthics: Privacy

The issue of privacy and the IP of an individual's DNA is a contested issue. It is now common to do a non-invasive prenatal test. Currently, the largest operator of these tests is BGI Genomics, a Chinese company operating from Shenzhen. In essence, each sample sent for profiling contains genomic material not only of a child but also of a mother. While most people would be reluctant to undergo genomic testing with a company not located in their own country or not under strict local jurisdiction, most patients do not realise that their material is actually processed, sequenced, and analysed abroad.

One could argue that the process of genetics is unique, with many years of transfer of unique characteristics and the body's response to specific conditions that make up an individual. Hence, there should be an IP value attached, especially if the information is used for monetisation. However, in this case, the issue of privacy rights is ambiguous (see Box 6).

Box 6: Privacy

Gene codes may lie in proprietary DNA banks (e.g. crop seed banks) or in open-source databases. A study in the United States found significant gaps in consent forms for DNA banks.[75] There are several population genome databases launched by governments or consortiums in countries that include Iceland, Sweden, Finland, Denmark, Norway, Estonia, Latvia, Lithuania, Spain, France, the Netherlands, the United Kingdom, China, Saudi Arabia, Qatar, Egypt, the UAE, Bahrain, and Iran.[76]

The largest human DNA database is Ancestry followed by 23andMe, and they typically commercialise anonymised genetic data.[77] Commercial DNA testing companies fall outside the United States' privacy rules – such as the Health Insurance Portability and Accountability Act of 1996 (HIPAA) – which focus on the more regulated category of health providers or insurers.[78] The largest gene bank in the world is the China National GeneBank, with 27 million human genetic samples among other plant, animal, and disease material.[79]

75. Huang S.J., Amendola, L.M., & Sternen, D.L. (2022). Variation Among DNA Banking Consent Forms: Points for Clinicians to Bank on. J Community Genet. 13(4):389-397. doi: 10.1007/s12687-022-00601-3. Epub 2022 Jul 14. PMID: 35834113; PMCID: PMC9314484.

76. Ateia, H., Ogrodzki, P., Wilson, H. V., Ganesan, S., Halwani, R., Koshy, A., & Zaher, W. A. (2023). Population Genome Programs across the Middle East and North Africa: Successes, Challenges, and Future Directions. Biomedicine Hub, 8(1), 60; Smetana, J., & Brož, P. (2022). National Genome Initiatives in Europe and the United Kingdom in the Era of Whole-Genome Sequencing: A Comprehensive Review. Genes, 13(3), 556.

77. Hart, K. (2019). Genetic Testing Firms Share your DNA Data More than You Think. Available: https://www.axios.com/2019/02/25/dna-test-results-privacy-genetic-data-sharing

78. Ibid.

79. China National GeneBank Database (CNGdb). Available: https://db.cngb.org

Open-source databases may also come with challenges in terms of privacy and security. Patenting DNA molecules based on research (often from open-source databanks) may mean that the cures are too expensive for many.

Then there is the problem of data privacy and what can happen when you have no control over your DNA (as it can be used for identification, but it is also possible to recreate an indivdual's DNA). DNA data have been incredibly useful in crime solving. It is estimated that because of the extensiveness of the records, 60% of white Americans can be identified using these datasets, even if they have never contributed their DNA.[80]

Recently, one of the genetic testing companies, 23andMe, had a huge data breach in which 4 million profiles from the United States and the United Kingdom were leaked. The hacker was able to breach the system using 'recycled' login details exposed from other hacks.[81]

3.5. Bioethics: Cultural and Socio-Economic Impact

Indigenous Peoples have been impacted disproportionately by the developments in this field. Impacts include a loss of biodiversity, through the introduction of GM seeds, and exploitation of the benefits of the land, which can be synthesised in a laboratory, with no benefit to the people who live off the land.[82] Further, economic benefits may not be inclusive, concentrating economic power in the hands of a few players and countries. These concerns are addressed in the CBD but the ability to implement policies for redressal and for Indigenous Peoples to flourish has not had much impact. Traditional knowledge is a public good and the exploitation of it, with the capture of genetic biodiversity (e.g. the Amazon Bank of Codes), which is more ambitious than the human genome code, may result in unfairness, particularly for Indigenous Peoples, who form 5% of the world's population but are primarily responsible for the care of 80% of the earth's biodiversity.[83]

80. Egbunike, C. C. (2021). The Human Patent: What Intellectual Property Rights Does an Individual Have in Their Own Genetic Material, and What Are the Global Biosecurity Implications? Journal of Biosecurity, Biosafety, and Biodefense Law, 12 (1): 25-48.

