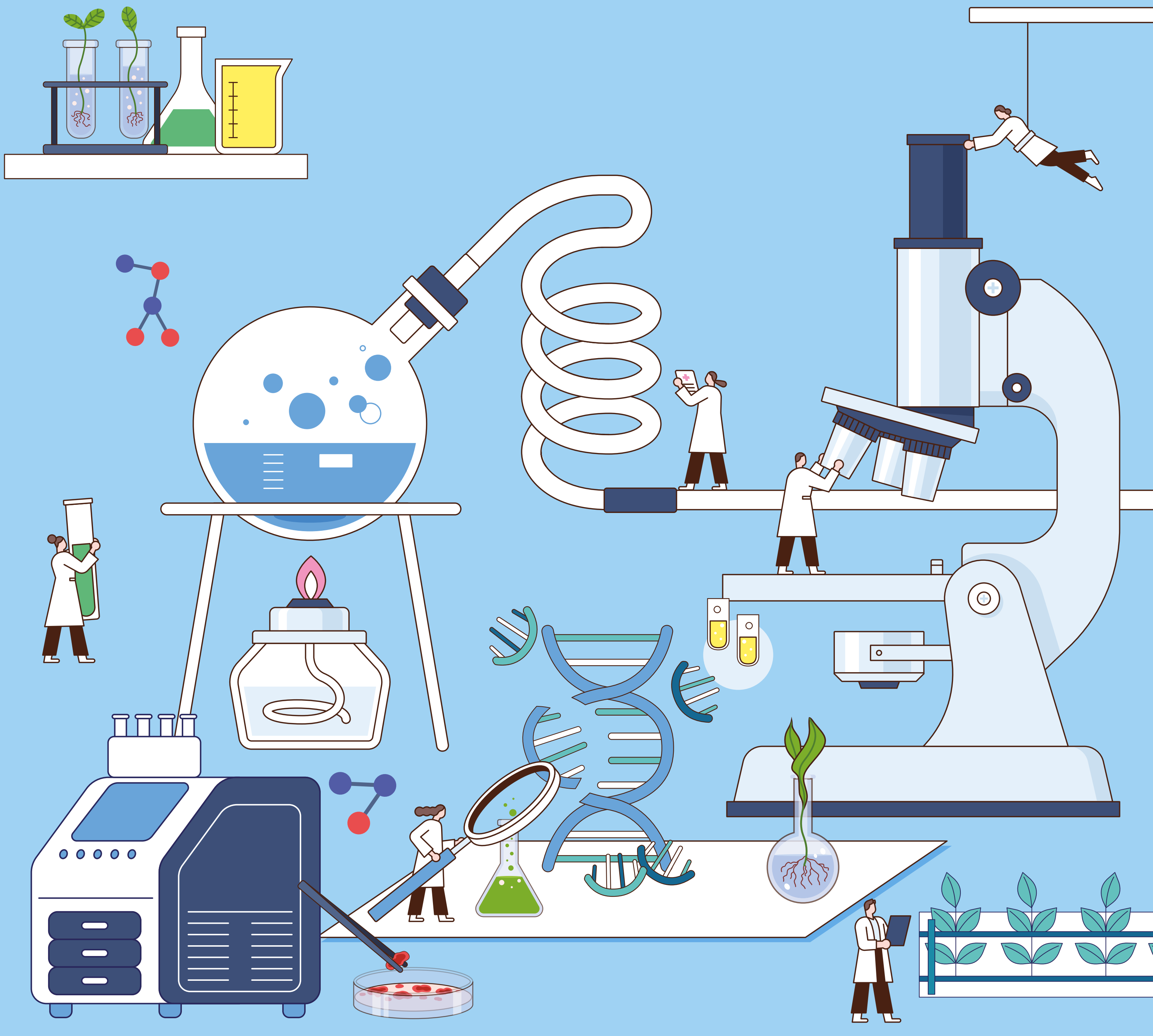
ENGINEERING BIOLOGY

International guidelines for constructing higher education curricula



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SHORT SUMMARY

Engineering Biology Curriculum Framework equips learners with interdisciplinary skills

Engineering Biology—an emerging field at the nexus of biological sciences and engineering principles—stands at the forefront of the Fourth Industrial Revolution alongside Artificial Intelligence (AI) technologies. Job creation remains a strong policy driver. In the EU, for example, bio-based industries account for over €2.7 trillion in value in 2023 and 17.1 million jobs (roughly 8.5% of the workforce). This framework therefore responds to the global call for inclusive and responsible education in the interface of Engineering, Biology, and AI, by providing higher education institutions and their policy governance entities with a modular curriculum framework adaptable to diverse regional contexts. While many curricula emerge in the high-resource/high-income regions, the technologies themselves are often deployed in the Low- and Middle-Income Countries (LMICs), solicitating the focus of this framework.

EU bio-based industries account for **€2.7 trillion** and **8.5%** of the workforce

Designed under the visionary of UNESCO's International Basic Sciences Programme, the Engineering Biology Curriculum Framework equips learners with interdisciplinary skills in biodesign, biomanufacturing, bioinformatics, and AI-driven biological engineering while embedding ethics, biosafety, and sustainability throughout its structure. Aligned with the United Nations Sustainable Development Goals (SDGs), this curriculum framework aims to trailblaze an educational platform to foster equitable, ethical, and sustainable education ensuring that every learner, regardless of geography, can contribute to a resilient and inclusive bioeconomy.

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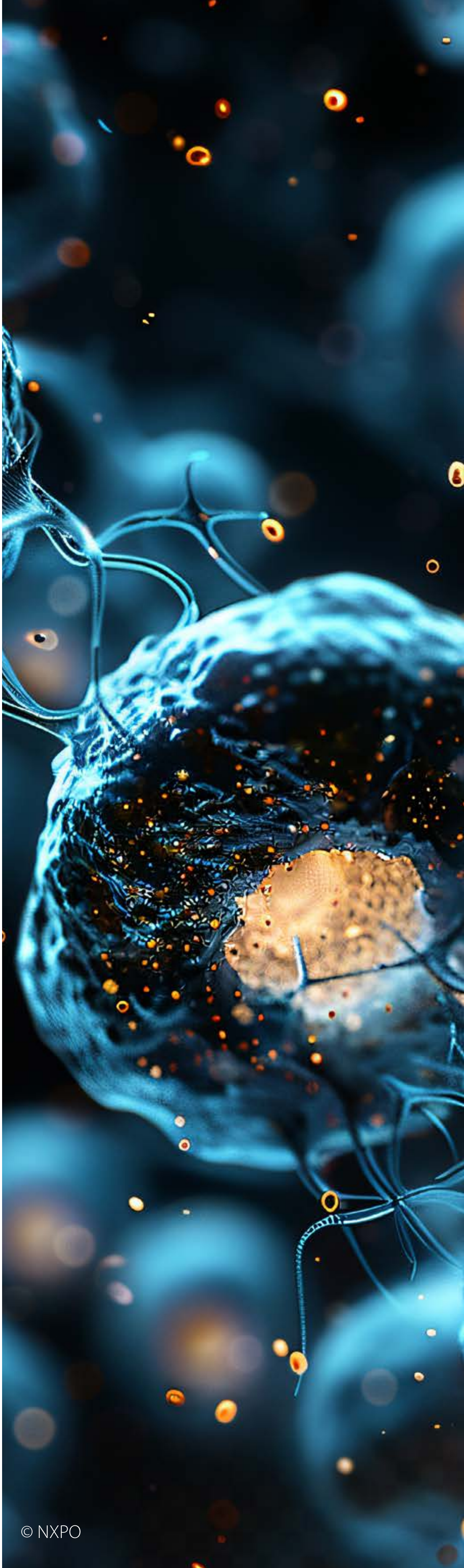
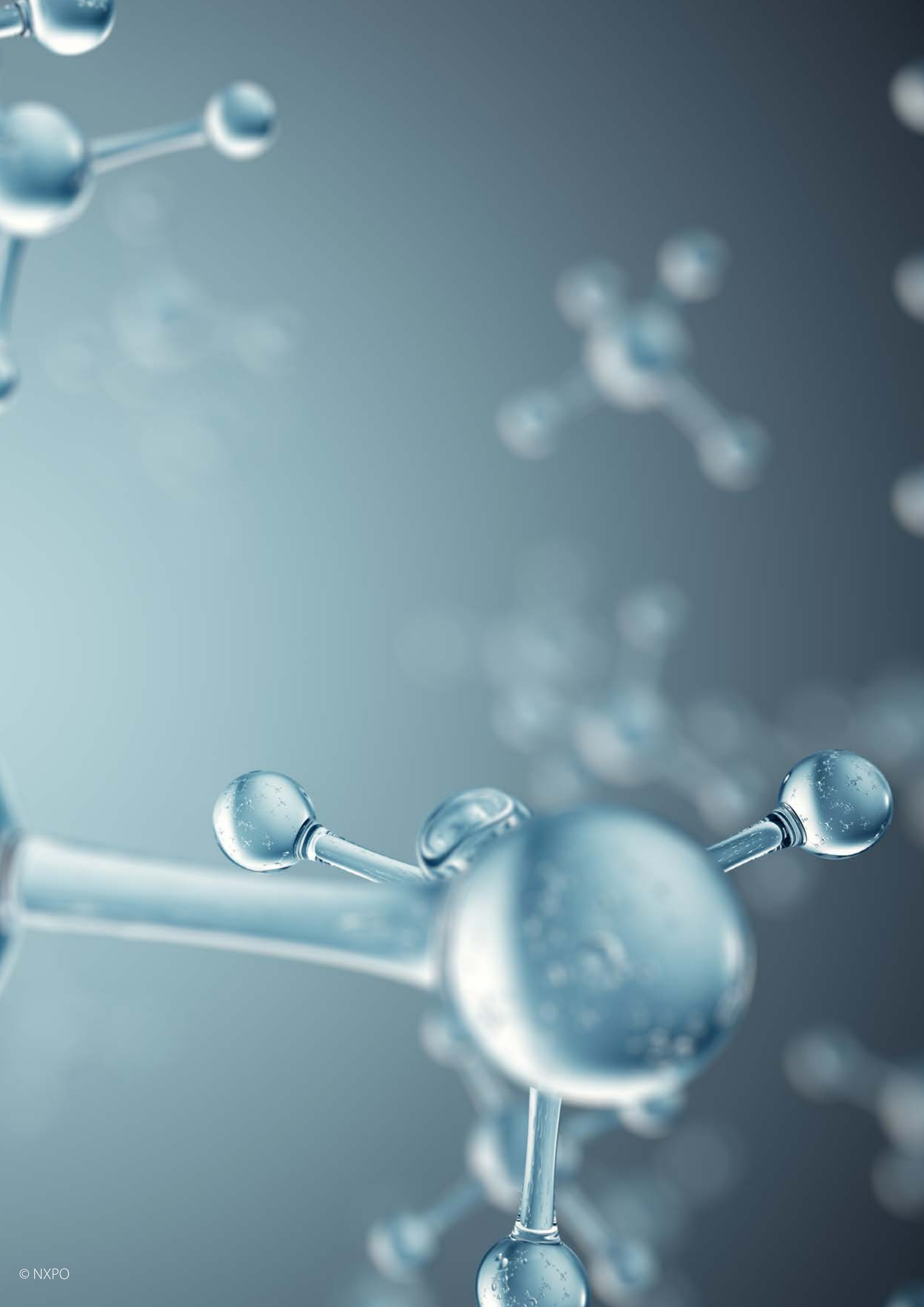
Table of Contents





Foreword

One of the main drivers of the 4th Industrial Revolution is the accelerated advances in the biological sciences, in particular the confluence between engineering, computer sciences and biology which is fuelling global economic growth in what is now established as the bioeconomy sector. Engineering biology or synthetic biology as it is often referred to has taken traditional concepts and research in biotechnology of the last three decades to another level. This was globally demonstrated during the COVID-19 pandemic when for the first time in human civilisation a silico-designed biological code was used to timely address human biological vulnerability en masse via an mRNA substrate in the vaccines that saved the lives of hundreds of millions of people around the World. It demonstrated the power of cyber-biological convergence in the age of engineering biology to address critical global societal challenges[1].

The significance of engineering biology, as an academic interdisciplinary subject as well as a multi-million research industry in both public and private sector organisations, has been highlighted on several occassions in the scientific board recommendations of UNESCO International Basic Science Programme (during its 12th and 13th sessions), and most recently in the report of the International Bioethics committee on the ethical issues related to the research, development and application of synthetic biology during the 32nd Ordinary Session of the IBC and the 14th Session of the Intergovernmental Bioethics Committee (IGBC) in September 2025, which urged UNESCO and its Member States, academic institutions, industry and civil society to, independently or collaboratively, establish, sustain, and develop comprehensive education programs in synthetic biology. Recently, the IUCN policy “Motion 087” was also accepted for utilization of synthetic biology in relation to nature conservation.

Therefore, the present international framework on engineering biology for higher education aims to establish a modular curricula programme—from foundational and interdisciplinary concepts through broad ethical frameworks, advanced AI-driven design and biosafety-by-design techniques. Ensuring continuous upskilling of university students, researchers, and practitioners at every career stage, by integrating learning science with cross-disciplinary ethics, policy and societal-impact training, will cultivate a knowledgeable global society and a competent workforce capable of responsibly navigating engineering biology’s evolving challenges and opportunities.

Engineering biology is on the brink of transformative advances that promise to revolutionise environmental applications. Recent developments have been particularly promising in biosensing, bioremediation, bio-sequestration, pollution monitoring, and waste valorisation[2]. The UNESCO framework is therefore open to be customized to different sectors; environment, agriculture health, energy, manufactring, wherein biolgical materials are being used. It is hoped that universities and higher education institutes around the world who are embarking on desgining undergraduate or postgraduatre courses in engineering biology will benefit from this framework in their endevour towards equipping future generation workforce in a bioeconomy sector that is planteary sustainable and socially ethical.

1 Nature Communication. (2022) 13:3516

2 Nature Communication. (2025) 16:3538

Acknowledgements

This Engineering Biology Curriculum Framework is the outcome of a wide collaborative effort among educators, researchers, policymakers, and experts across disciplines and regions. The framework was developed under the guidance of UNESCO, as part of UNESCO's commitment to advance responsible education and research in the life sciences for sustainable development alongside the emerging technological advances.

The overall direction for this publication was provided by Ahmed Fahmi, Chief of Science Unit at UNESCO Regional Office for Asia Pacific (Bangkok) and Cholpisit Kiattisewee, PhD from Massachusetts Institute of Technology (USA). The project was coordinated by experts from Vidyasirimedhi Institute of Technology (VISTEC) and Thailand's Office of National Higher Education Science Research and Innovation Policy Council (NXPO), with technical support from the working group on Engineering Biology Education from Thailand and Globally.

The day-to-day coordination of this work from start to end was provided by NXPO team, Tidarat Komolwanich, PhD, Teerapong Namhapis, Oraphan Wiarachai, PhD and Pattira Kuakim. UNESCO extends its gratitude to those individuals who made it all happen.

Peer review and feedback were generously provided by an international panel of experts in biosciences, ethics, and higher education curriculum development. Their critical inputs ensured the framework's scientific accuracy, ethical grounding, and pedagogical applicability across diverse education systems.

UNESCO extends its gratitude to all institutions and individuals who participated in consultations and regional workshops on Engineering Biology education held between 2023 and 2025. Special thanks to the editorial and design teams at NXPO and UNESCO Headquarters for coordinating the preparation and production of this publication.

Finally, UNESCO wishes to acknowledge the support of its partners in academia, industry, and civil society whose collaboration made this framework possible, and whose shared commitment ensures that Engineering Biology education continues to foster innovation, responsibility, and sustainability worldwide, through the guideline developed in this publication and beyond.

Acronyms and Abbreviations

AI	Artificial Intelligence
AMR	Antimicrobial Resistance
ASR	Ancestral Sequence Reconstruction
BCG	Bio-Circular-Green (Economy) Model
CAD	Computer-Aided Design
CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
DBTL	Design-Build-Test-Learn
DNA	Deoxyribonucleic Acid
ELMs	Engineered Living Materials
ELSI	Ethical, Legal, and Societal Issues
FBA	Flux Balance Analysis
iPSCs	Induced Pluripotent Stem Cells
LMICs	Low- and Middle-Income Countries
ML	Machine Learning
NGS	Next-Generation Sequencing
ODEs	Ordinary Differential Equations
PCA	Principal Component Analysis
PCR	Polymerase Chain Reaction
RNA	Ribonucleic Acid
SDGs	Sustainable Development Goals
STEM	Science, Technology, Engineering, and Mathematics

Glossary of Terms

Subjects / Disciplines

Engineering Biology: an interdisciplinary field that applies engineering principles to understand, design, modify and control biological systems. The emphasis is on applying engineering methods (optimization, modeling, standardization) and scientific principles to achieve the desired outcome.

Synthetic Biology: a precursor, narrower term of Engineering Biology which focuses on the design-build-test-learn of modified or new biological systems. The biggest point is the ability to synthesize new biological systems using accumulated knowledge from multiple disciplines, especially Electrical Engineering principles.

Biological (Biomedical) Engineering: a relatively new engineering discipline that sparks a collaborative effort in medicine and engineering conventionally started as utilization of engineering principles to solve medical problems such as tissue and biomolecular engineering and biomechanics. Later term, biological engineering encompasses broad non-medical problems such as environmental issues and climate change problems.

Biotechnology: an application focus discipline that uses biological systems or derivatives to develop new products or technologies to serve specific applications.

Other subfields

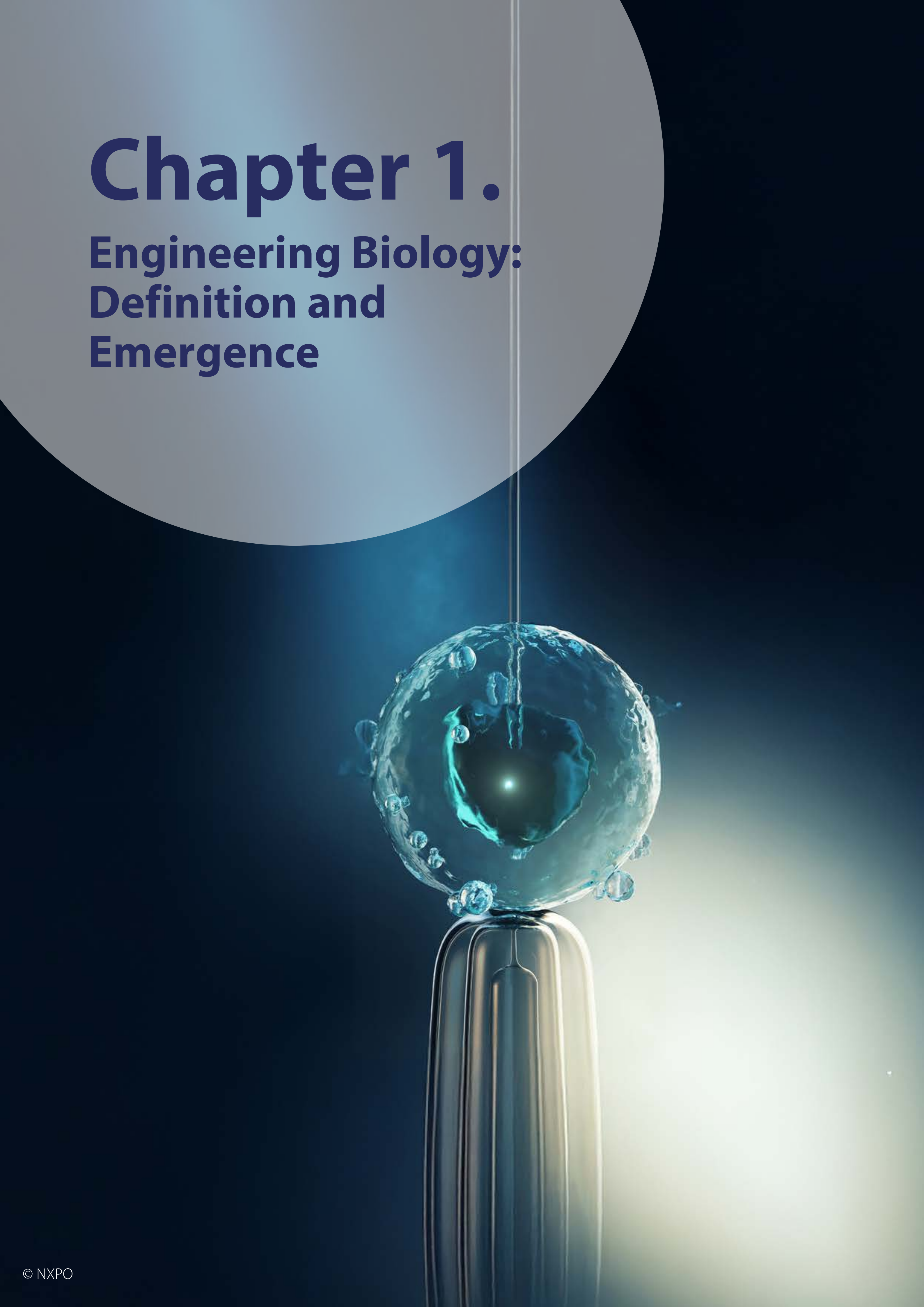
Genetic Engineering: involves modifying the genetic material of organisms to achieve desired traits.

Metabolic Engineering: terms as modification of the metabolic pathways of organisms to increase the production of specific biochemicals.

Systems Biology: the study of acquiring and analysis of multisets of biological data, and modeling of complex biological systems to understand their behaviors and predict how they will respond to changes.

Biomanufacturing/Biomaterials: the use of biological systems to produce commercial products, such as enzymes, biofuels, bioplastics, biochemicals or biomaterials.

Other highly relevant fields are **Chemical Biology, Chemical Engineering and Biocatalysis. Artificial Intelligence (or Deep Learning), Bioinformatics**.



Chapter 1.

Engineering Biology: Definition and Emergence

Background and Definitions

Engineering Biology is the multidisciplinary area of science that combines principles from biology, engineering and computer science to design, construct and commercialize new or modified biology-derived products and services in areas such as medicine, agriculture, and environmental sustainability. Although 'Engineering Biology' is a relatively new term, it is by no means a new study. We have been modifying biology for about 12,000 years with farming, which has sought to continuously improve the effectiveness of crops and domesticated animals through selective breeding and currently could redesign biological components for novel purposes in the multidisciplinary field of biotechnology and synthetic biology. The industrial application of synthetic biology, in combination with rational engineering principles, to create new products brings us to the present day and the emergence of what we know as engineering biology.

However, for the purpose of this review, it would be undermining not to mention that scientific terms often pass through series of permutations to what they denote. For example, the term 'Biological Engineering' was first mentioned in a paper in the magazine Science in 1944 by Hudson Hoagland in an article entitled Adventures in Biological Engineering which mainly focused on experimental biology. The term is currently synonymous with Synthetic Biology which in its own right has an intriguing history in the use of the term; wherein Stéphane Leduc (1853-1939), a French biochemist first used 'biologie synthétique' in 1910, in his book Théorie physico-chimique de la vie et générations spontanées and then again in 1912 in La Biologie synthétique. Leduc asked an important question regarding synthetic biology, in this case: "Why is it less acceptable to seek how to make a cell than how to make a molecule?"

Engineering Biology means designing and building a biological system, be it some sort of genetically engineered system, or cell, or biological process; testing it to see how well it works; and then feeding in the learnings from this analysis to another round of design, iteratively improving the system. The cycle incorporates many different capabilities and disciplines including gene editing, modelling and AI and machine learning – see Figure 1 for examples of key capabilities underpinning Engineering Biology. While the term sounds very close to that of Bioengineering and Biological Engineering, Engineering Biology is distinctive from the previous disciplines due to its broader scope beyond engineering specific part or machinery used in biology. Engineering biology encompasses the usage of engineering principles in any biological system, whether they are naturally occurring or engineered by humans. In fact, many examples of exciting and innovative research and development in this area contain no genetic manipulation at all[3] . Additional descriptions of each discipline were provided in the Glossary of Terms..

3 Research and analysis Report. Engineering Biology Aspirations. April 2025. UK Government Office for Science.

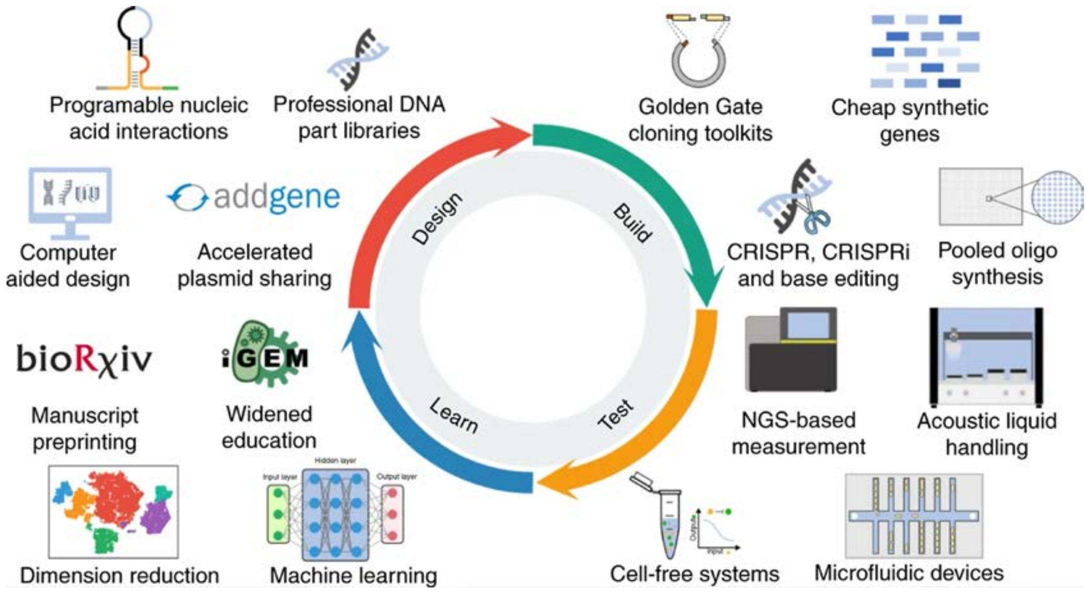


Figure 1. Figure shows the engineering cycle used in synthetic biology (centre) with cartoons illustrating some of the key technologies and ways of working that now help accelerate each phase of the cycle.[4] © NXPO

Engineering Biology or Synthetic biology falls within the scope of biotechnology as defined by the Convention on Biological Diversity, i.e. "... any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use"[5]. Furthermore, the potential impacts and oversight of engineering biology's tools, technologies, and applications are topics of sustained international interest within the CBD process. Synthetic biology, a component of engineering biology, was introduced in the CBD in 2010 to examine whether the scope and definitions pertaining to biotechnologies in the CBD were sufficient[6]. This included the development of an operational definition of synthetic biology. Two protocols to the CBD, the Cartagena Protocol on Biosafety and the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization also address engineering biology. The Biological Weapons Convention (BWC) does include important prohibitions on the weaponization of biological processes, but further development may be needed to effectively manage the complexities of modern synthetic biology. It has been 50 years since the first meeting of Biological Weapons Convention, a month after a historical meeting at the Asilomar camp ground in 1975 where a moratorium to halt any DNA modification experiment was proposed to the scientific community[7]. Last year, in 2025, the engineering of DNA has been democratized much beyond expectation from that of 1975, leading to participation from low- and middle-income countries (LMICs) at Asilomar[8]. Modern biotechnology, has transformed how mankind perceives biological systems equivalent to how Artificial Intelligence (AI) challenges our definition of intelligence itself. Therefore, the global community must embrace the ongoing and upcoming transformations with the best educational platform accordingly. Furthermore, If there is one lesson from Asilomar, it is that scientists, policymakers and the global public need to be aware of the potential dangers posed by any knowledge.

4 Meng, F., Ellis, T. The second decade of synthetic biology: 2010–2020. Nat Commun 11, 5174 (2020). https://doi.org/10.1038/s41467-020-19092-2 (Under a Creative Commons Attribution 4.0 International License)

5 Hung-En Lai et al. Synthetic Biology and the United Nations. Trends in Biotechnology. Volume 37, Issue 11, November 2019, Pages 1146-1151

6 https://www.cbd.int/synbio

7 Paul Berg. Asilomar 1975: DNA modification secured. Nature volume 455, pages 290–291 (2008)

8 Editor. Asilomar conference took courage and foresight — today, inclusivity would also be crucial. Nature. Vol 640. 10 April 2025

Application-specific innovations

While genetic modification is a major tool in Engineering Biology, not all Engineering Biology involves genetic modification. The field also includes non-genetic techniques, such as bioprocess engineering, to manipulate and optimize biological systems via processes such as fermentation, without altering the genetic makeup of the organisms involved. In 2024, artificial photosynthetic systems offered hope for new solar-to-fuel energy conversion[9]. Engineering Biology is being marketed as a method of "bioremediation" for making or digesting plastics in a carbon-negative manner[10]. To further leverage the bioremediation applications of Engineering Biology, the Nymphe project sponsored by the European Union is actively working on deploying the emerging technology to solve this global issues[11]. The environmental remediation market is valued at approximately US$115 billion,with many companies offering a wide range of in-situ or ex-situ remediation strategies, including physical, chemical, and biological remediation of soils, water (e.g., Microvi), brownfield sites or industrial wastes. Growth is driven by increasing regulatory frameworks and policies to reduce environmental pollutants such as PAHs (polycyclic aromatic hydrocarbons), PCBs (polychlorinated biphenyls), PFAS (Per- and polyfluoroalkyl substances), plastics, pharmaceuticals, pesticides, and heavy metals/metalloids[12]. Another way is to engineer microbes to produce products, such as biosurfactants, that can be used in remediation. However, to date, no commercialization of these products has been achieved due to technical and regulatory challenges to do with use of GMOs in the environment. Other products include a yeast engineered to produce meaty flavours to aid taste in plant- based burgers (promising 90% reductions in land use and green-house gases), thin films for electronics from molecules produced from engineered organisms, and engineered bacteria for nitrogen fixing in soils to reduce chemical fertilizers and to improve soil health[13] .

To support the materialization of these innovations, frontier infrastructure is necessary.. The Global Biofoundry Alliance (GBA) is the ongoing international initiative that focuses on infrastructure development and innovation enabling resource and knowledge sharing by various institutional leaders in the Engineering Biology field. Facilitation of infrastructure development not only enables the bioremediation and bioproduction approaches but can also establish an engineering route to acquire biological systems for specific goals in other fields. Standardized systems assure the drug discovery process especially in the BUILD and TEST pipeline.. Lastly, integration of emerging technologies, e.g. Large-Language Model Artificial Intelligence, also opens the door to a new paradigm of biological modelling by empowering the in-silico test both in terms of speed and quality. The following section will dive deeper into the technology integration aspect.

Integration with emerging technologies

The integration of engineering biology with emerging technologies such as Artificial Intelligence (AI) and biomolecular design is ushering in a new era of innovation at the intersection of life sciences and computational technologies. By combining the precision of synthetic biology with the predictive power of AI, researchers can rapidly design and optimize functional biomolecules—such as proteins, nucleic acids, and polysaccharides—for targeted functions in medicine, materials science, and environmental sustainability.

Machine learning techniques enable the analysis of large-scale experimental datasets, such as gene expression profiles and metabolic fluxes, to uncover complex patterns and forecast system behaviors. By training deep learning

9 Ennist, N.M., Wang, S., Kennedy, M.A. et al. De novo design of proteins housing excitonically coupled chlorophyll special pairs. Nat Chem Biol 20, 906–915 (2024).

10 Aminian-Dehkordi, J., et al., "Synthetic biology tools for environmental protection," Biotechnology Advances (2023)

11 https://www.nympheproject.eu/

12 David J. Lea-Smith et al. Engineering Biology Applications for Environmental Solutions: Potential and Challenges. Nature Communication 2025, Vol16: 3538

13 Christopher A. Voigt. Synthetic biology 2020–2030: six commercially-available products that are changing our world. Nature Communications volume 11, 6379 (2020)

models on extensive genotype–phenotype data leading into sophisticated genome-scale model and genomic languages, researchers can accurately predict the effects of genetic modifications, including gene knockouts and point mutations. These predictive models are instrumental in rational organism design, helping to reduce trial-and-error experimentation and enabling the creation of novel genetic circuits, metabolic pathways, and synthetic organisms with targeted traits.

Recent developments in deep learning have significantly advanced the ability to predict protein structures with a level of accuracy comparable to traditional experimental methods. A leading example is Google DeepMind's AlphaFold, which has been cited in the context of the 2024 Nobel Prize in Chemistry. Utilizing publicly available datasets of protein sequences and their experimentally determined structures, AlphaFold can reliably predict a protein's 3D conformation from its amino acid sequence alone[14]. Its latest version, AlphaFold 3 further expands these capabilities by modeling interactions between proteins and other biomolecules such as DNA and RNA. These breakthroughs offer a major advantage, as traditional structural biology techniques are often labor-intensive, time-consuming, and costly—factors that have long posed challenges to innovation in biotechnology.

One notable application of this convergence is in the sustainable production of biopolymers, such as plastics and resins, using engineered microorganisms. Synthetic metabolic pathways have been introduced into microbial hosts like bacteria and yeast, enabling the conversion of renewable inputs—such as plant oils and sugars—into monomers that serve as the building blocks for biodegradable polymers. Another exciting application of synthetic biology is the development of novel materials with unique properties. Researchers are using synthetic biology to create materials that can self-assemble, self-repair, or respond to external stimuli. For example, scientists have engineered bacteria to produce biofilms that can be used as living materials for applications such as water filtration. Synthetic Biology also enables the production of smart materials that can sense and respond to their environment. Researchers have developed synthetic gene circuits that can be integrated into materials, such as hydrogels or fabrics, to create sensors that can detect specific molecules or changes in pH, temperature, or light[15]. These responsive materials have potential applications in areas such as drug delivery, wound healing, and environmental monitoring. This multidisciplinary convergence not only streamlines the discovery process but also opens new pathways for creating intelligent, bio-based solutions to some of the world's most pressing challenges.

Finally, the attempt to make frontier technology more accessible also brings about the novel philosophy of frugal science and citizen scientists where technology is not limited to high resource communities and exclusive to conventional higher education training. For instance, Foldscope, a scientific instrument invented with both utility and affordability in mind led to magnification of biological entities in-field at a the cost as low as $1[16]. Other technological developments are also implanting these low-cost scientific and educational instruments and reagents, e.g. establishment of Africa Open Science Hardware (OSH)[17] and Reclone: Reagent Collaboration Network[18]. These accessible technologies contributed to advancement in scientific research through positive feedback loop and will continue to reform emerging scientific fields such as. Engineering Biology.

14 Abramson, J., Adler, J., Dunger, J. et al. Accurate structure prediction of biomolecular interactions with AlphaFold 3. Nature 630, 493–500 (2024).

15 Sheryl Li Yan Lim et al. Mammalian synthetic gene circuits for biopharmaceutical development & manufacture. npj Systems Biology and Applications volume 12, (2026)

16 Cybulski JS, Clements J, Prakash M (2014). «Foldscope: origami-based paper microscope». PLOS ONE. 9 (6) e98781

17 https://www.africaosh.com/

18 https://reclone.org/

Biosafety and biosecurity

Engineering biology applications may challenge current risk assessment and oversight processes established by domestic and international frameworks, including the Convention on Biological Diversity[19]. The current state of biosafety and biosecurity standards related to environmental biotechnology both overlaps with and leaves gaps in relation to other regulations[20]. Well-established guidelines exist for traditional biotechnological applications (contained use). For most application types, the risk assessment for genetically modified or edited organisms will account for the nature of the intended modification and will assess the relative risk to the environment, and animal or human health (e.g., hazards, severity, likelihoods, etc.). Containment level (BSL1 to BSL4), safeguards, control measures, and assignment of GM Activity Class require consideration. However, as we venture into more advanced areas like synthetic biology and gene editing, existing frameworks often fall short, especially when considering the potential of these technologies to bring solutions that may require deliberate release Important technical challenges remain in terms of containment strategies and procedures and control measures (Fig. 2).

An engineered organism that might be released into the environment accidentally, maliciously or with positive intent may bring risks that need to be managed. These include (a) the potential of the engineered organisms to “out-fitness” the native microbiome, (b) that the engineered organisms might not perform as intended with a phenotype that, while optimal to the target environment, might be detrimental in a different one, (c) that a trait of the engineered organism might unintentionally spread through the native microbiome by, e.g., horizontal gene transfer

Through a similar lens of biosafety and biosecurity, the concerns on ethical and responsible research practice should also be incorporated into all engineering biology products and processes. Failure to properly address the ethical prong could end up as a public distrust to upcoming innovations. Therefore, the bioethics of engineered biological systems will serve as a safeguarding procedure not only at the macro-scale, e.g. regional and national, but also to individuals and end-users as stakeholders of the global community.