81. Roth, E. (2023). 23andMe Says it's Looking into Another Possible Data Leak. The Verge. Available: https://www.theverge.com/2023/10/19/23923861/23andme-possible-data-leak-hack

82. OHCHR (2003). Dangers of Genetically Modified Seeds, Impact of Climate Change Among Issues Raised in Indigenous Forum Debate on Environment. Available: https://www.ohchr.org/en/press-releases/2009/10/dangers-genetically-modified-seeds-impact-climate-change-among-issues-raised

83. WEF (2020). Recognizing Indigenous Peoples' Land Interests Is Critical For People and Nature. Available: https://www.worldwildlife.org/stories/recognizing-indigenous-peoples-land-interests-is-critical-for-people-and-nature#:~:text=Although%20they%20comprise%20less%20than,they%20have%20lived%20for%20centuries

SynBio, a multidisciplinary field that aims to design and engineer biological systems, has attracted considerable interest in recent years because of its potential to transform various industries, including agriculture, medicine, and environmental management. As this groundbreaking field progresses, it is essential to address the bioethical implications that emerge, particularly concerning cultural and socio-economic impact. A comprehensive understanding of these implications is vital for directing responsible research and development (R&D) and promoting equitable access to the benefits of SynBio.

The cultural impact of SynBio is complex, as it involves diverse viewpoints on the ethical limits of manipulating natural systems, the potential changes to our perception of life, and the consequences for human identity.[84] These concerns necessitate a thorough exploration of societal values and beliefs, as well as continuous dialogue among various stakeholders, including scientists, ethicists, policymakers, and the public.

Regarding socio-economic impact, the fair distribution of benefits, risks, and costs associated with SynBio R&D is of the utmost importance. This includes addressing potential disparities in access to the technology and its applications, especially for economically disadvantaged nations, and the need for regulatory frameworks that ensure equitable participation in the field.

The newly approved sickle cell anaemia treatment Casgevy from CRISPR Therapeutics marks a seminal moment for gene therapy, but there are various issues, including the price at $2.2 million per patient, the ex vivo treatment of bone marrow cells, that it requires chemotherapy to rid the body of remaining bone marrow, and the unknown long-term 'off-target' event ratio.[85] Policies on pricing and 'once in a lifetime treatments' need to be established.

In conclusion, the cultural and socio-economic implications of SynBio R&D warrant careful consideration within the broader context of bioethics. By engaging in a comprehensive analysis of these issues, researchers, policymakers, and society as a whole can collaborate to ensure that advancements in SynBio are guided by ethical principles, ultimately leading to a more just and sustainable future.

84. Smith, K. (2020). The Ethics of Synthetic Biology Research and Development: A Principlist Approach. In: Singh, V. (eds) Advances in Synthetic Biology. Singapore: Springer. https://doi.org/10.1007/978-981-15-0081-7_20

85. More information available here: https://www.biopharmadive.com/news/crispr-sickle-cell-price-millions-gene-therapy-vertex-bluebird/702066/

4.0 Regulatory Challenges

"The door is open for all of us. Whether we like it or not, we are all marching towards it. Our future awaits."

Jamie Metzl – Hacking Darwin[86]

The regulatory landscape is fragmentary when it comes to SynBio. Regulations fall between the cracks of old laws, regulations that are constrained by definitions, the lack of foresight on generational impact, and transparency regarding what has worked and what has not. For example, only a few countries have central registers of products, like Australia.[87] Often oversight is divided between food, health, environment, and defence ministries. Business and research have vested interests and it is perhaps necessary that those creating new products should not be managing oversight. Since products may have spillovers across sectors, this also poses a problem with accountability. The confluence of engineering and AI with SynBio also compounds the accelerated development in this space.

There is a lack of clear ethics guidelines for R&D, open-source platforms, knowledge of IP (see Box 7), data privacy, and implications for trade and safety. Much current regulation is concerned with the output of R&D. Take, for example, the United States, where controls are largely focused on limiting the release and exposure of modified organisms into the environment. There is arguably now a greater risk associated with the process of research and the very real risks that arrive, for example the accidental (or intentional) release of highly virulent strains of a virus developed during research into disease, unethical conduct during human embryo research, or development of bioweapons. It is not sufficient to control only what intentionally comes out of a laboratory. We must ensure that policies and procedures are in place that regulate the conduct of research institutions.