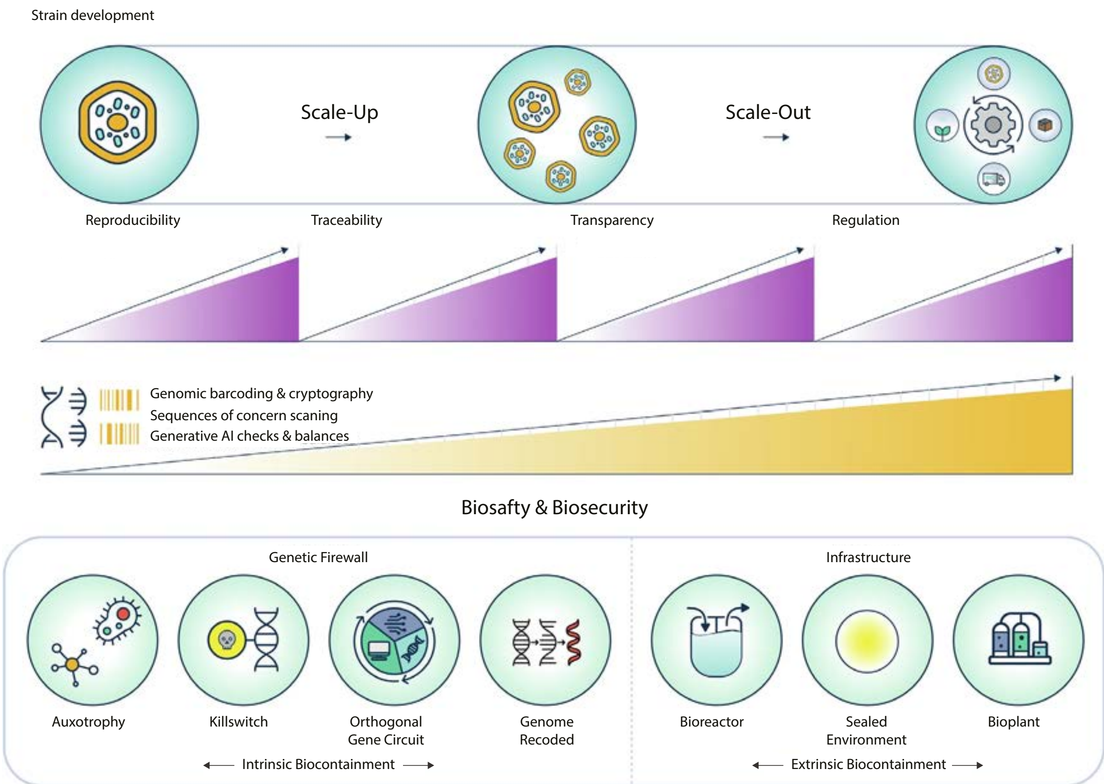


Figure 2 Strategies for biosafety and biocontainment in environmental biotechnology[21] © NXPO

19 CBD Technical Series No. 100, Synthetic Biology, April 2022

20 Beeckman, D. S. A. & Rüdelsheim, P. Biosafety and biosecurity in containment: a regulatory overview. Front. Bioeng. Biotechnol. 8, 650 (2020).

21 Lea-Smith, et al. (2025). Engineering Biology Applications for Environmental Solutions: Potential and Challenges. Nature Communications, 16, Article 3538. https://doi.org/10.1038/s41467-025-58492-0 (under a Creative Commons Attribution 4.0 International License)

Recognizing these profound risks, many countries have enacted targeted legislation on biosafety standards. While regulations might be capable of managing the specific risks within a national context, they do not cover the potential harm that synthetic biology may trigger globally. Regulatory framework is also limited by the uncertainties inherent to rapidly evolving synthetic biology research, and overly regulated rubrics could adversely limit innovative creations. Existing international frameworks may not be fully equipped to address the evolving risks. As biotechnology becomes more data-driven and amalgamates with automation and AI, it will be necessary to review through intergovernmental organs such as UNESCO Intergovernmental Bioethics Committee and International Bioethics Committee mechanisms to ensure the safeguarding of biological data, privacy and IP. An ongoing effort to safely deploy engineered biological systems in the open environment takes a great leap. UNESCO 2025 report on ethical issues related to the research, development and application of synthetic biology and the Biotechnology Beyond Conventional Containment topic at the Spirit of Asilomar meeting in February 2025 will play an important part in creating consensus around this issue[22].

Biotechnology's growing complexity makes it hard to create universal standards, specifically universal biocontainment standards. Scalable solutions across laboratory, pilot, and industrial scales would be necessary for biocontainment to become a viable strategy. To help bridge this gap, a more pragmatic approach has been suggested built around traceability of genomic bar- codes, DNA-based error-correcting codes[23] emerging within the field of DNA data storage and nucleic acids-focused cryptography, that are supported with existing technologies accessible to most laboratories and industries, can provide sufficient assurance to scientists, industry, regulators and the public at large.

Three pillars of Engineering biology impact

Engineering biology exemplifies a transformative approach to addressing global challenges across three key pillars: economic growth, environmental sustainability, and social benefit . Advances in engineering biology are driving new bio-based industries and fostering innovation-led economic development. Environmentally, engineered biological systems contribute to cleaner manufacturing, renewable materials, and carbon reduction strategies aligned with global climate goals. Socially, engineering biology contributes to significant job creation. Together, these contributions position engineering biology as a cornerstone of sustainable and inclusive development in the 21st century.

1. Economic Dimension

A new wave of innovation is being unleashed through the convergence of biological science, decades in the making, with fast-evolving digital technologies including AI, automation, and high-performance computing. This convergence is expected to reshape key sectors of the economy—from healthcare and agriculture to materials and energy . For biotechnology to become a foundation of this future, it must demonstrate clear and lasting economic value.

Evidence to support this is emerging. One influential study by the McKinsey Global Institute (2020) assessed the potential contributions of what it termed the "bio-revolution." It projected multi-trillion-dollar economic impacts across several industries, based on current and emerging applications of biotechnology[24]. Figure 3 is an overarching chart from the report.

22 Matthew Cobb. Money and murder: the dark side of the Asilomar meeting on recombinant DNA. Essay. Nature, Vol 638, 20 February 2025

23 Sabary, O., Kiah, H. M., Siegel, P. H. & Yaakobi, E. Survey for a decade of coding for DNA storage. IEEE T Mol. Biol. Mult. 10, 253–271 (2024).

24 The Bio Revolution Innovations; transforming economies, societies, and our lives. McKinsey Global Institute 2020

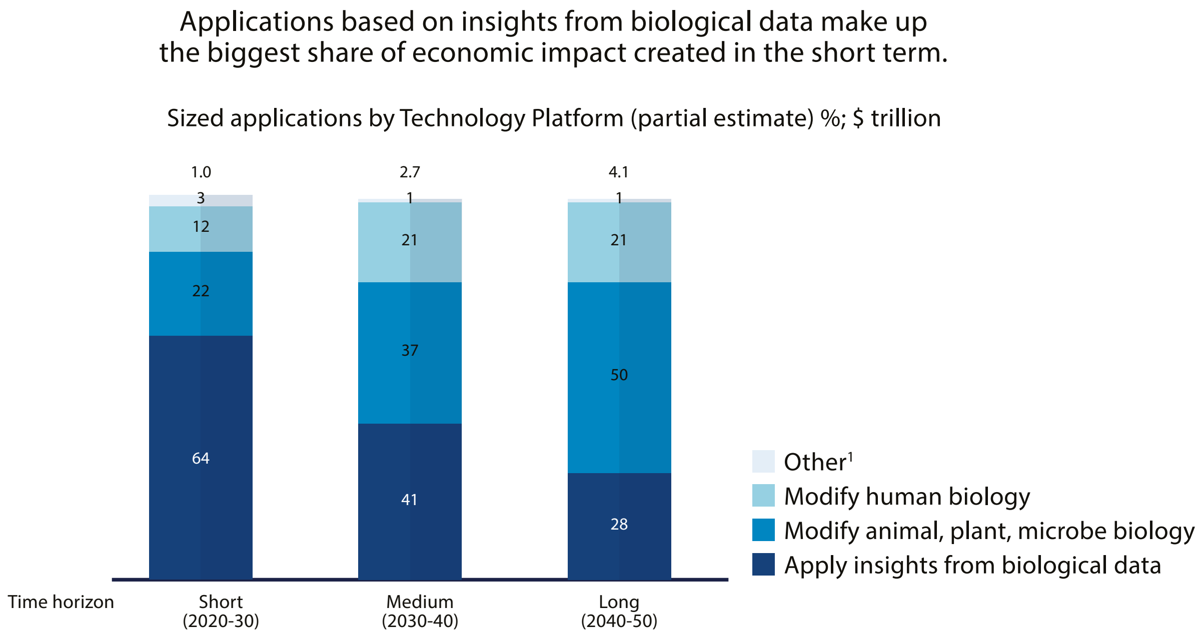


Figure 3. Estimated economic impact of the bio-revolution in the near, medium and long term. Sized applications by technology platform (partial estimate). Exhibit from "The Bio Revolution: Innovations transforming economies, societies, and our lives," May 2020, McKinsey Global Institute, www.mckinsey.com/mgi. Copyright (c) 2026 McKinsey & Company. All rights reserved. Reprinted by permission.

2. Environmental Dimension

A large body of life cycle analysis (LCA) research highlights the environmental benefits of bio-based alternatives. For instance, Weiss et al. (2011) reviewed 44 LCA studies covering 60 bio-based materials and found that, on average, such materials save 55 ± 34 megajoules of non-renewable energy and reduce CO_2 emissions by 3 ± 1 kg per kilogram of product, compared to fossil-based counterparts[25]. While biofuels have received policy attention through government quotas and mandates, the broader environmental value of bio-based chemicals and materials has often been overlooked[26]. Beyond manufacturing, microorganisms play vital roles in carbon and nutrient cycling, ecosystem health, agriculture, and food security—roles that remain underappreciated in national policy frameworks[27].

Engineering biology could significantly support climate mitigation. For example, it enables the production of next-generation biofuels aligned with IPCC decarbonization models. More radically, engineered microbes and plants might support "negative emissions" by capturing atmospheric CO_2 directly. This kind of innovation—direct air capture through biological routes—could complement or enhance carbon mitigation strategies that are still underexplored[28]. Table 1 below illustrates Engineering Biology potential climate mitigation contribution by mapping some of its potential applications against significant mitigation challenges characterized by the IPCC [29].

25 Ray Weiss and Ronald Prinn. Quantifying greenhouse-gas emissions at atmospheric measurements: a critical reality check for climate legislation. Philosophical Transaction of the Royal Society A. 28 May 2011

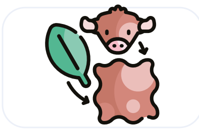
26 J. Philp. Balancing the bioeconomy: supporting biofuels and bio-based materials in public policy. Energy and Environmental Sciences (2015) Issue 11.

27 Ricardo Cavicchioli et al. Scientists' warning to humanity: microorganisms and climate change. Nature Reviews Microbiology volume 17, pages569–586 (2019)

28 Onyeaka, H. & Ekwebelem, O. C. A review of recent advances in engineering bacteria for enhanced CO2 capture and utilization. Int. J. Environ. Sci. Technol. 20, 4635–4648 (2023).

29 J. Symons et al. Engineering biology and climate change mitigation: Policy considerations. Nature Communications volume 15: 2669 (2024).






Replace fossil fuels in transport	**Reduce emissions from production processes: industry, construction and agriculture**	**Substitutes for emissions-intensive products**	**Sequester or mitigate in environment**
Biofuel from agricultural biomass or atmospheric/oceanic CO_2 Electricity storage/rewired carbon fixation: Electromicrobial production (EMP) that combines engineered biological and electronic components might convert CO_2 into high-density, non-volatile fuels or energy storage polymers. Engineered E. coli directly uses carbon dioxide (CO_2) to produce biofuels, bypassing photosynthesis in the production of biofuels (e.g. Ginkgo Bioworks). Hydrogen Dark fermentation processes produce hydrogen from biomass using engineered microbial consortia.	Industrial processes: Absorb CO_2 waste streams and sequestration or conversion to useful by-products e.g., ethanol or sequestration. Construction/Materials: Cement/concrete: Biomineralisation via application of bacteria during the preparation of mortar or concrete—leading to reduced carbon emissions and longer-lasting, self-repairing concrete. Agriculture: N_2O and MMO-transformed plants capable of reducing emissions (or drawing down atmospheric) N_2O and methane CH_4. Low-methane rice. Rice varieties that do not require irrigation, with altered methane/carbon fluxes, or increased yield.	Animal proteins: Biofermentation: Synthetic animal proteins (displacing CH_4), meat and milk. Fertilisers: Cultivation or engineering of nitrogen-fixing microbes (or plants/biofertilisation) is already at early-stage commercialisation. Chemical manufacturing: Building metabolic pathways in microbes for Hydrogen production which is not dependent on fossil fuel feedstock.	Sequester or mitigate carbon/GHGs in environment: Engineering crop root systems for enhanced carbon sequestration Increased production of suberin—a lipo biopolymer complex biopolymer; Microbes transforming organic carbon into stable carbonates. Direct air capture carbon/non-carbon GHGs.

Table 1 illustrates EngBio's potential climate mitigation contribution[29] © NXPO

3. Social Dimension

Rapid advancements in engineering biology raise important governance and public trust questions. In some countries, biotechnology regulation is already in place, with some experts arguing that these are adequate. Others caution that current frameworks may be outdated, particularly given the rise of community-based, non-traditional innovators in the field. The concern is not only about technical oversight but also about fostering trust and accountability in the governance of engineered organisms.

Instead of viewing diverse innovation communities as a regulatory challenge, they could be seen as an opportunity to co-create flexible, trusted standards. Tools such as regulatory sandboxes and internationally agreed technical standards could complement national regulation, especially in areas like component design, system assembly, and quality control.

At the same time, job creation remains a strong policy driver. In the EU, bio-based industries account for over €2.7 trillion in value in 2023 and 17.1 million jobs (roughly 8.5% of the workforce)[30]. U.S. bio-based manufacturing supports 4 million jobs and $370 billion in value, while India's bioeconomy passed $4 billion in 2013. Brazil's sugarcane sector alone accounted for 2% of its GDP and 4.5 million jobs in 2012.

Public awareness, however, lags far behind. While the public is attuned to sectors like healthcare, energy, and climate change, the central role of microbiology in sustaining life systems—what Timmis et al. (2019) call "microbiology literacy"—is not widely appreciated[31]. Gaining public trust in engineering biology will require scientists and engineers to improve how they communicate, using accessible and relatable language[32].

McKinsey (2020) estimates that nearly 70% of the potential impact of the bio-revolution depends on public, regulatory, and consumer acceptance. That makes communication a critical skill for future engineering biologists—alongside scientific and technical expertise.

A robust talent pipeline—from school to advanced training—will be essential. Interdisciplinary curricula, well-resourced universities, and strong R&D funding will enable the field to grow. Mechanisms that help translate research into real-world applications are also vital. Without a strong knowledge base and trained workforce, progress in engineering biology will stall. These needs are echoed across major foresight and strategy papers, which consistently call for expanded investment in training and innovation ecosystems.

30 https://ec.europa.eu/commission/presscorner/detail/en/ip_25_2819

31 Commission presents new Bioeconomy Strategy to drive green growth, competitiveness and resilience across Europe, European Commission Press Release, Nov 26, 2025 [https://ec.europa.eu/commission/presscorner/detail/en/ip_25_2819]

32 Aguilar A, Patermann C. Biodiplomacy, the new frontier for bioeconomy. N Biotechnol. 2020 Nov 25;59:20-25

Chapter 2.

Initiatives and Curriculum on Engineering Biology

Representative National Initiatives relevant to Engineering Biology

United States

Engineering Biology Research Consortium (EBRC)

The Engineering Biology Research Consortium (EBRC) is one of the first international organizations behind the Engineering Biology paradigm shift, partnering with academic institutions, industry members, and government institutions. EBRC also hosted the Student and Postdocs Association (SPA) which fosters new initiatives developed by younger scientists.

Since Engineering Biology was broadly defined as an umbrella term, all engineering and scientific principles applied to biological systems are relevant to some extent, making the knowledge established by other disciplines repurposable as practices in Engineering Biology. Throughout the plethora of engineering practices, an inaugural roadmap by the **Engineering Biology Research Consortium (EBRC)** serves as a thorough starting point for Engineering Biology stakeholders and incoming enthusiasts to explore the field in the mid-2010s. EBRC is an international-facing organization based in the US founded in 2016 right after the conclusion of SynBERC (Synthetic Biology Engineering Research Center) project which laid groundwork on parts and systems standardization for synthetic biologists and genetic engineers. Outstanding establishments during the SynBERC collaboration are standard parts and assembly strategies for biological circuitry now available through iGEM and BioBrick foundations.

As for the scope of Engineering Biology research, one seminal document from EBRC is the technical roadmap which focuses on connecting the research landscape from the state-of-the-art to the upcoming future technologies. EBRC's first roadmap, published in 2019, categorized the Engineering Biology core concept into 4 themes and 5 application impact sectors. The technical themes are 1) **Engineering DNA,** 2) **Biomolecular Engineering,** 3) **Host Engineering,** and 4) **Data Science** while application sectors are 1) **Industrial Biotechnology,** 2) **Health & Medicine,** 3) **Food & Agriculture,** 4) **Environmental Biotechnology,** and 5) **Energy.** The following EBRC technical roadmaps involve both academic-oriented topics (Microbiome Engineering, Engineering Biology and Materials Science, Climate and Sustainability, and Space Health) and public-facing topics (e.g. Enabling Defense Applications, Metrics and Technical Standards, and Synthetic DNA Screening).