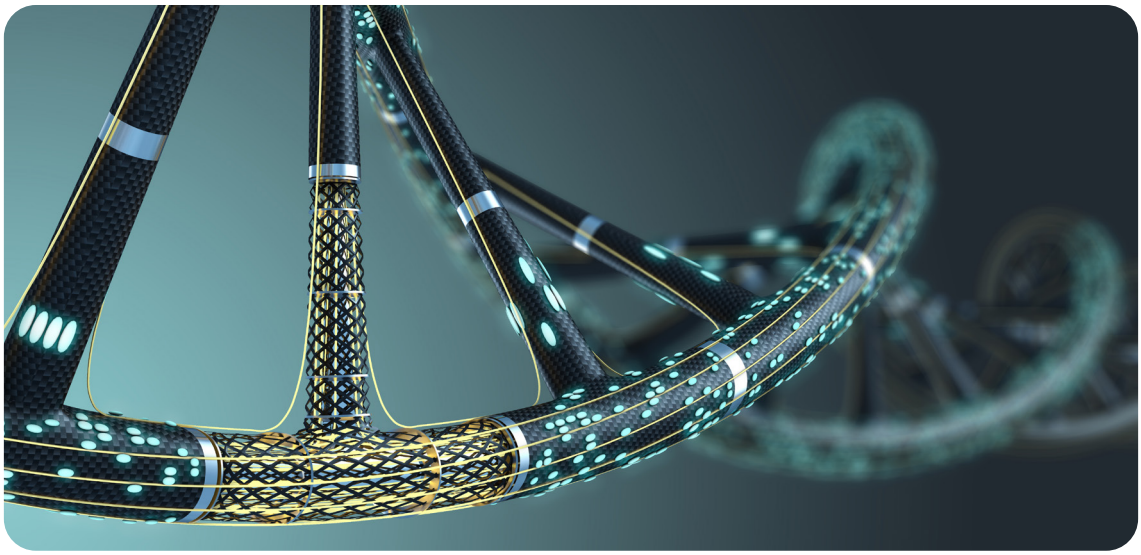
86. Metzl, J. (2020). Op. Cit

87. For example, Australia has the GMO register. More information: https://www.ogtr.gov.au/what-weve-approved/gmo-register#:~:text=The%20GMO%20Register%20lists%20activities,they%20have%20been%20licensed

Box 7: Intellectual Property and Human DNA

So far, human DNA has not been copyrighted. Take, for example, the case of *Molecular Pathology v. Myriad Genetics, Inc.*, in which the Supreme Court ruled that human genes cannot be patented in the United States because DNA is a product of nature.[88] Prior to the ruling in 2013, it was estimated that approximately 4,300 human genes were patented. The court ruled that DNA known as complementary DNA, which is artificially produced from mRNA, the molecule that serves as the instructions for making proteins, can be patented.

There are subtle differences in patent interpretation and DNA IP across the world.[89] There are 30,000 human genes patented in the United States under three gene patent invention categories:[90] (1) diagnostics (testing of genetic differences, examples including cancer genes and cystic fibrosis genes, methods including DNA chips, polymerase chain reaction tests, etc.), (2) compositions of matter (i.e. chemicals and genetic materials, including drugs, viral vectors, and gene transfer 'therapies', etc., where the patented gene has been inserted or knocked out; new variety of plant patents), and (3) functional uses (where the compositions of matter or the method is claimed by identifying the role of chemicals in genes in disease or other bodily and cellular functions or pathways). In compositions of matter, there are over 200+ drugs and vaccines approved by the U.S. Food and Drug Administration, such as human insulin and biologics, with another 370 in clinical trials.[91]



88. MedlinePlus (2021). Can Genes Be Patented? Available: https://medlineplus.gov/genetics/understanding/testing/genepatents/#:~:text=Myriad%20Genetics%2C%20Inc.%2C%20the,so%20patents%20cannot%20be%20granted [Accessed 8 August 2023].

89. For more information read https://www.taylorwessing.com/synapse/ti-patenting-gene-sequences.html or https://www.ipaustralia.gov.au/patents/what-are-patents/what-biological-inventions-can-be-patented

90. Merz, J. F., & Cho, M. K. (2005). What are Gene Patents and Why Are People Worried About Them? Community Genet., 8(4):203-8. /

91. Ibid.

The fuzziness of ethics can be demonstrated with HeLa cells. Henrietta Lacks was a cancer patient. Her doctor from The Johns Hopkins Hospital, United States, discovered that the prolific nature of her cells (they doubled every 20–24 hours) was perfect for research. Her cells have been used in outer space, in the development of vaccines, including vaccines to protect against polio and COVID-19, and in testing the effects of radiation, poisoning, and cancer. This was done without her consent (it was the 1950s). While Johns Hopkins offered the cells for free, the issue of consent[92] and the fact that the family neither knew nor profited until 50 years later[93] are issues that SynBio will increasingly face.

Another example is the case of John Moore, whose spleen following removal was – unknown to him – used for research and a cell line derived from it because of its particular lymphokine activity. In *Greenberg v. Miami Children's Hospital Research Institute, Inc. (2003)*, a physician who received donor samples identified and isolated the gene causing Canavan disease and patented it. It subsequently proved commercially successful. In this case, since it was willingly given for research, the parents lost.[94] Unfortunately, HIPAA was not comprehensive enough, and the United States subsequently introduced the Genetic Information Nondiscrimination Act on 21 May 2008.