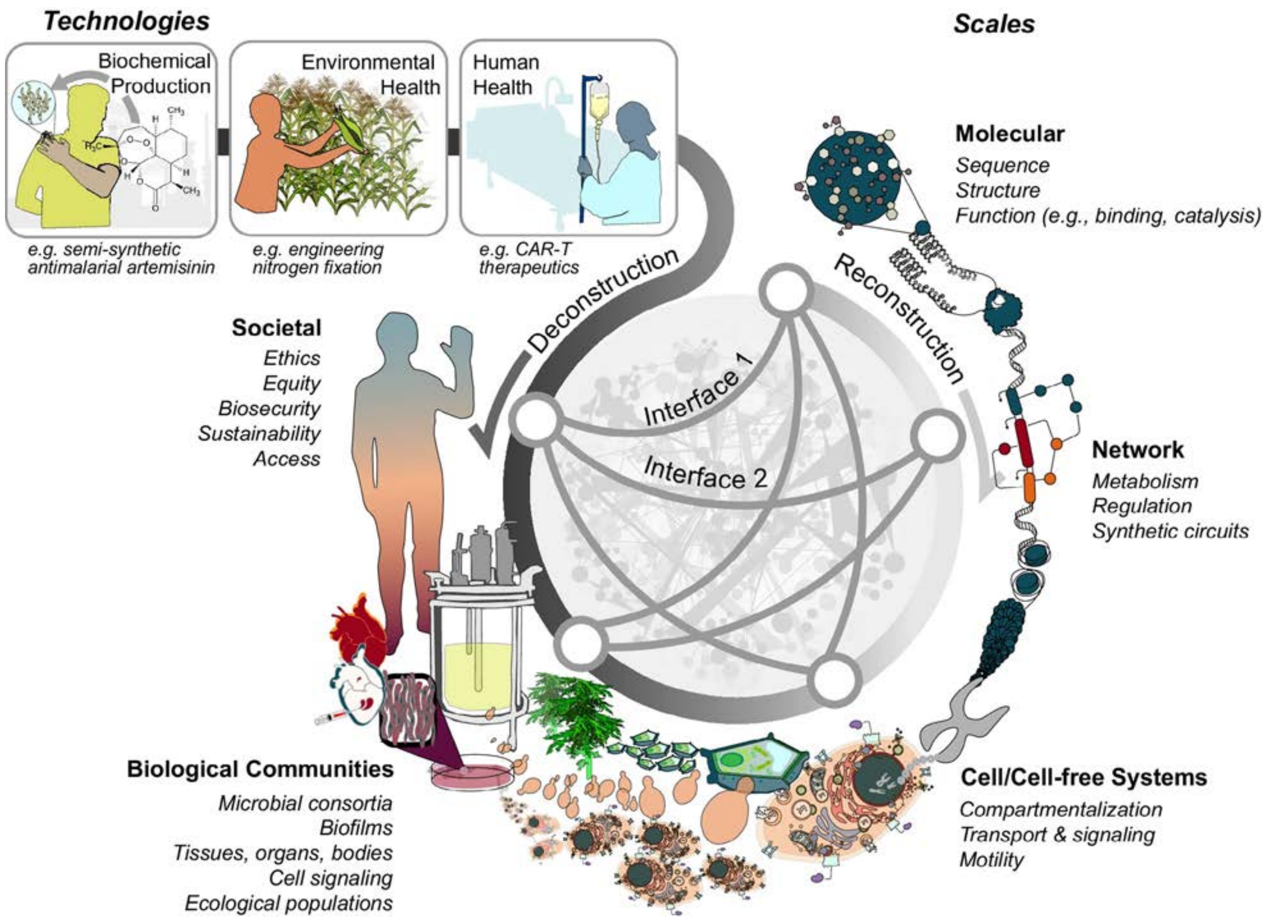


Figure 4. A schematic representation of the deconstruction framework from the work of Ashty Group at NorthWesetern University (USA): biotechnologies can be deconstructed along scales to identify biological phenomena that are important to the technology at each scale, understand the principles by which these phenomena work at that scale, and identify the important interfaces between scales where engineering challenges often arise. Deconstructing technologies along scales allows multidisciplinary concepts to be mapped and applied at individual scales (annotated) and allows new technologies to be reconstructed by combining elements and applying concepts at each scale. [33] © NXPO

33 Karim, A.S., Brown, D.M., Archuleta, C.M. et al. Deconstructing synthetic biology across scales: a conceptual approach for training synthetic biologists. Nat Commun 15, 5425 (2024). https://doi.org/10.1038/s41467-024-49626-x (under a Creative Commons Attribution 4.0 International License)

Key Initiatives and Frameworks developed at EBRC are based on four categories:

- **Roadmapping:** EBRC developed a comprehensive roadmap that outlines core areas of Engineering Biology research and emerging topics including microbiome engineering, biomaterials, climate & sustainability, technical standards, and space health. The roadmap identifies research gaps, technological challenges, and potential societal impacts, guiding future investments for US funding agency and policy makers.
- **Security:** One unique point of EBRC which outshines its prevalent organization, SynBERC, is its expanded focus on biosecurity. Security working group of EBRC has provided numerous programs led by faculty and SPA members, e.g. Malice Analysis: a workshop for dual uses training for biological parts and products. This training was also provided to participants of Gogec virtual competition.
- **Policy & International Engagement:** This working group focuses on international collaboration through various events being a binational gathering, e.g. US-U partnership, or multi-national meeting such as Engineering Biology Global Forum happened every 2 years since 2021. This international engagement emphasizes the potential collaboration across nations and regions.
- **Education:** EBRC has supported various programs focusing on Engineering Biology education at multiple levels. EBRC focuses on mentorship between students and professionals, internships with collaborative industry partners, and outreach programs to a broader audience. SPA also conducted various training programs e.g. Grad school panels for Future SPA and podcast program — EBRC In Translation — where stakeholders in Engineering Biology were invited to provide unique perspectives on various topics.

EBRC plays a key role in shaping US national strategies for Engineering Biology, providing scientific expertise and policy recommendations to policymakers. Its roadmaps, white papers, and other deliverables serve as models for other countries developing their bioeconomy strategies from an independent organization. By fostering public-private partnerships, EBRC strengthens the US's position as a global leader in Engineering Biology innovation.

The US Bioeconomy Act and White House Executive Order

The Bioeconomy Research and Development Act of 2021 represents a landmark policy framework in the US, designed to strengthen the nation's leadership in bio-based industries and accelerate the translation of Engineering Biology innovations into marketable products. It aligns with White House strategies, such as Executive Order 14081, which calls for advancing biotechnology innovation to strengthen US supply chains and address global challenges, including climate change, health security, and sustainability. The act was part of a broader White House initiative to promote biotechnology and biomanufacturing as strategic priorities for national security, economic growth, and sustainability. The bioeconomy act and executive order focuses on research and development investments, infrastructure and workforce development, and collaboration between public and private sectors. The Bioeconomy Act complements the US's broader bioeconomy goals by promoting biotechnology-driven economic growth.

European Union

EUSynBioS Initiative

The **European Synthetic Biology Society (EUSynBioS)** is a grassroots initiative that connects scientists, policymakers, and industry experts across Europe to promote Engineering Biology. It focuses on networking and collaboration among European researchers through conference and workshops organization. It also focuses on policy advocacy and educational programs through various events across the continent. EUSynBioS plays a key role in shaping EU policies on Engineering Biology by advocating for sustainable and responsible practices.

IBISBA

The **IBISBA (Industrial Biotechnology Innovation and Synthetic Biology Accelerator)** is a pan-European research infrastructure that supports industrial biotechnology and synthetic biology innovations by providing access to state-of-the-art facilities and expertise. It offers a network of advanced biomanufacturing facilities, helping researchers and industry partners scale up bio-based processes. The initiative bridges academia and industry, ensuring the translation of synthetic biology research into industrial applications. It also promotes green biotechnologies and circular bioeconomy goals. Its focus aligns with the need for bioeconomy-driven curriculum development.

Denmark

Novo Nordisk Foundation

The Novo Nordisk Foundation is one of the world's largest philanthropic organizations supporting life sciences and health research. The foundation, linked with the company Novo Nordisk, has a strong emphasis on advancing synthetic biology and engineering biology in Denmark and globally. Through strategic investments in centers like DTU Biosustain and the BioInnovation Institute (BII), the foundation drives innovation in metabolic engineering, biomanufacturing, and health biotechnology. It funds interdisciplinary research, infrastructure, and education initiatives that bridge academia and industry, fostering entrepreneurship, technology translation, and global collaboration in engineering biology.

DTU Biosustain

The **Novo Nordisk Foundation Center for Biosustainability (DTU Biosustain)** is a leading European research center focused on synthetic biology and metabolic engineering to develop sustainable industrial biotechnology solutions. They focus on all angles of biotechnological research including engineered microbes for sustainable chemical and pharmaceutical production. Machine learning and AI to optimize synthetic biology workflows are also emphasized with training programs from diverse groups of students and professionals in industrial synthetic biology with emphasis on technology-driven education and industry collaboration.

BioInnovation Institute (BII)

The BioInnovation Institute (BII), established by the Novo Nordisk Foundation in Copenhagen, is an international incubator that supports life science startups with a strong focus on engineering biology, biotherapeutics, and health tech. BII provides funding, lab facilities, mentorship, and acceleration programs to help translate cutting-edge synthetic biology and biotechnology research into commercially viable solutions. With emphasis on entrepreneurship and cross-disciplinary innovation, BII nurtures a vibrant ecosystem where researchers and founders can develop solutions in areas such as microbial production platforms, cell-based therapies, and molecular design.

France

France has taken strategic steps to position itself as a competitive force in industrial biotechnology and synthetic biology as part of its broader national bioeconomy and innovation strategy. France Bioeconomy Strategy (Stratégie Bioéconomie pour la France) was initially released in 2017 and revised in 2021 that direct the national investment in sustainable, circular, and innovation-driven bioeconomy. The French government supports Engineering Biology through national research programs, industrial development initiatives, and integration with European Union strategies (e.g., Horizon Europe). Engineering Biology in France is largely anchored within the life sciences and sustainability goals of the national Green Industrialization Strategy, with cross-cutting integration into health, agriculture, and environmental resilience.

France recognizes synthetic biology as a key enabling technology to support the transition to a bio-based economy, reduce dependency on fossil fuels, and ensure food and pharmaceutical security. Major efforts are coordinated through national research institutes like INRAE, CEA, CNRS, and through industrial partnerships with companies such as METABOLIX EXPLORER and EUROLYSINE, the latter being Europe's only producer of fermentation-derived amino acids for animal feed.

United Kingdom[34]

UK National Vision

The UK Research and Innovation (UKRI) is a leading government-funded organization that promotes biotechnology and bioeconomy research. UKRI together with the UK government have established dedicated initiatives to advance Engineering Biology, aiming to position the UK as a global leader in bio-based industries. This initiative is part of **national vision** with Engineering Biology as one of the key focus areas together with Artificial Intelligence (AI), Future Telecommunication, Quantum Technology, and Semiconductors. Some missions led by the UK system at national level include:

- Synthetic Biology for Growth Program: This initiative was launched in 2012 and invested over £120 million into Engineering Biology research and infrastructure. It supported the creation of Synthetic Biology Research Centres (SBRCs) at universities, including Edinburgh, Nottingham, and Bristol, driving academic-industry collaborations.
- Bioeconomy Strategy 2030: UKRI's bioeconomy roadmap outlines a vision for sustainable biotechnology innovation, including biomanufacturing, biomaterials, and bio-based energy. The strategy promotes public-private partnerships and workforce development.

Engineering Biology programs in the UK have significantly strengthened its bioeconomy infrastructure, fostering academic-industry partnerships and attracting private investment. The framework also promotes collaboration with the EU, US, and Asian countries, advancing global biotech standards.

Engineering Biology Aspirations (UK Government Office for Science)

The Engineering Biology Aspirations report, recently published by the UK Government Office for Science, proposes a strategic initiative exploring the transformative opportunities of engineering biology across sectors including health, agriculture, materials, chemicals, defence, and resilience. Through five expert-authored aspiration papers, the project defines evidence-based 10 to 15 year visions for how engineered biological systems, synthetic biology tools, and bioengineering principles could revolutionise industries with 5 focal technologies---Bioenergy, Engineered Crops, Fashion, Lab-derived Blood, and bio-based Metal factory. This report offers policymakers a guiding framework to support future infrastructure, investment, skills development, and regulatory approaches aimed at translating foundational research into societal and environmental impact within a policy context.

Brazil

Brazil is recognized as a leader in bio-based industries. Home to the amazon rainforest rich in biodiversity and possess vast agricultural land, advancements in Engineering Biology and sustainable biotechnology is very important to Brazil's and other South American nations bioeconomy. Key Developments in Engineering Biology in Brazil include National Bioeconomy Strategy supporting bio-based innovations, particularly in sustainable biomanufacturing and agricultural biotechnology. SynBio Brasil Initiative is also a growing community of synthetic biology researchers and startups driving local innovation in genome editing, metabolic engineering, and precision fermentation. With rapid growth of bioeconomy in Brazil and South America, new frameworks for workforce development for developing countries is necessary.

34 National vision for engineering biology, Department for Science, Innovation & Technology, 2023 [https://www.gov.uk/government/publications/national-vision-for-engineering-biology/national-vision-for-engineering-biology]

South Korea

South Korea, officially the Republic of Korea, has launched a nationwide Engineering Biology initiative to promote biotechnology innovation, bioeconomy growth, and global competitiveness. The initiative is part of the Korean Bioeconomy Strategy, introduced in 2021, which prioritizes biomanufacturing, synthetic biology, and biosecurity. The Korean government is allocating KRW 2 trillion (~USD 1.5 billion) over five years to boost biomanufacturing infrastructure and support biotech startups. They also establish National Biotech Clusters to expand biotech innovation hubs and foster academic-industry collaborations. With its advance infrastructure and dedicated focus in Engineering Biology, the new school focusing on Engineering Biology was recently founded at KAIST to strengthen the talent pipeline. Recently in 2025, Korea's National Assembly passed the "Synthetic Biology Promotion Act", marking one of the first laws globally focusing solely on synthetic biology. It is evident that South Korea aims to position itself as a global bioeconomy leader by enhancing biotechnology research and development capacity and promoting cross-border collaborations in this area.

Japan

Japan has established a robust national framework to advance engineering biology with a strong emphasis on biomanufacturing as a core enabler of its bioeconomy. Since the launch of its Bioeconomy Strategy in 2019, and most recently updated in 2024 by the Cabinet Office[35], Japan has clearly identified biomanufacturing as a key technological pillar. The strategy outlines a vision to leverage biotechnology and biological systems for sustainable production, industrial innovation, and carbon recycling. This national agenda reflects Japan's commitment to transforming its economy into a "bioeconomy society" by applying advances in synthetic biology, metabolic engineering, and genome technologies to real-world industrial and environmental challenges.

In alignment with this strategic vision, major Japanese ministries such as METI (Ministry of Economy, Trade and Industry) and MEXT (Ministry of Education, Culture, Sports, Science and Technology) are implementing R&D programs through their affiliated agencies NEDO[36] and JST[37], focusing on next-generation bio-based manufacturing technologies. Key initiatives include i) Carbon Recycling Biomanufacturing Technology, ii) Bio-based Production, and iii) Green Technologies. These national-level programs are complemented by human resource development efforts, including recurrent education for working professionals and graduate-level training programs.

Singapore

Singapore's National Research Foundation (NRF) established the National Synthetic Biology Task Force to position the country as a global leader in engineering biology. The nation hosts several internationally recognized research programs, including the Synthetic Biology for Clinical and Technological Innovation (SynCTI) at the National University of Singapore (NUS) and the Singapore Institute of Food and Biotechnology Innovation (SIFBI) at the Agency for Science, Technology and Research (A*STAR). Building on these efforts, the NRF supported the establishment of the National Centre for Engineering Biology (NCEB) as a nationwide initiative to consolidate existing research capabilities and outcomes, and to advance technologies and solutions that will strengthen Singapore's bioeconomy. Bridging academia and industry, the Singapore Consortium for Synthetic Biology (SINERGY), a national platform funded by the NRF, promotes research collaboration and commercialization in synthetic biology. SINERGY facilitates joint projects between academic institutions and biotechnology companies, accelerates technology translation, and supports skills training and curriculum development to prepare a future-ready workforce in engineering biology.

35 Bioeconomy Strategy June 3, 2024 Integrated Innovation Strategy Promotion Council Decision

36 Promotion of Carbon Recycling Using CO2 from Biomanufacturing Technology as a Direct Raw Material, NEDO Green Innovation Fund Projects [https://green-innovation.nedo.go.jp/en/project/bio-manufacturing-technology/]

37 https://www.jst.go.jp/gtex/en/field/bio.html

Policy brief By Dr Fernán Federici, Millennium Institute for Integrative Biology (iBio), Chile

A growing bioeconomy has placed biological engineering at the forefront of international priorities, including in Latin American countries. However, its development in Low and Middle-Income Countries (LMIC) is largely hampered by an asymmetric distribution of technological capacities and R&D infrastructure. As highlighted by the Spirit of Asilomar conference[38], the implications of engineering biology are far-reaching and its impact needs to be assessed. Engaging LMICs in the early stages of the growing field will allow these communities to better address the opportunities, risks and challenges of engineering biology.

In Latin America, a series of initiatives such as Gogec[39], Synbio Brasil[40], iGEM[41], BioBuilder[42] and TECNOx[43] have played a key role in introducing students (and academics) to synthetic biology. Despite this progress, bioengineering training in Latin America still remains limited by a series of barriers to access tools and technical documentation. The high cost of laboratory equipment and its maintenance makes them a scarce resource in universities. Access to the reagents is limited in Latin America due to the high cost of reagents that are imported from the north under expensive cold-chain logistics that are also prone to delays[44]. This centralized model creates global supply chain dependencies for Latin American countries, reducing their ability to exercise sovereignty over the application.

Enabling the local production and reproducibility of both biological reagents and hardware could be a key enabler for building capacity in bioengineering in Latin America. For instance, the Open Bioeconomy Lab, FreeGenes[45] and the Reagent Collaboration Network (Reclone)[46], has taken initial steps by sharing an Open DNA Collections over 500 researchers in approximately 50 countries globally to allow the local production of key reagents. Initiatives such as reGOSH and the Gathering for Open Science Hardware (GOSH)[47] are facilitating the local production of open-source hardware. Open source mini-labs can be employed to transform learning experiences that traditionally use proprietary devices as 'black boxes'. The use of open-source hardware can also trigger collaborations with emerging open hardware companies, such as IORodeo, GaudiLabs and IOWlabs. Open Educational Resources (OER)[48] for training can thus be composed of locally produced biological reagents, open-source hardware, free software and open access documentation. These OER can be designed to be reproducible and adapted to local supplies.

This proposal on open innovation models would also require nurturing future generations by including the concept in scientific education. Open-source technologies are able to capture how individual contributions map onto collective efforts, and can serve as a guide for rethinking how intellectual property is managed within universities and redefining intellectual property to accommodate collective more collaborative dynamics and freedom to operate. Open collaboration among students can also foster more effective learning as demonstrated by almost two decades of iGEM competition. International organizations like UNESCO are increasingly advocating for inclusive and equitable models of knowledge production. These resources can also include knowledge and guidelines to develop interdisciplinary skills needed to effectively engage in policy-making, regulatory committees and other advising roles[49].

38 https://repository.rice.edu/communities/4825def5-159e-4969-ae67-b2faf0c3b83d

39 Global Open Genetical Engineering Competition, https://www.gogecconference.org/

40 https://synbiobr.org/

41 https://igem.org/

42 https://biobuilder.org/

43 https://www.facebook.com/tecnoxlatam/?locale=es_LA

44 Pérez Ortega, R. Scientists in Latin America struggle to get key chemicals and other reagents for experiments. A group has begun to help. AAAS Articles DO Group (2024). doi:10.1126/science.zeje4i8

45 https://www.addgene.org/FreeGenes_Project/

46 https://reclone.org/

47 https://openhardware.science/

48 https://oercommons.org/

49 Zimmerman, E. H., Johnson, A., Elcock, L., George, D., Kiattisewee, C., Lardner, C., Palmer, X.-L., Seah, A., & Silberg, J. (2025). 5.3 Broadening Science Education within Existing Structures. Rice University. https://doi.org/10.25611/V3GE-GX89

Policy brief By Geoffrey Otim, Founder & CEO, SynBio Africa

Fostering Engineering Biology in Africa

Engineering Biology provides a timely opportunity for scientific advancement and sustainable development. Its introduction in African academic institutions remains in its infancy, largely constrained by uneven investment, regulatory ambiguity, and insufficient local expertise.

Nevertheless, Africa possesses a wealth of unique advantages that can be leveraged to build a globally competitive Engineering Biology ecosystem as one of the most biodiverse regions in the world. Africa's youth population presents another significant advantage. Over 60% of Africa's population is under the age of 25, and interest in STEM education is growing rapidly. Initiatives like iGEM teams in Uganda, Ghana, and Egypt highlight this grassroots momentum. SynBio Africa, a community-building organization founded in 2018, has harnessed this youthful energy to grow into a network of over 400 members from 30+ African countries. SynBio Africa has provided access to frontier tools and global expertise. Pan-African initiatives by SynBio Africa like ASSB and WiSBA are fostering inclusive, interdisciplinary, and gender-sensitive capacity building. Research exchange program like SynBREA, a collaborative initiative between SynBio Africa and Northwestern University, have allowed African students to gain hands-on experience in international laboratories. A powerful case study is the evolving role of SynBio Africa in advancing Engineering Biology across the continent, including hosting annual Synthetic Biology, AI, and Biosecurity Conference series (SBA 1.0, SBA 2.0, SBA 3.0 and SBA 4.0). It also established SynCell Africa initiative, focused on using engineered synthetic cells for addressing sickle cell disease. The success of these initiatives demonstrates the feasibility of world-class synthetic biology initiatives in low-resource environments when supported. One of SynBio Africa's most visionary goals is the establishment of a Center of Excellence in Synthetic Biology, based in Uganda to act as a regional anchor for research, training, entrepreneurship, and policy coordination. It will embed One Health principles, recognizing the interdependence of human, animal, and environmental health.

To successfully mainstream Engineering Biology in Africa, educational institutions must adopt flexible and modular curricula. These modules should cover synthetic biology principles, CRISPR and genome engineering, bioprocessing, computational modeling, and bioethics. Hands-on training is vital and can be supplemented through low-cost laboratory kits, mobile learning tools, and open-source platforms like Benchling or SnapGene. Universities should invest in the upskilling of lecturers and technical staff through faculty exchange programs and short-term sabbaticals with global synthetic biology centers. Collaborative curriculum development and co-teaching arrangements with institutions already leading in Engineering Biology can rapidly accelerate local capabilities. International events such as SynBioBeta, iGEM, and EBRC meetings offer platforms for exposure, collaboration, and benchmarking.

Finally, Engineering Biology education must embed innovation and entrepreneurship. Students should be trained to translate it into practical solutions. Courses in technology commercialization, bio-manufacturing, regulatory science, and business model design can help students bring their ideas to market. Africa's growing network of biotech hubs, accelerators, and innovation labs can provide the incubation and funding support to turn student projects into viable enterprises

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Otim, G. et al., SynBio Africa's story from the grassroots, the present, and the future, (Biotechnology Notes 4 (2023) 1–6)

Policy brief By Prof Yin Li, Institute of Microbiology, Chinese Academy of Sciences, China

Engineering Biology in China

China stands at the vanguard of a transformative global bio-revolution. Driven by coherent national strategies and unprecedented investment, the nation has cultivated world-class innovation ecosystems like Beijing, Shanghai, and Shenzhen. These hubs exemplify technological ambition, housing automated biofoundries capable of printing genetic circuits and engineering enzymes/strains, industrial-scale fermentation complexes producing million metric tons of bio-based products, and global pioneers such as BGI's genomic sequencing empire and WuXi AppTec's integrated drug development platforms. This concentration of capability has propelled China to global leadership in synthetic biology patent filings and positioned it at the forefront of CAR-T cell immunotherapies and AI-driven biodesign.

The geographical distribution of innovation resources reflects China's strategic approach to technological development. While Beijing's Zhongguancun hosts the National Center for Nanoscience and Technology's bio-nano fusion labs, Shanghai's Zhangjiang Pharma Valley concentrates multinational R&D centers alongside academic powerhouses like ShanghaiTech University. Meanwhile, Suzhou's BioBay has evolved into Asia's largest cell therapy industrial base. Cloud-based biofoundry platforms enable researchers nationwide to remotely access robotic strain engineering workflows. Expanded high-performance computing nodes now process complex metabolic models for extremophilic microorganisms.

China's competitive positioning rests upon three mutually reinforcing pillars of strength. Foremost is manufacturing scalability - an industrial translation engine unrivaled in speed and volume. This capability manifests in facilities like AHB's 30,000-ton L-alanine plant in Hebei.

Complementing industrial prowess is China's distinctive data-AI convergence. The longitudinal health data on citizens, combined with BGI's sequencing of millions genomes through the China National GeneBank, creates unparalleled datasets for target discovery. These resources synergize with AI capabilities demonstrated by Shanghai-based MoleculeMind's enzyme optimization platform. Beijing's Deepwise and Shenzhen's MindRank AI similarly accelerate antibody design.

Underpinning these advantages is sustained policy commitment. The 14th Five-Year Plan for Bioeconomy Development allocates significant investment into biotechnology. Venture capital follows strategically, with Qiming Venture Partners and Sequoia China funding over dozens of startups. Dedicated bioclusters such as Guangzhou's Bio-Island integrate these resources through one-stop regulatory guidance, increasing the pre-tax deduction, and shared GMP pilot plants.

Collaborative ecosystems are emerging through mission-oriented consortia. The National Innovation Center for Synthetic Biology coordinates dozens of universities and enterprises in developing AI-driven biomanufacturing platforms. Its IP-sharing framework has accelerated commercialization of a variety of microbial cell factories in the last 10 years.

Talent ecosystem reshapes human capital development. Leading universities now offer interdisciplinary degrees fusing synthetic biology with computational engineering. Adaptive governance mechanisms evolve alongside technological frontiers. In recent years, China has optimized the approval process for cell and gene therapies. China's Biosecurity Law establishes tiered risk frameworks for engineered organisms.

China's engineering biology ascendancy represents a deliberate synthesis of manufacturing prowess, data resources, and governance innovation. As coastal biofoundries and inland computational centers increasingly interoperate through digital networks, the nation demonstrates how geographical diversity can strengthen rather than fragment technological capability. This convergence positions China to transcend incremental advancement and instead define emerging bio-industrial paradigms. By leveraging engineering biology to simultaneously address healthcare accessibility, decarbonization imperatives, and food security challenges, China pioneers solutions with both domestic impact and global relevance. The forthcoming phase will likely see Chinese bio-manufacturing standards influence international regulatory frameworks, while its AI-biology fusion platforms set new benchmarks for R&D efficiency.

Representative Curricula with relevance to Engineering Biology

Multidisciplinary education for Engineering Biology

The challenge of multi- and interdisciplinary education Interdisciplinarity implies a problem-solving function not necessarily implicit to multi-disciplinarity A useful distinction was made by Boix Mansilla et al. (2000) who framed interdisciplinarity as the capacity to integrate knowledge and modes of thinking in two or more disciplines[50]. To equip engineering biology students with problem-solving capability implies the need for both. This, in fact, challenges the teachers as much as the students: traditional scientific education and training has remained divided by disciplines such as microbiology, chemistry and computing.

The long-standing conundrum of multi- and interdisciplinary education is the need for both breadth and depth. Training in sustainability itself needs multi- and interdisciplinarity as some of the depth skills needed are systems thinking, strategic planning, and evaluating environmental, social and economic performance. This educational conundrum for sustainability[51] is the same for industrial biotechnology and engineering biology: how to make the interdisciplinary approach not only substantive, but also practical for early-career scientists.

Multiple agency funding for projects that span disciplines are needed (National Academies of Sciences, Engineering, and Medicine, 2020). Life sciences industry-wide issues Life sciences PhD-level education remains focused on training for academic careers (American Society for Microbiology, 2013). In the Nature PhD survey of 2017, nearly 75% of (general PhD student) respondents said that they would like a job in academia as an option upon graduation[52]. In the quest for breadth, in multidisciplinary education, depth may become too diluted. This could certainly be cause for concern in engineering degrees if the certification bodies such as the Institution of Chemical Engineers found too little depth to certify engineers and courses. The burden of learning required to become familiar, if not expert, in various different disciplines may be too great, which could be especially true within the time limitations of Master programmes. The flexibility is greater within undergraduate degrees; nevertheless, careful attention would have to be given to curriculum design to prevent overload, with the attendant problem of student drop-out. Regarding this latter point, it is worth remembering that the drop-out rates in STEM subjects (science, technology, engineering and mathematics) are already alarming[53].

AI tools are reshaping education and training, making advanced engineering biology knowledge and techniques more accessible. The use of LLMs to simplify content, develop personalised curricula, answer student questions, and help draft reports is already common. AI and automation tools are also changing laboratories and shifting the skills needed by researchers. In foundational research laboratories, there is an increasing shift from using bioinformatics solely in the latter stages of research to analyse results to incorporating it in early experiment stages to design protocols and components. This is changing the skills that needed by scientists, requiring further multidisciplinarity. In the private sector, software engineers and life scientists often work hand-in-hand to develop computational tools for engineering biology, fostering a culture of recombination. Whether new AI tools in synthetic biology will overall lower barriers of entry or increase them is unclear, and the impact will likely be different for general purpose technologies and specialised tools. Publicly available large language models can quickly mine and analyse research papers to summarise their insights and respond to user questions, which could make scientific information more widely accessible to broader audiences. AI biodesign tools, on the other hand, may still require advanced training to operate and especially to harness the intelligence they produce (e.g. to set up the experimental conditions to produce a chemical of interest).

50 Boix Mansilla, Veronica and Elizabeth Dawes Duraisingh. «Targeted Assessment of Students' Interdisciplinary Work: An Empirically Grounded Framework Proposed.» The Journal of Higher Education, vol. 78 no. 2, 2007, p. 215-237. Project MUSE, https://dx.doi.org/10.1353/jhe.2007.0008.

51 Zabin K. Bagewadi et al 2020. Industry-Internship Program for Biotechnology Under-graduates- Enabling the Student-Workforce for Better Employability. Journal of Engineering Education Transformations, Volume 33, January 2020, Special issue, eISSN 2394-1707

52 Woolston, C. Graduate survey: A love–hurt relationship. Nature 550, 549–552 (2017). https://doi.org/10.1038/nj7677-549a

53 UNESCO 2017. Cracking the code: girls' and women's education in science, technology, engineering and mathematics (STEM). Document code:10.54675/QYHK2407

Examples of Higher Education Curricula in Relevance of Engineering Biology

In this chapter, representative curricula relevant to Engineering Biology are listed as references for further curriculum design. It is important to note that there are only a few programs at this moment that delegate their focus to the broad engineering biology field or have the terminology in the degree name. Furthermore, most of the curriculum listed in this chapter came from high-resource countries who are leaders in the research and development of the field. Trainings at low-resource countries are not broadly available and thus emphasize the importance of this curriculum framework which focuses on the Low- and Middle-Income Countries ecosystems.

Department of Genetic Engineering, A Roadmap – MIT

The recent report in 2025 proposed that a distinct cross-cutting discipline integrating biology, mathematical modelling, and engineering to "design life" can enable its own academic department naming "Department of Genetic Engineering", with comparison to the emergence of Chemical Engineering and Biological Engineering in the 20th century. The focus of genetic engineering should span biomanufacturing, defense, agriculture, materials, energy, in addition to that of biomedicine, a relatively conventional application. While this proposal is calling for an establishment of a four-year undergraduate program, it narrates a lot of higher education focus in the proposal including that of global analysis of the existing programs: 90 curricula across 60 universities. While this proposal is not the direct equivalent of the Engineering Biology curriculum framework, it is worth noting as the first cutting-edge proposal for a relevant establishment in the field.

Graduate degree Curriculum

Master's Program in Engineering Biology at KAIST, South Korea

KAIST's Master's in Engineering Biology, started in 2025, is designed to cultivate researchers and innovators in synthetic biology, metabolic engineering, and systems biotechnology. Given KAIST's strong portfolio in the field especially in systems metabolic engineering, they firmly represent the very first program in Asia with Engineering Biology in their degree name. The program integrates core biology, chemical engineering, and computational science, with a focus on designing and constructing biological systems for practical applications. Students typically complete foundational coursework in synthetic biology, bioinformatics, molecular biology, and biochemical engineering, followed by specialized modules in metabolic pathway design, chassis development, and biofoundry technologies.

Research opportunities are central to the program, with students expected to participate in lab rotations in their first semester before joining a lab for their thesis. KAIST emphasizes translational research and collaboration with the industrial sector through its Bio-Foundry Center and links to South Korea's biotech ecosystem. Projects may include developing microbial platforms for bioplastics or engineering cell factories for pharmaceuticals. The program is designed to be completed in two years, concluding with a thesis defense and often a publication-quality research project. This program is the best fit to this curriculum framework in term of program timeline.

Master's Program in Engineering Biology in the UK (EPSRC & BBSRC CDT)

This UK-wide program, led by the Engineering and Physical Sciences Research Council (EPSRC) and Biotechnology and Biological Sciences Research Council (BBSRC), is offered across a consortium of universities (e.g., Oxford, Imperial, Manchester). The four-year Integrated PhD and Master's program begins with a one-year MRes that introduces key engineering biology principles and techniques, including gene circuit design, synthetic genomics, and machine learning for biological systems.

The MRes phase emphasizes multidisciplinary training, with hands-on projects and short lab rotations. Students gain exposure to key platforms such as biofoundries, computational modeling environments, and high-throughput screening tools. Following this, students continue into a three-year PhD research phase under a chosen supervisor. Research areas span from biomaterials and biosensors to synthetic cells and bio-manufacturing. The program fosters strong links with industry and government, supporting the translation of academic findings into real-world biotech solutions.

University of Edinburgh – MSc in Synthetic Biology and Biotechnology

Offers a one-year taught Master's program through the School of Biological Sciences, focusing on molecular biotechnology, genetic circuit design, and microbial engineering. The program combines theoretical foundations in systems and synthetic biology with hands-on training in lab techniques, computational modeling, and industrial applications. Students engage in interdisciplinary projects and have access to the Centre for Synthetic and Systems Biology (SynthSys), which supports advanced research in biosensors, metabolic pathways, and bio-manufacturing. Graduates often continue into PhDs or biotech industry roles.

Systems, Synthetic, and Physical Biology (SSPB) PhD Program at Rice University

SSPB is a PhD program focused on training scientists in the design and analysis of biological systems through a systems and synthetic biology lens. It is one of the first PhD program to include Synthetic Biology, a very close term to Engineering Biology, to their degree name. The program blends biology, physics, engineering, and computational science, preparing students for research careers in academia or biotech.

Students begin with an intensive first-year core curriculum covering systems biology, synthetic gene networks, biophysics, and bioengineering. Lab rotations in the first year lead to selection of a thesis advisor. Research topics include metabolic pathway optimization, microbial consortia engineering, synthetic developmental systems, and biosensing platforms. Students are embedded within the Rice Center for Synthetic Biology, offering exposure to interdisciplinary collaboration and entrepreneurship. The program typically takes 5–6 years and emphasizes both foundational science and translational applications.

Modules as Part of Graduate Degree (Non-Degree Granting)

Engineering Biology Module at NUS, Singapore

As part of NUS's Life Sciences and Engineering curriculum, several synthetic biology modules are offered that provide focused overviews of synthetic biology principles, biodesign methodologies, laboratory techniques, and applications across environmental, medical, and industrial biotechnology. These courses include lectures, case studies, laboratory experiments, and mini-projects to familiarize students with tools such as CRISPR, metabolic modeling, and biosensor development. Emphasis is placed on interdisciplinary collaboration and responsible innovation, including considerations of bioethics and biosafety. These modules are integrated into broader MSc- or PhD-level coursework, equipping students with foundational synthetic biology skills applicable to both research and industry settings.

Integrated Graduate Program in Physical and Engineering Biology (PEB) at Yale University, US

The PEB program at Yale is a multidisciplinary graduate training track that complements a student's primary PhD department (e.g., Molecular Biology, Physics, Engineering). It is not a standalone degree but offers a unique curriculum emphasizing quantitative biology, systems-level analysis, and engineering approaches to biological questions. Students engage in core modules like quantitative imaging, computational modeling, and synthetic biology design labs. The program promotes collaboration across departments and includes a first-year summer bootcamp, coursework, and a teaching practicum. Students often work on projects like constructing gene circuits or analyzing cell behavior using physical modeling. PEB graduates are well-prepared for research at the interface of biology, physics, and engineering.

Examples of Undergraduate Track

Undergraduate Track at Princeton University, US

Princeton offers an integrated undergraduate track in Quantitative and Computational Biology (QCB), with a concentration in Synthetic Biology available through electives and research mentorship. Students begin with foundational coursework in molecular biology, physics, and programming, progressing into courses on biological circuits, systems biology, and biotechnology. Research is a strong component of the program, with opportunities to work in labs focused on CRISPR technologies, synthetic gene networks, and cellular engineering. Capstone projects and thesis work often involve engineering microbes for environmental sensing or bioproduction. The program also incorporates ethics, policy, and design thinking in biotechnology, preparing students for graduate study or careers in bioengineering.

University of California, Davis – B.S. in Systems & Synthetic Biology

Launched in Fall 2022, this Bachelor of Science program offers a comprehensive education in both systems biology and synthetic biology. Students begin with foundational courses in chemistry, biology, physics, and mathematics, along with an introduction to computing for biologists. As they progress, they delve into advanced topics such as systems theory, computational modeling, and biological engineering. The curriculum emphasizes integrative, computational, and quantitative approaches to solving biological problems and engineering new biological outcomes.

Collections of Relevant Centers within Academic Institutions

Engineering Biology Research Center (EGBRC) at Kobe University

EGBRC stands as Japan's premier institution dedicated to advancing the interdisciplinary field of engineering biology. The center's mission is to foster innovation at the intersection of biology, engineering, and digital technology, aiming to address global challenges such as sustainability and carbon neutrality. It partners with the graduate program at Kobe University to train the workforce toward Japan's bioeconomy goal.

Boston University Synthetic Biology & Biotechnology (SB2) Predoctoral Training Program

While not a standalone degree, BU's SB2 program is a pioneering training initiative in synthetic biology. It addresses the need for a comprehensive, sustainable curriculum to train the next generation of synthetic biologists. The program emphasizes interdisciplinary practices, integrating biology with engineering principles to prepare students for advancements in biotechnology, agriculture, medicine, and more.

MIT Synthetic Biology Center

Offers leading-edge research and graduate programs in synthetic biology through departments like Biological Engineering and the Media Lab. Focus areas include living therapeutics, biocomputation, and chassis development.

Harvard University Wyss Institute for Biologically Inspired Engineering

Hosts postdoctoral and research fellowships across bioinspired design, living materials, and synthetic organoids. Not a degree-granting program but closely affiliated with Harvard's SEAS and Medical School. Research areas include synthetic morphogenesis, cell programming, and therapeutic gene circuits. Known for translational research, high-impact publications, and startup incubation.

Imperial College London Centre for Synthetic Biology

Home to one of the UK's leading synthetic biology research hubs, offering graduate degrees including MRes and PhD programs through the Department of Bioengineering. Research focuses on genetic circuit design, synthetic microbial communities, and industrial bioproduction. Known for its dedicated London Biofoundry, UK SynBioCDT partnership, and strong emphasis on responsible innovation and public engagement.

University of Manchester Manchester Synthetic Biology Research Centre

Offers interdisciplinary graduate training through the Manchester Institute of Biotechnology (MIB) and hosts the SYNBIOCHEM center, focusing on fine chemical and pharmaceutical biosynthesis. Research includes synthetic metabolic pathways, bio-based materials, and scalable bio-manufacturing. Collaborative PhD opportunities available through the UKRI-funded SynBioCDT and Future Biomanufacturing Research Hub.

Technical University of Denmark (DTU) – DTU Biosustain & DTU Bioengineering

Graduate education in synthetic and engineering biology is embedded within interdisciplinary PhD and MSc programs offered by DTU Bioengineering and DTU Biosustain (The Novo Nordisk Foundation Center for Biosustainability). Focus areas include metabolic engineering, cell factory design, synthetic regulatory systems, and bioproduction of chemicals, pharmaceuticals, and food ingredients. DTU Biosustain houses advanced biofoundry and automation platforms, supports industrial-academic collaborations, and emphasizes computational-experimental integration through AI-guided strain design and genome-scale modeling.