Companies like 23andMe and Ancestry offer DNA analysis or help trace lineage but store and analyse collected DNA samples, raising questions about privacy and IP of DNA.[95] We are now able to identify individuals / match their DNA to a sample without actually having their genetic material. We now only need material from related family members to identify markers/traits leading to the identification of the person. There are a number of criminal cases in the United States now that rely on a suspect's family members' DNA rather than their own.[96] This raises questions about privacy at another level – because genomic testing is going to be more widespread, soon an individual's genome can be analysed by proxy from the material collected from a large group of even very distantly related individuals.[97] AI will make these predictions much easier than we can imagine today.

92. Beskow L.M. (2016). Lessons from HeLa Cells: The Ethics and Policy of Biospecimens. Annu Rev Genomics Hum Genet., 31(17): 395-417.

93. For example, Thermo Fisher Scientific, a biotechnology firm, profits from the cells. See: https://www.courtlistener.com/docket/60620589/parties/lacks-v-thermo-fisher-scientific-inc/

94. United States District Court, S.D. Florida, Miami Division. Greenberg v. Miami Children›s Hospital Research Institute. Wests Fed Suppl. 2003;264:1064-78. PMID: 15776537.

95. Egbunike, C. (2021). The Human Patent: What Intellectual Property Rights Does an Individual Have in Their Own Genetic Material, and What Are the Global Biosecurity Implications?. Journal of Biosecurity, Biosafety, and Biodefense Law, 12(1), 25-48

96. Tuazon OM, Wickenheiser RA, Ansell R, Guerrini CJ, Zwenne GJ, Custers B. Law enforcement use of genetic genealogy databases in criminal investigations: Nomenclature, definition and scope. Forensic Sci Int Synerg. 2024 Feb 8;8:100460. doi: 10.1016/j.fsisyn.2024.100460. PMID: 38380276; PMCID: PMC10876674.

97. Clayton EW, Evans BJ, Hazel JW, Rothstein MA. The law of genetic privacy: applications, implications, and limitations. J Law Biosci. 2019 May 14;6(1):1-36. doi: 10.1093/jlb/lsz007. PMID: 31666963; PMCID: PMC6813935.

The 2018, $300 million stake deal between GSK (United Kingdom) and 23andMe, and the acquisition of Ancestry first by Permira (Europe) in 2012 and then by Blackstone (United States) in 2020, highlight the commercial potential of the data. Based on these acquisitions, the average price per unit of DNA can be valued at $75–3,300 in the international market.[98] Awareness of the monetary potential that lies untapped in each person's genetic codes raises interesting questions.

The regulatory environment at a global level remains fragmented (Figure 2). While some regulations may exist for research and ethics, R&D, data privacy and consent (with respect to genetic material), genetic IP, open-source guidelines, defence and security (bioweapons or autonomous weapons), trade, and risk management, they are scattered across silos, including government entities in health, defence, agriculture, and the environment, making an overarching policy next to impossible, even though the technology can be embedded in every industry. Unlike AI there is no 'explainable technology' policy. Although some health organisations have robust policies, consent may have loopholes, especially when sourced as part of commercial activities such as genealogy mapping. The greatest challenge remains awareness of dual-use research of concern by the average citizen and policymaker.[99]

Within and across countries, SynBio has no common definition (a problem AI faces). In the United States, in the 2022 Summary of the Congressional Research Service Report on Synthetic/Engineering Biology, SynBio, 'sometimes referred to as engineering biology, is the application of engineering principles and the use of systematic design tools to enable the reprogramming of cellular systems at the genetic level for a specific functional output.'[100] In Canada, according to the Canadian Environmental Protection Act (1999), a broader definition is in place: 'the application of science and engineering to the direct or indirect use of living organisms of parts or products of living organisms, in their natural or modified forms.'[101] The EU, according to the Scientific Committee on Health and Environmental Risks,[102] defines the term as 'the application of science, technology and engineering to facilitate and accelerate the design, manufacture and/or modification of genetic materials in living organisms.' The challenge is that SynBio is a system of technologies that may result in the purposeful change of genetic material that can have unintended consequences on the larger human and environmental ecosystem, affecting health and the flourishing of our species and others. Using a definition that is too narrow may lead to regulatory gaps with major consequences.

98. Genomes,io (2019). How Much Is My DNA Really Worth? Medium, dated 7 October. Available: https://medium.com/@Genomesio/how-much-is-my-dna-really-worth-46787ccf585f [Accessed 8 August 2023].

99. Zeng, X., Jiang, H., Yang, G., Ou, Y., Lu, S., Jiang, J., ... & Su, L. (2022). Regulation and Management of the Biosecurity for Synthetic Biology. Synthetic and Systems Biotechnology, 7(2), 784-790.

100. 2022 Summary of the Congressional Research Service Report on Synthetic/Engineering Biology. Available: https://sgp.fas.org/crs/misc/R47265.pdf

101. Canadian Environmental Protection Act (1999). Available: https://inspection.canada.ca/plant-varieties/plants-with-novel-traits/general-public/overview/eng/1337827503752/1337827590597#:~:text=%22Biotechnology%22%20means%20the%20application%20of,their%20natural%20or%20modified%20forms.

102. Scientific Committee on Health and Environmental Risks. (2014). Opinion on Synthetic Biology I Definition. Available: https://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_044.pdf

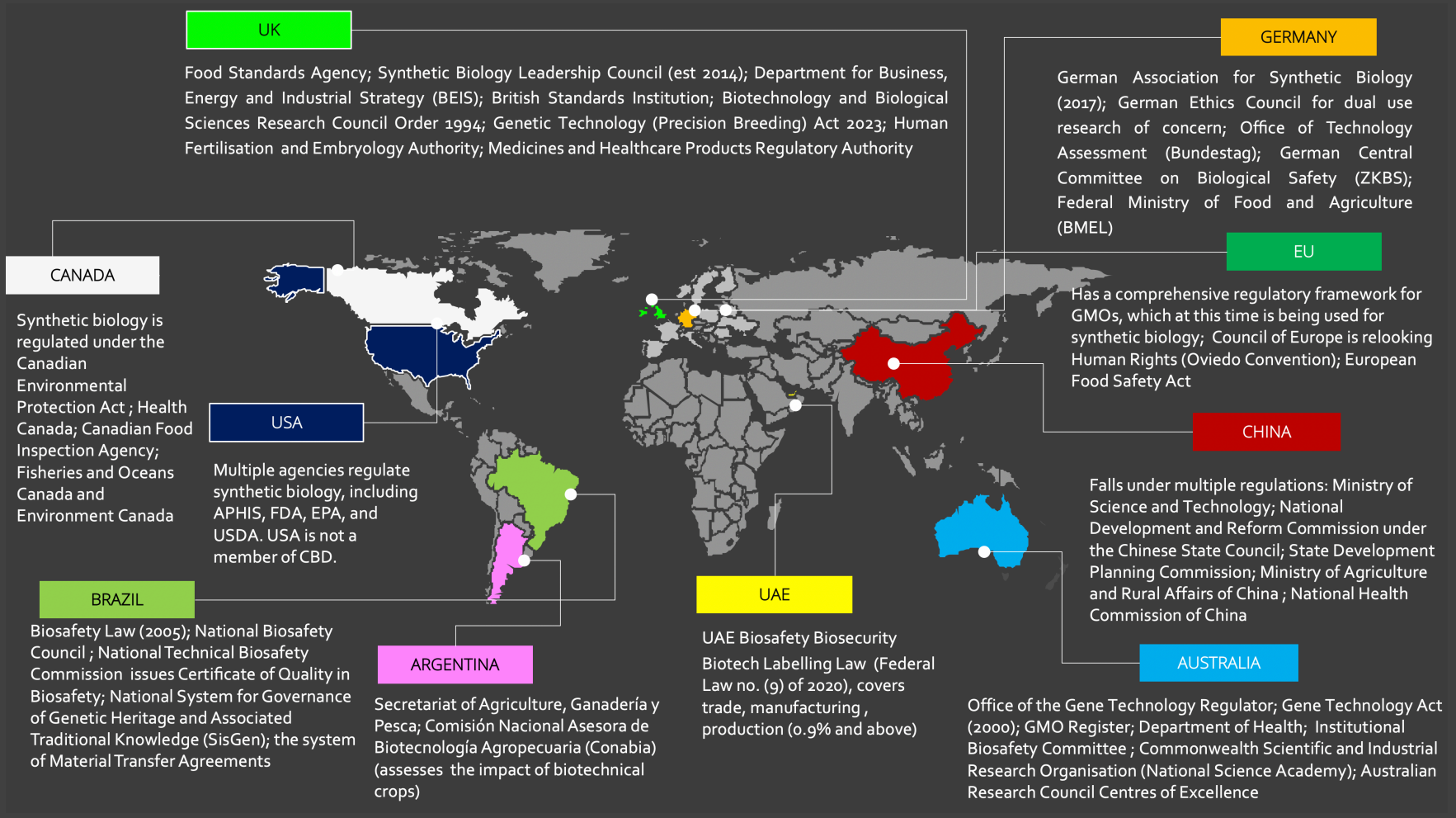


Figure 2. Fragmentary policy landscape

While much of the attention of policymakers was initially focused on GMOs and the boom in their development and use in the 1990s, the growth in SynBio technologies from 2000 onward has left regulators trying to plug regulatory gaps with GMO-specific regulations. It is arguable that more recently, certainly insofar as the public is concerned, awareness of SynBio developments and the risks that they bring have been overshadowed by higher profile topics such as the march of AI technology. Therefore, we posit that there is a lack of focus and scrutiny of the inherent risks from a management and control perspective.