Northwestern University Center for Synthetic Biology

Interdisciplinary PhD programs and undergraduate research focused on microbial engineering, synthetic genomics, and bioethics. Known for collaborative engineering-biology interface training.

University of Washington Center for Synthetic Biology

Offers graduate training through the MolES Institute and focuses on engineering biology research within the Center for Synthetic Biology. Strong in enzyme design, microbial chassis engineering, and digital-biological data system integration.

Rice University (Center for Synthetic Biology)

Hosts the SSPB PhD program and supports research in synthetic ecosystems, computational modeling, and biological control systems. Focuses on innovation and translational science.

University of Delaware (Center for Plastics Innovation & Delaware Biotechnology Institute)

Home to programs in bioengineering and sustainable synthetic biology, with emphasis on metabolic engineering, circular bioeconomy, and materials from biology.

University of California, Berkeley Innovative Genomics Institute (IGI)

Hosting the legacy of SynBERC (Synthetic Biology Engineering Research Center), the institute research focuses on CRISPR systems, metabolic rewiring, and biological system design. They exhibit cross-program collaboration across bioengineering, chemistry, and plant sciences.

ETH Zurich Department of Biosystems Science and Engineering (D-BSSE)

Offers graduate and doctoral programs in synthetic biology, systems biology, and computational biology through interdisciplinary institutes. Research includes synthetic developmental biology, programmable cells, and automated lab platforms. Known for integrating engineering design principles with data-driven biology and pioneering work on synthetic ecosystems and digital twins of cells.

Princeton University – Omenn-Darling Bioengineering Institute

Supports interdisciplinary research and graduate training in bioengineering, including synthetic biology, systems biology, and molecular programming. While Princeton does not currently offer a standalone degree in synthetic or engineering biology, the institute connects faculty and students across engineering, chemistry, and molecular biology. Research themes include synthetic gene networks, biomolecular computation, cellular decision-making, and engineering living systems. Students can pursue these interests through PhD programs in Chemical and Biological Engineering, Molecular Biology, or Quantitative and Computational Biology.

Challenges and Opportunities

Challenges and Gaps present in Low- and Middle-Income Countries

Despite the global advancements in Engineering Biology, developing countries or Low- and Middle-Income Countries, often face significant barriers in biotechnology education and research capacity. Existing curriculum frameworks in leading nations (e.g., the US, UK, and EU countries) are developed in the context of well-established infrastructures, advanced research facilities in the region, and streamlined public-private partnerships. In contrast, developing countries often lack access to cutting-edge tools, computational resources, and industry collaborations, limiting their ability to keep pace with global innovations. Conventional Engineering programs lack sufficient exposure to biology while life sciences programs are behind in data integration and high-throughput methodology. In addition to curriculum gaps, hands-on exposure are also limited within the LMICs where only a few programs are capable of offering real-world biomanufacturing equipment and engineering biology toolkits. Interdisciplinary mentorship is also extremely limited within the training in low-resource environments. Pertinent to infrastructure and tools, there are limited numbers of emerging biofoundries, and high-performance computing infrastructure for systems biology modeling.

The existing Global Biofoundry Alliance [ref] showcase that LMICs were hardly present. These gaps not only hinder the quality of education and research but also discourage public-private collaboration and foreign investment in bio-based innovation in developing countries or Low- and Middle- Income countries. Additionally, policy, governance, and biotechnology regulations still remain challenged. Biotechnology regulations in developed countries are either fragmented, outdated, or narrowly focused on specific national interest such as agriculture. Biosafety and biosecurity regulations are inconsistently enforced and rarely address emerging risks from advanced biotechnologies. Intellectual property regimes are not well adapted to support innovation in this sector, and public engagement is limited. This regulatory challenges discourages international partnerships and reduces the willingness of local institutions to engage in ambitious Engineering Biology initiatives.

Opportunities present in Low- and Middle-Income Countries

Engineering biology presents transformative opportunities for developing countries in achieving many aspects of Sustainable Development Goal (SDGs), the global values which are prominent in LMICs. For instance, Engineering Biology can well serve SDG 2: Zero Hunger purpose by enhancing agricultural productivity, resilience, and sustainability. Through techniques such as synthetic biology and genome editing, crops can be engineered to resist pests, tolerate drought, and yield more nutritious food, even under challenging environmental conditions. This is particularly vital for regions facing soil degradation, erratic rainfall, or limited access to arable land. Additionally, bioengineered microbial fertilizers and biopesticides reduce dependence on costly chemical inputs, making farming more affordable and eco-friendly. Specific examples of how engineering biology can help reduce post-harvest loss in developing countries include Genetically engineered Bt cowpea in Nigeria, which reduces post-harvest losses and decreases the need for chemical pesticides, improving storage life and food safety for smallholder farmers. These innovations, when supported by inclusive policies and capacity-building initiatives, can empower smallholder farmers, improve food security, and foster local bioeconomy in developing nations. Engineering biology also offer opportunities for developing countries to achieve SDG 3: Good Health and Well-being and SDG 12: Responsible Consumption and Production through the development of technology locally including CRISPR-based diagnostic and environmental-frienly productions in the Global South countries.

The curriculum framework aims to bridge this gap by framing different aspects of higher education based on knowledge-based and practice-based modules. The framework stands as a reference guideline that can be adapted to i) **develop a new curriculum** focusing training on Engineering Biology with available resources and expertise, ii) **restructure an existing curriculum** into Engineering Biology focus program, or iii) **incorporate Engineering Biology aspect** as a track into the established interdisciplinary program. The curriculum designer can choose to focus on equipping students and trainees with Engineering Biology knowledge or also emphasize incorporation of practical skills relevant to emerging industry in the field. Therefore, hands-on training in biology and engineering techniques can be inserted with awareness of available resources in the region. At the same time, this framework will emphasize the creation of open-source educational resources and cloud-based training platforms, enabling students in developing countries to access state-of-the-art training, regardless of their geographical location.

Furthermore, training in biosecurity, bioethics, and regulatory frameworks will be included to ensure that graduates are prepared to navigate the policy and governance landscape upon completion of the educational program. These aspects are often underemphasized in low- and middle-income regions despite sometimes having rich natural resources for technological deployment. By embedding these competencies into the Engineering Biology curriculum, the region will be equipped with proper human capital ready to contribute toward the development of global bioeconomy.

Technical and Pedagogical Approaches

To effectively design the curriculum that matches recent technical development and keep awareness of available resources, the framework will adopt a modular and interdisciplinary approach that balances technical knowledge with practical application that can be tuned for effective adaptation in the institutional context.

On the technical side, the curriculum will cover core areas of Engineering Biology and emerging topics, including:

- Genetic Circuit Design and Modulation: Focusing on the design and optimization of genetic circuits using CRISPR-based and other programmable technologies.
- Metabolic Engineering and Bioproduction: Focusing on hands-on experience in engineering microbial systems for bio-based manufacturing with emphasis on industrial application.
- Synthetic Biological Systems: Focusing on emerging techniques for large-scale DNA synthesis, genome engineering, and synthetic biological systems construction.
- Biological Data Science: Focusing on bioinformatics, computational modeling, and machine learning to enhance experimental design, data interpretation, and predictive approach.

On the pedagogical strategies, the curriculum will leverage active learning and project-based education, including:

- Experiential Learning: Focusing on lab-based training, virtual labs, and bioinformatics simulations, in which students will gain practical, problem-solving skills.
- Case Studies and Real-World Applications: Focusing on region-specific case studies, such as using bioengineering for sustainable agriculture in Southeast Asia or designing diagnostics for neglected tropical diseases.
- Collaborative and Peer Learning: Focusing on collaboration with international institutions and industry partners to offer exposure to global engineering biology practices.
- Open Educational Resources (OER): Focusing on enhancing accessibility. Ensuring that students in developing countries, often possessing limited resources, can access up-to-date course materials and experimental protocols.

Vision and Objectives

The vision of the Engineering Biology Curriculum Framework is to empower students, researchers, and professionals in developing countries with the skills and knowledge needed to lead and innovate in the global bioeconomy. The key objectives of the framework are:

- Ensure Technical Competency: Equip trainees with appropriate skills for relevant job sectors in engineering biology including research, startups, and industry.
- Promote Regional Bioeconomy Development: Design the curriculum to be modular and adaptive to regional/national strategy.
- Bridge the Global Education: Improve access to high-quality biotechnology education through open-source resources, and enable global collaboration on curriculum design.
- Foster Multidisciplinary and Ethical Expertise: Prepare students with ethical and policy perspective alongside technical knowledge through cross-disciplinary education.
- Catalyze Innovation and Entrepreneurship: Encourage students to apply Engineering Biology principles in solving local and regional challenges, promoting innovation-driven entrepreneurship.

Thailand as a representative context to implement curriculum

Context of this Framework: Using Thailand as Model

This Curriculum Framework is designed to support countries or regions for their development of new Engineering Biology curriculum, focusing on the higher education setting. Hence, we sought to use Thailand as a center for narrative due to its unique role in the frontier research in Engineering Biology from the Low- and Middle-Income countries region with dedicated policy on building bioeconomy in the past decades. Specific points on why Thailand serves as a good model for curricula development were listed below and some should be overlapping with other countries with lower access to resources, inclusive to the Global South.

1. Thailand's Strategic Position in Southeast Asia

Thailand serves as a hub in Southeast Asia, both geographically and economically, making it a good representation region for the Engineering Biology Curriculum Framework development. As a key member of the Association of Southeast Asian Nations (ASEAN), Thailand is well-positioned to influence and collaborate with neighboring countries in advancing biotechnology and bioeconomy efforts. With a population of over 70 million and diverse manufacturing sectors from agriculture, chemical industry, to advanced healthcare services, Thailand offers a substantial market and workforce for biotechnology innovations development and deployment. The curriculum framework in context of Thailand can effectively reach and influence surrounding nations in Southeast Asia immediately. At the same time, several challenges present in the region make it appropriate for identifying pain points that can be applied to other countries of similar situation.

2. Thailand's Bioeconomy Vision and National Strategy

In the past decade, Thailand has made significant strides in bioeconomy development fitting for the context of the curriculum framework development [ref]. The government's Bio-Circular-Green (BCG) economic model was adopted as a national agenda in 2021, aims to leverage biotechnology and biomanufacturing to drive sustainable economic growth. It was later introduced to APEC community in 2022. Engineering Biology plays a crucial role in realizing the BCG vision by enabling bio-based industries, green manufacturing, and sustainable biological recycling/upcycling toward circular economy. With active route established by the local government, the curriculum framework can align with national priorities and facilitate the implementation of new curriculum.

3. Existing Scientific and Educational Infrastructure

Thailand has a well-established scientific infrastructure that can support the curriculum framework. The Thailand Synthetic Biology Consortium recently found in 2021 serves as a bridge for partnership between public-private-academia. Several universities and institutes offer life sciences and biotechnology programs, including higher education level, providing a strong foundation for initiating Engineering Biology curriculum. By leveraging these existing resources and partnership, the curriculum framework can be integrated with local/national academic programs and foster interdisciplinary collaboration among Thai institutions and in nearby countries.

4. Regional Biodiversity and Agricultural Potential

Tropical climate in Thailand provides rich biodiversity and agricultural strength, advantageous for biotechnological applications. With over 30% of its labor force in agriculture, the country presents opportunities for Engineering Biology to develop and implement technologies surrounding food and bio-based manufacturing. By including Thailand-specific case studies and challenges in the curriculum framework, students will gain hands-on experience in applying Engineering Biology to address real-world agricultural and environmental issues. It is important to note that the deployment of Engineering Biology technology in Southeast Asia is still under-implemented and less widely recognized by the general public. Therefore, advancing education and engagement with local stakeholders will greatly benefit the community beyond the borders of any individual country.

5. Thailand as a Model for Low- and Middle-Income Countries

As a middle-income country, Thailand faces challenges common to many nations in the Global South, such as resource constraints, talent retention, and scaling biotech innovations. By focusing the curriculum framework on Thailand, the program can be adapted to other countries with similar developmental trajectories. Additionally, Thailand's bioeconomy policy experience, including regulatory reforms and public-private partnerships, offers valuable insights for other countries aiming to develop their bio-innovation ecosystems. The curriculum framework, therefore, has the potential to become a replicable model for many other countries, especially in Southeast Asia.

Beyond Southeast-Asia or other Asian LMICs, it is also applicable to apply the framework developed for Thailand to that of other Global South countries in other regions. In **Chapter 4**, **Exemplary Curricula** were narrated for Uganda, representative of Africa, and Chile, representative of South America, in addition to that of Thailand. Despite being located further from each other and possessing their own unique cultures, the general aspect of the curriculum can be transferred, especially for their shared tropical climate. At the same time, unique potentials of each region can also be leveraged; accordingly, Medical hub for Thailand, Nature conservation for Uganda, and Climate focus for Chile.

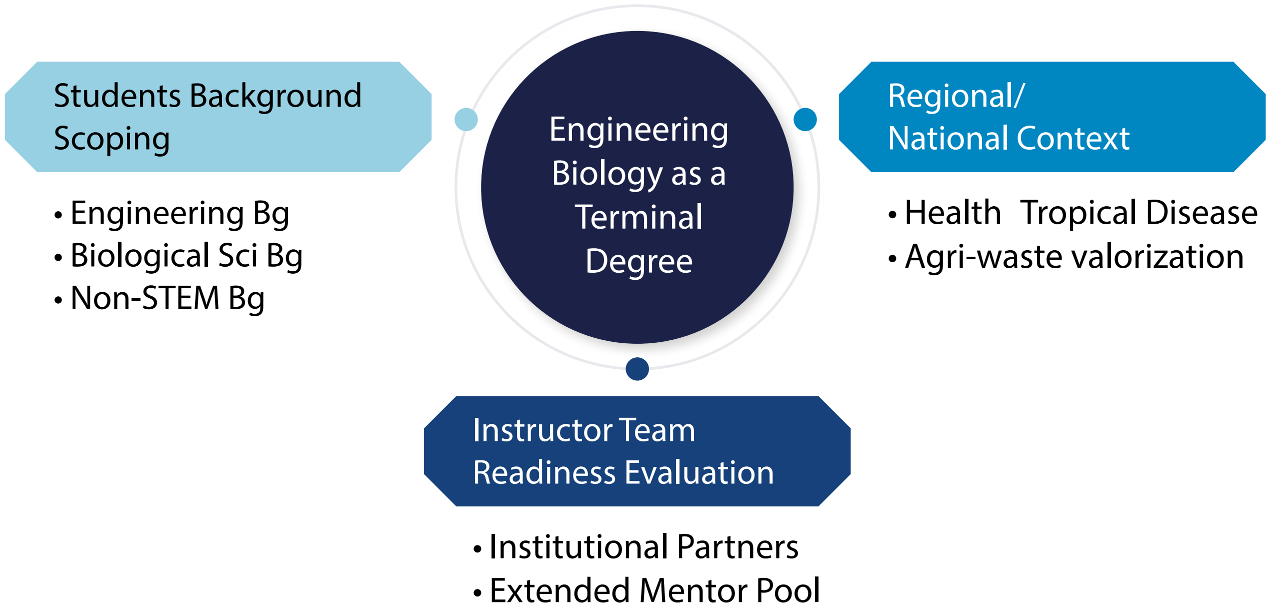
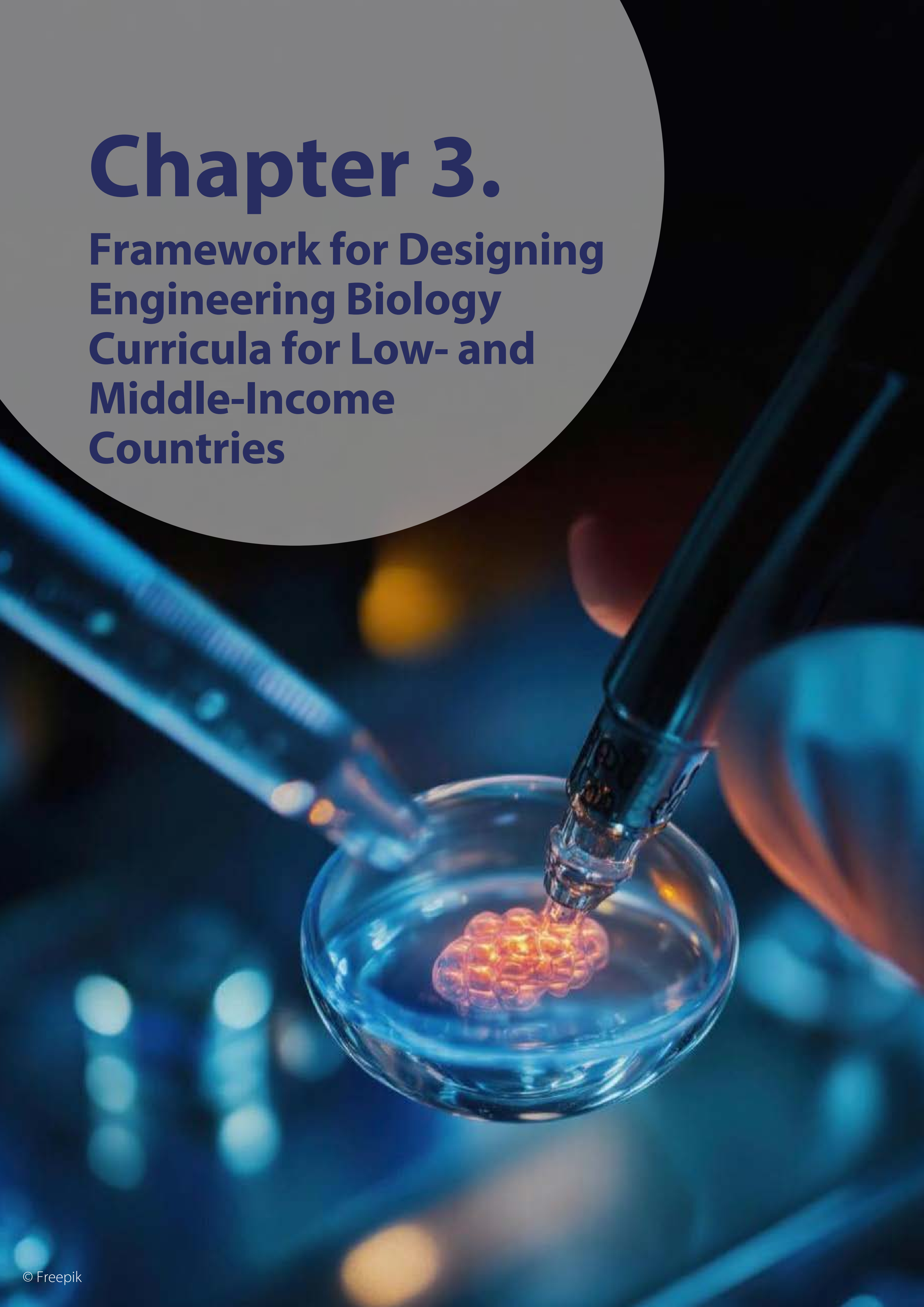


Figure 6: Guidance on Curriculum Use — Emphasizing Three Key Facto. © NXPO

Chapter 3.