5.0 Recommendations

"What does it mean to be Human?"

Reflections at the 2022 Dubai Future Forum
Synthetic Biology Design Thinking Workshop

While we focus on the need for regulation in this report, it is important to note that innovation is a fundamental pillar of SynBio and we recognise the enormous benefits that R&D in this space can bring for both humanity and the environment that supports us. There is, therefore, a delicate balance to be achieved between the need for control and the need to foster the right environment for innovation in a peaceful and sustainable manner.

As seen from our analysis and review of existing conventions, protocols, and implementation of regulations that touch on SynBio, many countries have implemented some form of regulation but these typically have their genesis in GMO risks with little true mitigation of broader SynBio risks identified in the past two decades. In many cases, experts hold the view that existing regulation is sufficient, demonstrated by the low or non-occurrence of issues arising from SynBio research. We argue that it would be unwise to continue with this approach of applying controls in a backward-looking manner, i.e. based on the assessed risks of prior research. The issue here is that as research and technical ability evolves, we expose ourselves to risks not previously contemplated and we risk having to continuously play catch up with the need for control. Further, should we face a 'black swan' event in this space and the potential catastrophic impact that may have, closing the gate after the horse has bolted may not be a feasible risk mitigation approach.

Accordingly, we propose that regulations and policies specifically for the biosafety, biosecurity, and bioethics of SynBio are urgently needed. Initially, regulation needs a top-down approach, as proposed in the next section. Once the correct structure is in place, an ongoing bottom-up assessment of the evolution of SynBio risks and therefore the continuing effectiveness of regulation must be a continuous obligation.

5.1 International Collaboration and Cooperation

While a number of countries are looking at regulatory frameworks, alignment at a high level is essential to ensure a coordinated risk management approach. Much work previously done has relied on prior regulations related to GM crops but which are not sufficient to cover the full scope of SynBio.

5.1.1: Establishment of a multilateral, multisectoral and multidisciplinary think tank/ international working group will be key

The issues of governance extend beyond government capabilities and must include all relevant actors. This necessarily must include scientists, researchers, and practitioners in the SynBio space, together with government representatives and industry/commercialisation partners and investors. The focus should be:

1. A global definition of SynBio systems and a high-level approach to SynBio regulation, perhaps in the form of an international treaty akin to the CBD or introduction of international standards and treaties (like nuclear and space technology) since it is a technology that, unlike any prior, can be easily relocated and deployed.

2. Creating transparent regulations and tracking. Currently, most regulations are so muddy that one can navigate around them quite easily.

3. Categorising SynBio innovations to ensure that the full basket of risks is identified and classified looking at genetic material, chemicals, hardware, software, and data. For example, see Table 2.

Table 2. Risk categorisation of SynBio innovations (examples for illustrative purposes only)

RISK LEVEL	DESCRIPTION
01: Unacceptable Risk (prohibited)	These will be defined as harmful uses that contravene human rights (create modifications in humans against their will; test without subject awareness or without their freely given and knowledgeable consent), create unfairness (by creating superior humans through purposeful design), and can cause intergenerational harm (for humans and any other living creature).
02: High Risk (conformity assessment)	These systems (direct intervention on genes and indirect interventions, such as using AI for sequencing missing genetic parts) need approval and generational studies. The interventions need to be studied in the context of the ecosystem (not just as an individual unit). Results need to be transparently published for the public and assessed not just in terms of efficiency, disposal, security of process, ease of access to knowledge, and lives positively affected but also in terms of costs, impact on society, employability, balance of power, etc. (Examples: personalised medicine; predicting future diseases (genomics); 3D printing of organs; 3D-printed meat, GM mosquitoes; DNA libraries of populations; chimeras (interspecies))
03: Limited Risk	These systems augment the SynBio process and may belong to possible adjacent industries – chemicals, hardware, data-collecting systems (genetic crop or human genome libraries). They may push an innovation into the high-risk or unacceptable-risk category. (Examples: CRISPR-Cas9 equipment; AI algorithm for protein testing; genetic DNA kits for science; robotics)
04: Minimal Risk	These are innovations that fall under existing regulations but need to be flagged if one of the possible adjacent industries is SynBio. (Examples: tools used to understand human biology; mobile telephones used for genetic assessment via saliva; 3D printers; syringes)

5.2 National Implementation of Regulations

This step would be a detailed application of the principles established at a global level. These policies include: (1) research and ethics guidelines for SynBio systems, (2) access to material that may be deemed sensitive and oversight of such material (including the material for the process and open-source banks of genetic material), (3) R&D guidelines (basic, frontier, and commercial research), (4) IP of genetic material and privacy, (5) need for explainable technology, (6) open-source and responsible use guidelines, (7) classification of technology based on high risk (e.g. that can be used as autonomous weapons and for biowars), (8) trade guidelines, and (9) national risk management and assessment guidelines.

5.2.1 Mandated Policy and Codes of Conduct at Laboratory/Institutions Level are Required to Address Process Risk

This means setting up regulatory bodies at the national level, equipped with resources and the authority to oversee players in the space. Currently, the majority of countries have multiple regulatory entities dealing separately with issues such as health, food security, education, research, environment, defence, equipment, and economy, for example. SynBio regulation will often straddle a number of these bodies. A bespoke entity should be tasked with impactful oversight; it should not be managed on an unsystematic, piecemeal basis.

SynBio governance in the United Kingdom encompasses various elements, including the formation of research alliances and consortiums, the development of standardisation protocols, and the creation of regulatory frameworks.[103] Furthermore, SynBio governance in the United Kingdom also addresses the challenges associated with the commercial translation of SynBio research. This encompasses the cultivation of a skilled workforce and the effective mitigation of risks to support potential industrial partners and investors for responsible innovation.[104]

5.3 SynBio Education

There is a need to develop an education framework that promotes awareness and underpins self-regulation. Bioethics must be at the core of the education journey in much the same way that ethics is a fundamental issue in law degrees or the Hippocratic oath was the foundation of Greek medicine. Education must happen at the grassroots level across subject disciplines – engineering, chemistry, AI, environmental biology, etc. – and not just for policymakers. Users or consumers of SynBio need to be aware of their choices and the implications of innovations that have been introduced to them without their knowledge.

103. Clarke, L. & Kitney, R. (2020). Developing Synthetic Biology for Industrial Biotechnology Applications. *Biochem Soc Trans.*, 48 (1): 113–122.
104. Ibid.

5.4 Agile Governance

There will be unintended spillovers of this new technology as we are still learning about the building blocks of life even when, currently, mass-scale experimentation is taking place. Technologies like AI are bringing forward the inflection point. Some recommendations for appropriate controls that mitigate the most severe risks but which do not stifle innovation follow.

5.4.1: Creation of a Clearing House of Best Practices & Regulations

Set up a repository of best practices that can be shared across countries, sectors, and institutions for opportunities, good governance, and speed of action in risk mitigation.

5.4.2: Establish a Risk Register (with details of innovations and consequences)

We need to begin thinking in binary not just one-sided. This means recommending scientists and startups working in this space think both what are positives and negatives, to ensure we have a balanced approach to this life-changing technology. We must think in trade-offs, not risks alone.

5.4.3: Setting up Guidelines for Regulatory Labs or Sandboxes

Regulation for new technologies is lagging, especially for SynBio. Some work is taking place in this area but it is fragmentary:

- The UAE has created a regulatory laboratory (RegLab) that includes health data and AI.[105]
- Singapore has a health sandbox focusing on telemedicine.[106]
- The state of Massachusetts in the United States has 12 digital health sandboxes.[107]
- Denmark has created a National Health Data Science Sandbox for training and research.[108]
- Sweden has started a biotechnology sandbox with GE.[109]

105. UAE (2023). Regulatory Sandboxes in the UAE. Available: https://u.ae/en/about-the-uae/digital-uae/regulatory-framework/regulatory-sandboxes-in-the-uae

106. Ministry of Health, Singapore (2023). Licensing Experimentation and Adaptation Programme (LEAP) - A MOH Regulatory Sandbox. Available: https://www.moh.gov.sg/home/our-healthcare-system/licensing-experimentation-and-adaptation-programme-(leap)---a-moh-regulatory-sandbox

107. MassDigitalHealth (2023). Digital Health Sandbox Network. Available: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjb5I3SkfOBAxVbgP0HHdQKB-gQFnoECBQQAQ&url=https%3A%2F%2Fmassdigitalhealth.org%2Fsandbox-network&usg=AOvVaw1N6_qFrgzzZEuOa4kbJVCL&opi=89978449

108. Novo Nordisk Fonden (2020). National Health Data Science Sandbox for Training and Research. Available: https://datascience.novonordiskfonden.dk/projects/national-health-data-science-sandbox-for-training-and-research/

109. Kellner, T. (2018). Biotech Sandbox: New Swedish Center Helps Startups Develop The Treatments Of Tomorrow. GE.com. Available: https://www.ge.com/news/reports/biotech-sandbox-new-swedish-center-helps-startups-develop-treatments-tomorrow

The focus for the sandboxes or RegLabs still seems largely focused on data (bio, health, and synthetic data, molecules, proteins, etc.). This is a challenge for policymakers and regulators as they will always not have enough foresight on new market introductions.