Framework for Designing Engineering Biology Curricula for Low- and Middle-Income Countries



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Before Framing the Curriculum

This Engineering Biology Curriculum Framework is developed with the narrative for implementation in low- and middle-income countries (LMICs), including Thailand and other Southeast Asian (SEA) countries. Therefore, it is contextualized to address region-specific challenges and leverage local opportunities. Unlike high-income countries that have well-established bioeconomy strategies and educational infrastructures, many LMICs face limitations especially in scientific funding capacity, research infrastructure, and access to advanced biotechnological tools [Asilomar_Accessible-Biotech-Education]. Thus, designing the curriculum for these regions requires a flexible and resource-conscious approach that prioritizes accessibility, practicality, and scalability distinct to existing design frameworks in the high-resource community [EBRC-Framework, Northwestern-framework]. Thailand was chosen as a representative model for curriculum development due to its in-development scientific infrastructure and its prominent Bio-Circular-Green (BCG) economic policy. The curriculum, while tailored to Thailand, will serve as a template for other LMICs, especially those in the Global South, aiming to build workforce capacity in Engineering Biology.

- **Modular Curriculum Components:** The curriculum framework provides a curriculum outline with modules for the basic establishment of Engineering Biology program and advanced modules to allow each institute to emphasize regional/institutional strengths or address local challenges.
- **Open-Source Materials:** To maximize accessibility, the framework encourages the utilization of open-source educational resources, virtual or simple labs, and cloud-based or low-resource bioinformatics platforms, making it adaptable to resource-limited institutions.
- **Context-Specific Case Studies:** Practical examples from Thailand and neighboring LMICs are integrated to make the curriculum regionally relevant. For example, courses on industrial biotechnology will include case studies on fermentation-based production of biochemicals, while biosensing modules will address locally relevant diseases and environmental challenges.

Technically, the curriculum designer should evaluate their institutional readiness before proceeding into the extensive technical module sections (Chapter 4) so that the downstream design coincides with regional, national, and institutional narratives. In brief, the educator team is expected to craft four elements from the key sections described in Chapter 4: **Pre-requisite, Essential Modules, Special Topics,** and **Practical Trainings,** so that a **2-year training** is crafted equivalent to a master's degree. In cases where institutional expertise and resources are limited, we encourage to explore additional resources provided by open-access programs listed in the appendix or extend the invitation to other educators with appropriate expertise for each training.

Higher Education Training in Engineering Biology from Different Backgrounds

Given that the curriculum is designed for postgraduate education, the students pursuing Engineering Biology degree are likely to come from different backgrounds. Training students who practice mainly in Biological Sciences in undergraduate degree require a distinct strategy from that of students from Engineering background. Moreover, those who are not extensively trained in Engineering or Biology, e.g. Social Sciences or Management, also necessitate an alternative guideline if decide to enter the realm of engineering biology. Here, initial suggestions are articulated as a curriculum design guideline for three student groups with technical expertise in i) **Engineering**, ii) **Biology,** and iii) **Non-STEM or Interdisciplinary**. For curriculum designs toward non-master's degree education, different approaches are needed for each educational level, described in detail in Chapter 5.

To ensure equitable and effective training for all learners entering Engineering Biology at the postgraduate level, it is crucial to design curriculum pathways that acknowledge and leverage the diversity in students' prior academic training. The following guidelines outline tailored strategies for three primary student groups: those with a background in Engineering, Biology, and non-STEM or interdisciplinary fields (e.g. Social Sciences, Management, Policy). These guidelines aim to foster interdisciplinary fluency, fill foundational knowledge gaps, and cultivate cross-functional competencies essential in the field of Engineering Biology.

◆ Engineering Background

Students with an engineering background are encouraged to invest more initial training in biology focus modules, especially on experimental training. Understanding the intricate workflow, especially in that of Molecular Biology and Synthetic Biology, will ensure their ability to promptly apply engineering principles to biological systems.

Modular Emphasis:

- Introductory Modules in Biology: Especially molecular biology, microbiology, and cell biology.
- Lab Rotations or Bootcamps: Hands-on training in wet-lab methods (e.g., molecular cloning, PCR, transformation, culturing techniques).

◆ Biology Background

Students with training in natural science focus, e.g. Biology or Biochemistry, are encouraged to get started in quantitative focus modules, especially on computational modelling and hardware fabrication. Understanding the capability of in silico tools, such as predictive design and data, will expand their visions beyond conventional biological techniques.

Modular Emphasis:

- Programming and Modeling: Training in computer languages e.g. Python and introduction to computational modeling of gene circuits and metabolic networks.
- Hardware Exposure: Workshops on specialized systems such as biosensors, microfluidics, bioreactors, and automation tools.

◆ Non-STEM or Interdisciplinary Background

Students with expertise in non-STEM disciplines are encouraged to explore introductory modules from both Engineering and Biology focus, thus may require more starting time than that of students from Engineering or Biology background. At the same time, the uniqueness of their background should be emphasized with optional tracks in the responsible supermodules, e.g. biosecurity, public engagement, international policy, etc.

Modular Emphasis:

Engineering Biology introductory modules: Conceptual overviews of the central dogma, genome engineering, synthetic circuits, and other design-based workflow.

Project-Based Learning: Invest in interdisciplinary projects that can leverage their backgrounds in non-STEM techniques such as technoeconomic analysis, policy development, or public communication.

Guideline for Instructor Team Formation and Acquisition

Given that Engineering Biology is an emerging interdisciplinary field, the expertise of instructors in the school designated for the Engineering Biology curriculum development might be insufficient. Referring to various Engineering Biology adjacent programs available, only the school with strong background in both Engineering and Biology can design this curriculum using only their core instructors. However, frontier interdisciplinary programs emerged in the past decades are much less restricted to the instruction or training style. Invited lecturers from external institutions or even from industry can visit the program for a short period for a series of lectures. Therefore, in this curriculum framework, it is important to note that **not all instructors are required to be part of the degree-granting institution** while core faculty can serve as a **course director** to oversee the whole course, especially for small institutions with small numbers of instructors, such as research institutes which offer education only at the graduate level. Further details on the numbers of instructors needed are descried in Chapter 4 together with exemplary degree progression and coursework credits assignment of the curriculum.

◆ Adaptive Mentoring Processes

While graduate students are expected to join a group of researchers to explore further in their academic endeavors, this curriculum suggests that a mentoring committee comprised of instructors from diverse backgrounds is formed to assist students learning. While technical learning can be done through project-based within the research group, an interdisciplinary project should be encouraged to develop a workforce of broader basic knowledge. The mentoring committee should be comprised of at least 3 members with each mentor's expertise covering one or more fields listed: Biology, Engineering, and Non-STEM. In a case where core instructors cannot provide sufficient coverage, cross-institutional committee should be attempted in order to prepare the workforce with the breadth of Engineering Biology practice. Note that this suggestion is meant for adaptive mentoring process, it is up to institutional discretion to determine whether requirement of Engineering, Biology, and Non-STEM experts into the mentoring process is mandatory.

Framing by Regional/National Context

By framing the curriculum to align with regional/national interest and investment, the program will fit into external support through infrastructure development and economic expansion. For example, Thailand's BCG economic model aims to leverage Engineering Biology for sustainable development and industrial transformation and make Thailand a new leader for technology development and deployment altogether. Specific focus areas for Thailand include:

- **Biomanufacturing with Agricultural and Industrial Wastes:** With 30% of the Thai workforce in agriculture, the curriculum should include metabolic engineering and precision fermentation in the context of available waste material in Thailand for sustainable food production and bio-based valorization and pollutant remediation. Biotechnology for engineering climate resilience crops and novel biological pest management techniques are also of benefit for the agricultural sector.
- **Health Surveillance and Therapeutics for Tropical diseases:** Due to the unique geography of Thailand, the curriculum should include modules on synthetic biology-based diagnostics that focuses on tropical diseases over the existing ones developed for relatively cold countries in the northern hemisphere.

Also, since Thailand's higher education institutions and research centers already provide a foundation for implementing the curriculum, the framework can be integrated into existing STEM programs or established as a standalone specialization in collaboration with various institutes including:

- **Vidyasirimedhi Institute of Technology (VISTEC):** A new leading higher education institute in chemical and biochemical science and engineering in Thailand. Its flexible operation fits the immediate implementation of this curriculum for restructuring graduates to fit with emerging demand of Engineering Biology job sectors.
- **Leading Universities with existing Life Sciences Programs:** Institutions such as Chulalongkorn University, Mahidol University, Kasetsart University, King Mongkut's University of Technology, and Suranaree University of Technology can host pilot programs within their biotech track and relevant research capabilities using the suggested framework.
- **National Science and Technology Development Agency (NSTDA):** As a major player in biotechnology research and development sector, NSTDA offers opportunities for pilot partnership that can provide expanded workforce training beyond university-led initiatives.

Finally, as an extension from Thailand as a model region, the curriculum can be adapted and scaled to other Southeast Asian and LMICs with similar bioeconomy goals. Key considerations for scalability include:

- **Flexible Delivery Models:** The established curriculum is built with modular coursework allowing institutions in nearby region with similar infrastructure and context. Specific modules can be directly adopted or modified with appropriate context with institutional or regional focus.
- **Open Educational Resources (OER):** The curriculum encourages utilization of open-access materials, ensuring accessibility in resource-limited regions. Therefore, implementation of the developed curriculum can be facilitated without having to develop the whole course materials given that inter-institutions partnership within the region can be established.

Engineering Biology as a Terminal Degree or Specialized Training for an Emerging Paradigm Shift

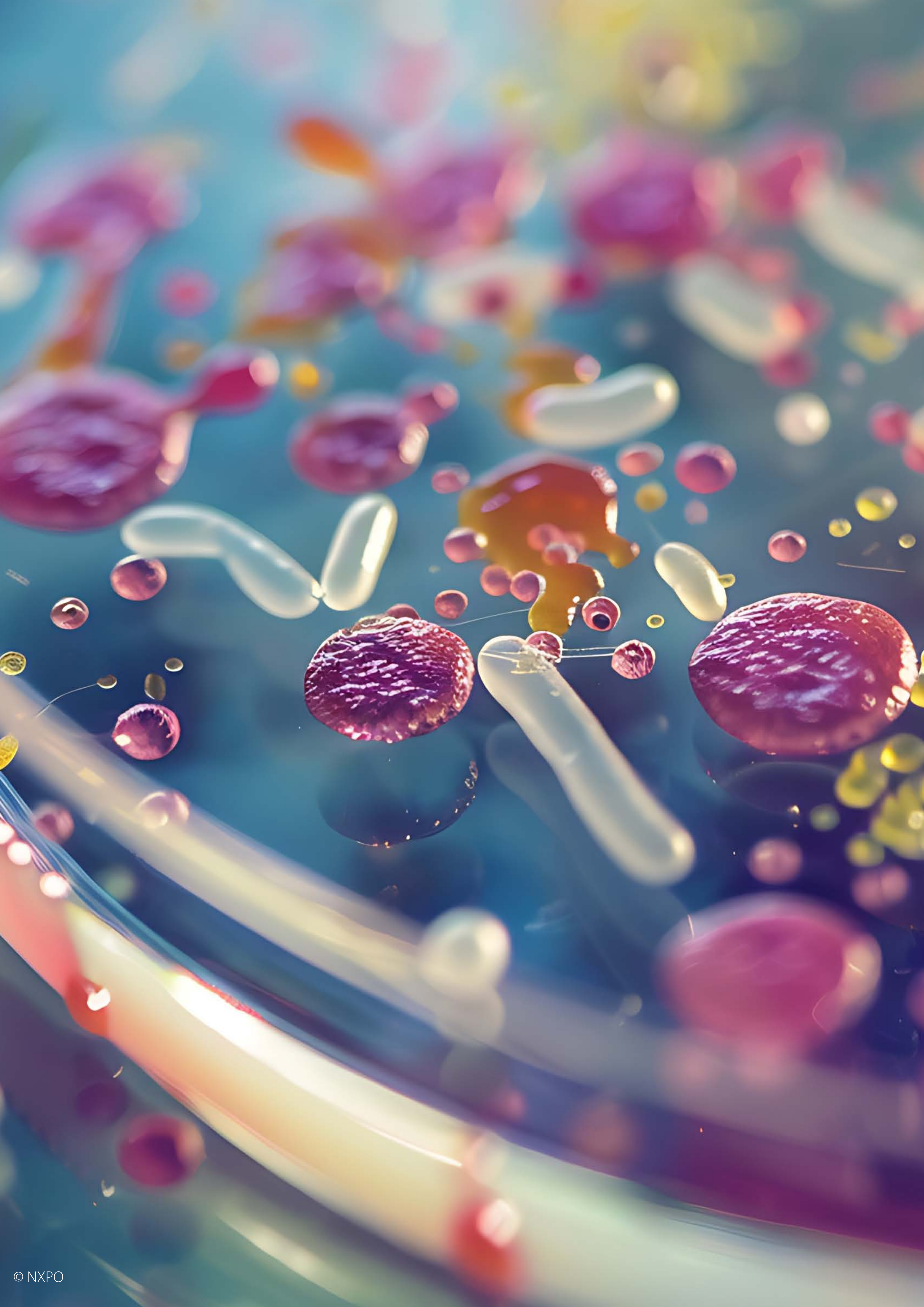
Unlike traditional life sciences degrees, Engineering Biology encompasses emerging interdisciplinary topics that blend biology, engineering, and extend to computation/automation studies to create programmable biological systems. The interdisciplinary nature of Engineering Biology is not easily confined in a single department; offering of Engineering Biology as a standalone terminal degree therefore is still limited in traditional university settings. Specialized training programs and advanced certifications are increasingly being developed as alternatives. Similar to the rise of Data Science, Artificial Intelligence (AI), and Software Engineering degrees, Engineering Biology is positioned to become a critical workforce qualification in the near future, driven by rapid expansion of bioeconomy across the globe.

In the context of low- and middle-income countries, an Engineering Biology curriculum also has the potential to function as a specialized vocational or technical degree aimed at rapidly upskilling the workforce already equipped with relevant engineering or biology background. Key features include:

- **Flexible Format as Modules:** To accommodate diverse educational systems, the curriculum can be delivered as standalone modules, allowing institutions to integrate it into existing biosciences or biotechnology programs, or use these modules to create a new program if preferred to.
- **Interdisciplinary Competency:** The curriculum will emphasize interdisciplinary fluency so that students from different backgrounds can be trained in Engineering Biology in the context of their expertise. This approach can adopt existed strategy used in Data Science and Artificial Intelligence trainings to that of Engineering and Biology education. [Cite UNESCO Framework on AI Teaching]
- **Hands-On Technical Skills:** The plausible routes on practical lab skills, biomanufacturing techniques, and biological circuit design will be included so that students can be trained toward appropriate job roles post-training.

As for the upcoming expansion of bioeconomy so trainee's employability is promoted together with innovation-oriented training, the paradigm shifts can be included in the new curriculum design in many ways including:

- **Bio- and Green Industry Transformation:** Equipping students with skills in various biomanufacturing approaches from metabolic engineering, precision fermentation, and cell-free systems to support sustainable industrial development.
- **Advancement in Healthcare:** Preparing students for familiarity in engineering biology-based diagnostics, personalized medicine, and emerging genetic-based therapeutics that will bring about future healthcare innovations.
- **Tech-Bio Convergence:** Fostering interdisciplinary expertise especially in the intersection of computer and biotechnology. These two areas are rapidly evolving and the demands for workforce with convergence expertise in both fields.



Chapter 4.

Technical Framing for Graduate Degree in Engineering Biology

Using the Technical Framework

This Engineering Biology Curriculum Framework is organized into a modular system with a repertoire of **modules** that can be used in curriculum design. This approach allows flexible implementation based on different backgrounds. Adaptation, expansion, or reconstruction of existing modules can be framed based on available resources and policy guidelines depending on regional, national, and institutional contexts.

Modular Structure of the Engineering Biology Framework

The framework is divided into knowledge-based modules and practical modules. The knowledge-based modules can be organized into a pre-requisite course, essential modules and special topic modules, ensuring a comprehensive yet adaptable curriculum:

- **Pre-requisite:** Introduce the idea of Engineering Biology and knowledge from different traditional disciplines required for further in-depth learning in the following modules.
- **Essential Modules:** Cover fundamental principles of Engineering Biology, including molecular biology, synthetic biology, and computational biology. These modules form the essential foundation for trainees taking the Engineering Biology curriculum.
- **Special Topics Modules:** Allow for specialized learning in areas that require specific expertise such as genetic code expansion, engineered living materials, and microbiome engineering. Institutions or programs can select these based on national, regional, or institutional priorities and expertise.
- **Practical Modules:** Encourages hands-on experience driven by research questions, industry collaborations, and real-world problem-solving.

It is important to note that module is not equivalent of a course but is intended to be a modular parts that can be assembled into a suitable course for each institution.

--- a conceptual figure describing the utilization of module into course ---

Implementation Guidelines

To ensure effective adoption, institutes should include the pre-requisite class if the student background is diverse, 3-6 essential classes based on academic year organization to cover basic Engineering Biology knowledge, and an appropriate number of essential or special topics courses depending on regional regulation on course credit requirement. The pre-requisite is undeniably important and should be provided as the first course to prepare trainees with the basic concept for studying other courses. If the curriculum planning is tight or if the curriculum is designed for specialized training with comparable students' background, the introductory module can be assembled into the core courses instead. Essential modules are categorized into **Engineering, Biology, Frontier-Technology**, and **Responsibility** tracks with at least one class (for semester system) or two classes (for quarter system) of each track constructed from essential modules. Finally, the rest of the graduate program requirement can be filled with courses assembled from essential and special topics modules and other non-Engineering Biology coursework with relevant national or regional standards.

See design prompts in this chapter as a guideline followed by an exemplary curriculum for a 2-year master's program in LMICs.