SynBio RegLabs would need guidelines on mandate and scope as well as governance and operations (see Table 3). Further there is a need to treat different categories of SynBio product systems differently based on risk - highest risk could be for those products directly used on humans, as an example (see Table 4). However, as we see with SynBio, equipment and processes could also be risky, hence these risk buckets could be for each category.

While this report is just a starting point for discussion, it is based on diverse viewpoints. People from different backgrounds, industries, countries, policy experience, and scientific backgrounds contributed to the thinking behind the report. This is needed because SynBio is interdisciplinary and regulations need to be overarching. We hope that this report sparks dialogue to create a world with guard-rails so that a safer, flourishing, and inclusive future is shaped for the future of humanity and the world we call home.

The management and oversight of SynBio, particularly in its role as a catalyst for bioeconomic expansion, necessitate meticulous attention. While SynBio and industrial biotechnology are distinct entities, they are mutually reinforcing technologies that can significantly propel a bioeconomy driven by technology. Given SynBio's comparatively recent inception, it is imperative to establish suitable governance mechanisms to foster its continuous evolution and to ensure that the strategic advantages of this technology are harnessed.

Table 3. Sandbox framework[110]

Mandate and Objectives (Scope)	Governance	Operations
✓ What is the moral mandate of the regulator? ✓ What is the legal mandate of the regulator? ✓ What are the regulatory and policy objectives? ✓ Whare are the boundary conditions? ✓ What are the national objectives? ✓ What are the market objectives? ✓ What are the public value objectives? ✓ What are the global citizenship objectives? ✓ What are the cross-border objectives (internationally)?	✓ Who operates the sandbox? ✓ Do they have the qualifications for making informed decisions? ✓ What information is needed for an informed decision and how is it collected? ✓ How is the information shared both internally and externally? ✓ How is the learning communicated for future learnings? ✓ How transparent is the process of experimentation? ✓ How are risks minimised? ✓ How do you ensure fairness of the process for choosing participants of the sandbox? ✓ Is the cost of participation communicated clearly (fees, any other binding requirements)?	✓ Who can participate in the sandbox (eligibility and evaluation criteria)? ✓ What can happen in the sandbox (boundary conditions)? ✓ What is the process (onboarding)? ✓ What is the reporting mechanism for collecting data needed for evaluation (reports and reporting)? ✓ What happens when the sandbox concludes (exit procedures)? ✓ How is the feedback loop for policy interventions captured? ✓ How do you measure that human subjects of the experiment are adequately compensated for the discontinuation or from adverse risks? ✓ How do you ensure the liability of the participants admitted to the sandbox is restricted post-experiment, if they stayed withing the boundary conditions outlined by the sandbox regulators?

Table 4. Categories and regulatory concerns for sandboxing[111]

	Category 1	Category 2	Category 3
Categories	Health related (based on equipment)	Health related process (apps, management processes)	Health related (based on people)
Predictive analytics (examples)	Hospital equipment tracking breakdowns are usage; CRISPR supply requirement	Manpower management (use of chatbots for depression counselling at peak hours); blockchain payments (insurance liability)	Predicting future diseases (genomics), precision medicine, telemedicine capacity requirements
Invasive technologies (examples)	Robotics for surgery; DNA mail order kits, 3D printers body replication (forensics)	Using wearables, mobiles or social media to gather health information. Crowdsourcing images for health symptoms (plants, animals and humans)	Brain-computer implants
New frontiers (examples)	Tissue growth equipment	AI to decode and snip genes	3D printed organ transfer, cloning, stem harvesting, vector management
Applicable Regulations	Equipment standardisation; Industry regulations; Biomedical ethics; Data privacy; Data sharing; Data storage, etc		

110. Al Hajaj, K., & Stephens, M. (2020, 17-18 February). Regulatory Sandbox: Health RegLab Design Elements. UAE Public Policy Forum: Agile Government - Being Future Proof. Dubai, UAE.

111. Ibid.

6.0 Way Forward

The way forward will be messy and difficult. Navigating change due to technology upheavals always is. However, where there is a collective will to do greater good for the whole of humankind, surely, we can. We sit at the edge of a future that can unleash a wave of tremendous good that can take humanity to our next higher evolution if we establish the correct guard-rails.

We need to move swiftly together and put aside political differences, the lure of economic profits, and the blindness of science without foresight. At this point, with the resources available at our fingertips we do not have that luxury anymore.

Hopefully this report will start a dialogue and we hope that the recommendations outlined here help in the establishment of the necessary safety nets and guard-rails.

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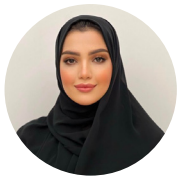

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Disclaimer: This is an exploratory report. The views are our own observations borrowing heavily from research across disciplines, and sectors.

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