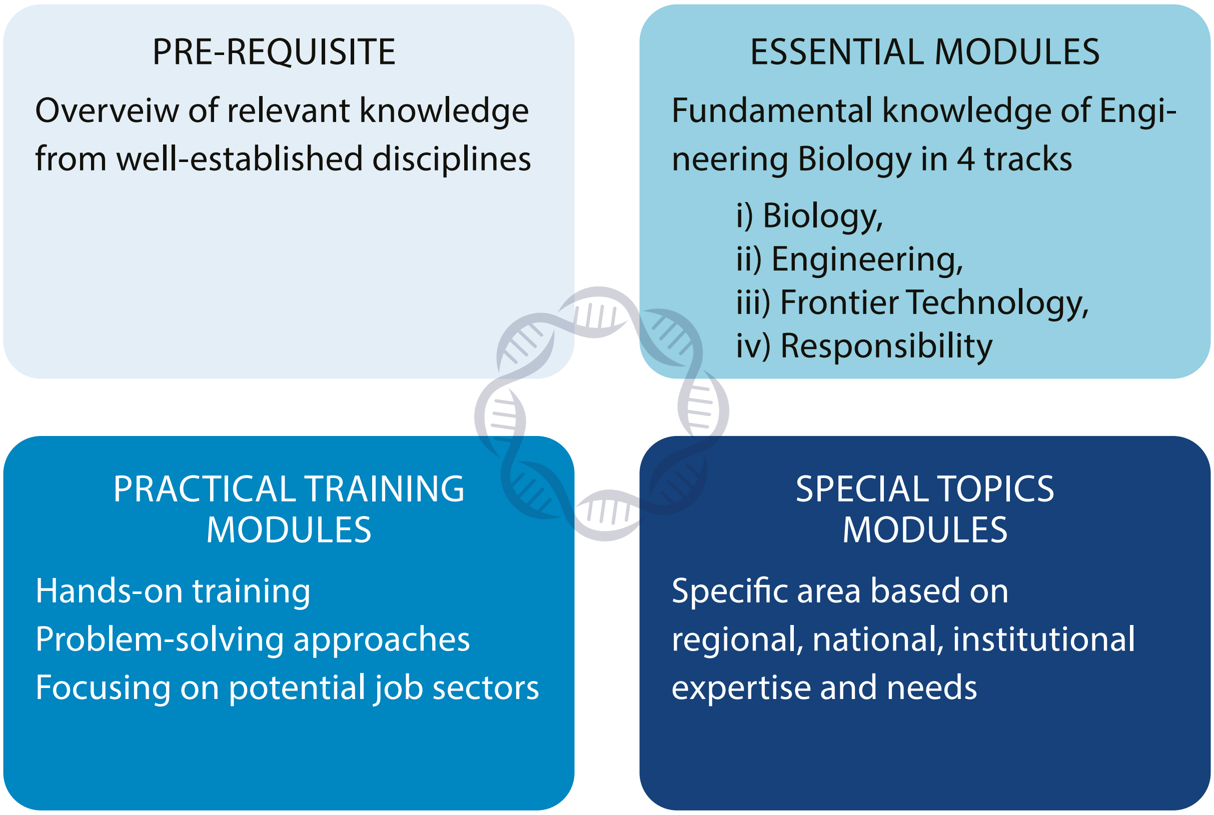


Figure 7: Curriculum Structure for Engineering Biology This Figure presents the core structure of an Engineering Biology curriculum, including: (i) prerequisite courses, (ii) essential modules and four specialization tracks, (iii) special topics with illustrative examples, and (iv) practical modules. Draft for review; final design pending revision. © NXPO

◆ Degree Progression for the Representative Master's Program

To exemplify the structure of the representative Master's program in Engineering Biology, we're proposing two common structures commonly used in different academic settings: i) semester system with two major semesters plus an optional summer training or ii) quarter systems with three major quarters plus an optional summer quarter. The progression of coursework will follow the CORE ❯ SELECTIVIE ❯ PRACTICAL crafted based on modules provided in the following modules collection.

◆ Representative Semester-style Curriculum Framing

For the 2-year master's program, the two-semester-based curriculum usually requires 30-36 credits (24-30 credits for coursework and 6-12 for thesis where 1 credit equates to approximately 3-hour learning per week), with roughly 10-15 courses provided as options. The first year should generally emphasize lecture-based training to prompt students from different backgrounds with the core concept of Engineering Biology. A seminar-based course is encouraged to keep students up to date with recent developments in the field (See Exemplary Courses section). Students are expected to use summer period to work on practical training, either toward their research project at the program-administering institution or to conduct internship at partnering companies.

Year 1			Year 2		
Fall 1	**Spring 1**	**Summer 1**	**Fall 2**	**Spring 2**	**Summer 2**
2 CORE [1 ELECTIVE]	1 CORE 2-3 ELECTIVE	[PRACTICAL] [ELECTIVE]	1-2 ELECTIVE PRACTICAL	[1 ELECTIVE] PRACTICAL	PRACTICAL
10 Credits	7-10 Credits	Optional	8-10 Credits	5-9 Credits	Optional

Degree Timeline						
	Fall 1	**Spring 1**	**Summer 1**	**Fall 2**	**Spring 2**	**Summer 2**
CORE						
ELECTIVE						
PRACTICAL						

Courses	Required,	Suggested

◆ Representative Quarter-style Curriculum Framing

This section is equivalent to the Semester-based degree progression described above but intended to provide inclusive planning for institutions which operate in a different academic year, such as that of quarter or trimester systems. Since most of the formal education months are divided into 3 quarters instead of 2 semesters, the number of credits may increase to that of 45-54 Credits. Note that credits per hour allocation might differ between regions and should be adjusted accordingly.

Year 1				Year 2			
Fall 1	**Winter 1**	**Spring 1**	**Summer 2**	**Fall 2**	**Winter 2**	**Spring 2**	**Summer 2**
2 CORE [1 ELECTIVE]	1 CORE 2 ELECTIVE	1 CORE 2 ELECTIVE	[PRACTICAL]	2-3 ELECTIVE	1-2 ELECTIVE PRACTICAL	[1 ELECTIVE] PRACTICAL	PRACTICAL
10 Credits	8-10 Credits	7-10 Credits	Optional	7-10 Credits	7-10 Credits	6-8 Credits	Optional

Degree Timeline								
	Fall 1	**Winter 1**	**Spring 1**	**Summer 1**	**Fall 2**	**Winter 2**	**Spring 2**	**Summer 2**
CORE								
ELECTIVE								
PRACTICAL								

Courses	Required,	Suggested

◆ Instructors team formation and outsourcing approach

Since at least 12 courses (2 CORE and >10 ELECTIVE) are required, it is recommended that courses were divided among instructors within the institute or through outsourcing from other schools or internationally. To provide options to students with diverse research practices during their practical training, the curriculum should host at least 5 research groups of distinct interests, led by PhD level researchers. It is also recommended that elective courses were designed based on expertise of faculty members, assuming each of them can provide 1-2 elective courses, that should account to 5-8 courses out of 10-15. In the case that the institute's human resources are limited, it is recommended **Teaching-focus instructors**, who teach at least 3-4 courses every academic year, can replace **Research-focus faculty members**, who are expected to teach 1-2 courses annually.

For emerging topics beyond faculty members' expertise (especially for a small school), it is recommended that the team seek external support either from other schools within the same institute or from other universities, either locally or internationally. The faculty member (or teaching instructor) should serve as a course coordinator and co-instruct part of the course while inviting experts in the field to provide insightful lectures to the students. For an emerging field like Engineering Biology, most of the rich expertise lies in the Global North, The US, Europe, and some Asian countries. Inviting leaders in the field to share their scientific expertise is the best approach to grow the community into the right direction toward the global standard.

Introductory course prior to the main curriculum

Description and Objectives

This section is oriented as an introductory preparation for students prior to starting the Essential Topics of Engineering Biology or to conducting Engineering Biology research. The course is divided into two key concepts, Historical and Ethical perspectives, and two sub-modules, a review of multidisciplinary knowledge and a quick overview of Engineering Biology research. The topics listed below are introductory parts which can be emphasized later in the specific class composed of essential and special topic modules. Depending on the focus of the curriculum, regional context, and instructor's expertise, topics in sub-module can be expanded or omitted as appropriate. These introductory modules should be crafted into 2 required classes or a single required class plus 2 distinct classes where students have to choose one according to their concentration of background.

◆ History and Philosophy of Engineering Biology Research

Engineering Biology was developed with various breakthroughs in biotechnological research. Understanding the historical context and common philosophy of the field can facilitate students learning and awareness.

- Engineering Biology through Science History lens
- Biotechnological breakthrough works and events
- Philosophy of Engineering Biology and its distinction from other fields

◆ Ethical and Societal Perspectives in Engineering Biology

Ethics in the lens of Engineering Biology and perception from public

- Biosafety and Biocontainment of Engineered Organism
- Biosecurity of de novo DNA
- Public Perception and Communication

Sub-Module 1:

Review of Multiple Disciplines involved in Engineering Biology

This sub-module will provide an overview of other disciplines, emphasizing their relevance to Engineering Biology.

◆ Molecular Biology Overview

Understanding Molecular Biology is important prior to learning how to engineer the living biological systems. This overview serves as an introduction to the flow of biomolecular information and function.

- Central Dogma of Molecular Biology
- Gene Regulation: Transcriptional, Translational, and Post-transcriptional Controls
- Recombinant DNAs: DNA Synthesis and Engineering DNA Vectors

Basics in Biochemistry

All biological functions were driven by chemical reactions or interactions. This overview depicts biochemical phenomena commonly found in living organisms.

- Intracellular Chemical Reactions and Metabolic Pathways
- Biomolecules: Nucleic acids, Proteins, Carbohydrates, and Lipids
- Enzymes and Reaction Engineering
  - Basic enzymology and steady-state kinetics
  - Enzyme Engineering at Protein Sequence
  - Reaction Engineering based on Concentrations of each Component

Basics in Chemical Biology

Chemical modifications of biomolecules are crucial techniques in Engineering Biology. This section will showcase longstanding examples.

- Chemical genetics
- Bio-orthogonal and Click Chemistry
- Chemical tools to probe biomolecules not directly encoded from the genome

Synthetic Biology

Synthetic Biology is the closest sibling field to Engineering Biology. Every aspect of this field will be considered a subset of Engineering Biology umbrella.

- DNA-based Genetic Circuitry
  - Assembly of DNA parts
- RNA-based Technology
  - RNA-guided CRISPR Technology
- Protein Engineering and Design
- New-to-Nature Biotechnology
- Design-Build-Test-Learn process

Biomolecular Tools for Genetic Engineering

Genetic engineering tools are hallmarks of methodologies for Engineering Biology techniques.

- Genome Engineering
  - Knock-out, Knock-in
  - Dynamic Gene Regulation
- Existing Biomolecular Pathways
- Metabolic Pathway Assembly, Design, and Engineering

Engineering Biochemical Reactions

This section introduces a mathematical modelling aspect into Engineering Biology

- Metabolic Flux Analysis and Optimization
- Rational Design of Biological Systems
  - RNA Design
  - Protein Design
- Directed Evolution of Biological Systems
  - Protein Evolution
  - Organismic Evolution

Hosts Engineering

Describe possible routes and common trends in genetic engineering of living systems

- Microbial Diversity and Engineering Platform
  - Model Bacteria Engineering (E. coli)
  - Yeast Engineering (S. cerevisiae)
  - Non-model Bacteria Engineering
  - Microbial Community
- Higher Eukaryotes Engineering
  - Cell Biology and Tissue Engineering
  - Model Eukaryotes
    - Biomedical Engineering
    - Plants/Crops Engineering

◆ Multicellular Consortia Engineering

An extension of host engineering with support from other disciplines

- Microbiome Science and Engineering
  - What is Microbiome?
  - Engineering Microbiome
- Cell-to-cell signaling
  - Bacterial signaling
  - Eukaryote signaling
- Host-Microbe Interactions
- Population Biology
  - Mathematical Model Approach
- Division of Labor and Design of Multi-Organism Consortia

Sub-Module 2:

Overview and Scope of Engineering Biology

Overview and scope of Engineering Biology versus their Precursors

◆ Data Science for Engineering Biology

Overview of data organization and analysis in Engineering Biology

- Tools in Molecular Biology
  - Data Conversion from DNA to Proteins
- Data Processing and Organization
- Machine Learning and AI in Biology
  - The Ideology of Digital Twins
- Automation in Engineering Biology

◆ Experimental Methods in Engineering Biology

Depiction of common experimental protocols necessary to Engineering Biology research

- DNA Read: Sequencing Technology
  - Sanger sequencing
  - Next-generation Sequencing
    - Short- and Long-read sequencing
- DNA Write: Synthesis and Assembly
  - Oligonucleotide synthesis
  - Large DNA synthesis
  - Synthesis of DNA library
- RNA Analysis
- Protein Characterization
- Metabolites Analysis
- Omics: System Biology approach of biological data

◆ Frontier Applications for Engineering Biology

Outstanding and timely examples in the field

- Energy, Commodity Chemicals, and Sustainability
  - Green Biosynthesis
  - Circular Economy
- Food and Agriculture
  - Crops Engineering
  - Cultivated Meat
- Healthcare
  - Novel Biologics
    - De novo Proteins and Antibody
    - RNA therapeutics
  - Living Therapeutics
    - Chimeric Antigen Receptor (CAR) T-Cell
    - Engineered Probiotics

Knowledge-based Modules

This section serves as a collection of Engineering Biology knowledge repertoire organized into different topics as "Modules" which can be i) used to construct a new course as is; ii) expanded into detailed coursework; or iii) mixed into a new course based on institutional calendar and instructors' expertise. A new Engineering Biology curriculum can be designed for either 2-semester or 3-quarter systems using provided modules in this knowledge-based technical section.

To be cognizant of diverse school sizes across multinational settings and broad training backgrounds of instructors within an umbrella discipline like Engineering Biology, the modules set-up serves as a malleable framework for optimization. The topic-based module guidelines are modular and independent of credit systems necessary for degree requirements. Any institution adopting this guideline for designing a new higher education curriculum will be equipped with technical guidelines while free of bureaucratic regulation which is oftentimes difficult to port from one region/country to another.

Essential Topics for Engineering Biology Curriculum

Essential Topics are key modules necessary for understanding the development of novel Engineering Biology technologies. Each module will consist of multiple topics to be considered for course design. Here, diverse topics are categorized into **Responsibility, Biology, Engineering**, and Frontier-Technology supermodules. For an effective curriculum, 50% of essential topics modules—or their subsets—are encouraged to be provided within the graduate degree course selections. At least two essential topics of each supermodule should be provided as a core course or integrated into other courses to ensure students' broad understanding of Engineering Biology concepts, Frontier of technological advancement, and Responsible research conduct post-graduation. Particularly for the Responsibility supermodule, this curriculum framework encourages that selected modules of this section are incorporated into every course in the curriculum either as a standalone lecture, accompanying case studies, or as reading materials alongside the core technical contents.

A list of Essential Topics modules is outlined below with categorization into **Responsibility, Biology, Engineering**, and **Frontier-Technology** supermodules. Suggested contents of each module to be covered are provided which can be used as a starting point for instructors to design course syllabi.

It is important that incorporation of computational approach into each module is encouraged especially when they can be linked to Practical Modules. The modelling section, Design-Build-Test-Learn concept, and AI/ML focus modules are also increasingly accessible with emergence of powerful small computers and cloud computing systems. On the other hand, this strategy is especially useful in the low-resource settings to bypass some existing infrastructure barriers. For instance, SynBio4ALL Africa has been operating an online lecture plus pilot experimental process where significant portion of participants use mobile phones throughout the course, avoiding the necessity of bigger personal computers and scientific apparatus.

Note that some suggested contents may require extensive resources inappropriate to that of LMICs setting. Sections with expensive set-up will be marked as "High-Resource". Accordingly, content with outstanding applications in the LMICs will be marked as "Low-Resource".

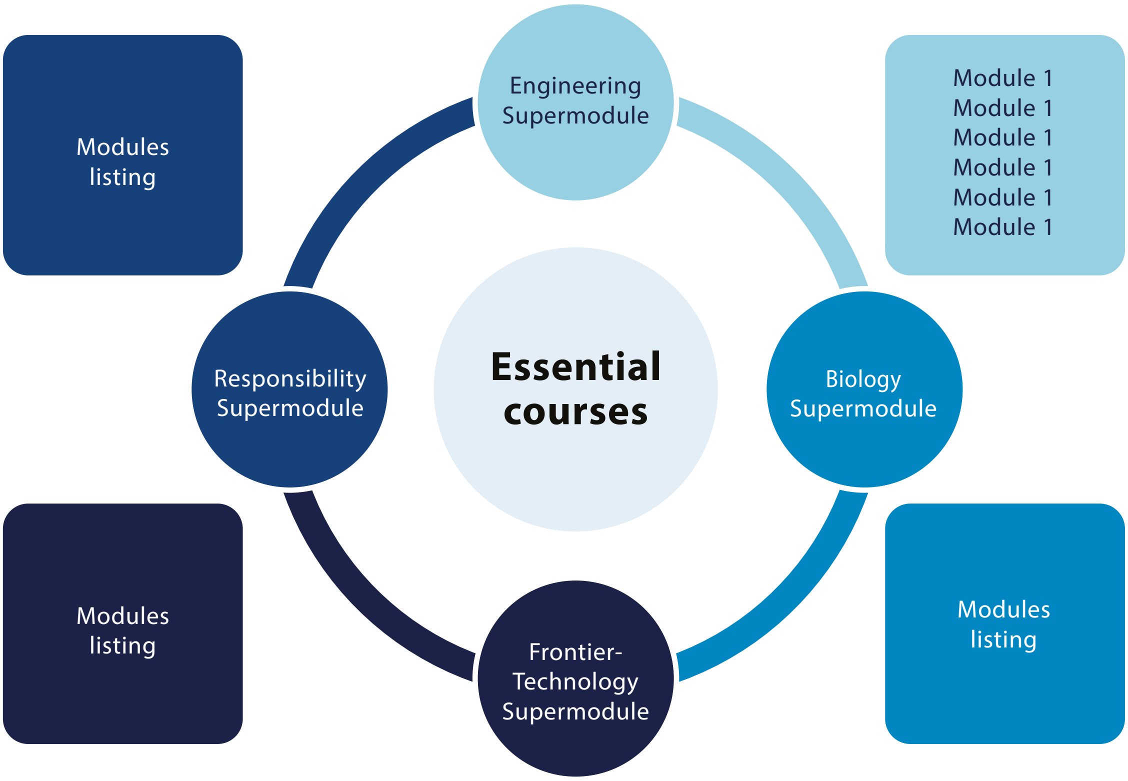


Figure 8: The following list of modules is intended to be integrated into a single illustrative figure. © NXPO

Responsibility Supermodule

- Ethical, Legal, and Societal Issues (ELSI)
- Biosafety and biosecurity
- Responsible Design and Research Practices
- Business and Entrepreneurship in Engineering Biology
- International Regulatory Framework of Biotechnology
- Technology Development for Low-Resource Environments

Biology Supermodule

- Molecular Biology and Genetics
- Systems Biology and Omics Analysis
- Holistic Approach to Synthetic Biology
- Biochemistry and Chemical Biology
- Microbiology and Cell Biology
- Biodiversity, Ecology, and Evolution

Engineering Supermodule

- Nucleic Acids Engineering
- Protein Engineering
- Enzymes and Biochemical Reaction Engineering
- Metabolic Pathway Engineering
- Organismic Engineering
- Bioprocess Design and Engineering

Frontier-Technology Supermodule

- Sequencing Technologies
- Separations and Analytical Methods
- Bioinformatics and Data Science
- System Biological Modelling
- Artificial Intelligence and Machine Learning (AI/ML)
- High-throughput Methodology, Automation, and Biofoundry

Responsibility Supermodule

The Responsible supermodule is essential for ensuring that technological advancements in synthetic biology, bioengineering, and related fields are developed, implemented, and used ethically, safely, and equitably. There are 4 modules listed in this supermodule of which can be used independently to craft an individual course or combined all of them into a single course. While this module is important and deserves its own supermodule allocation, the responsible research practice should be incorporated into all courses regardless of the key module being used for content building.

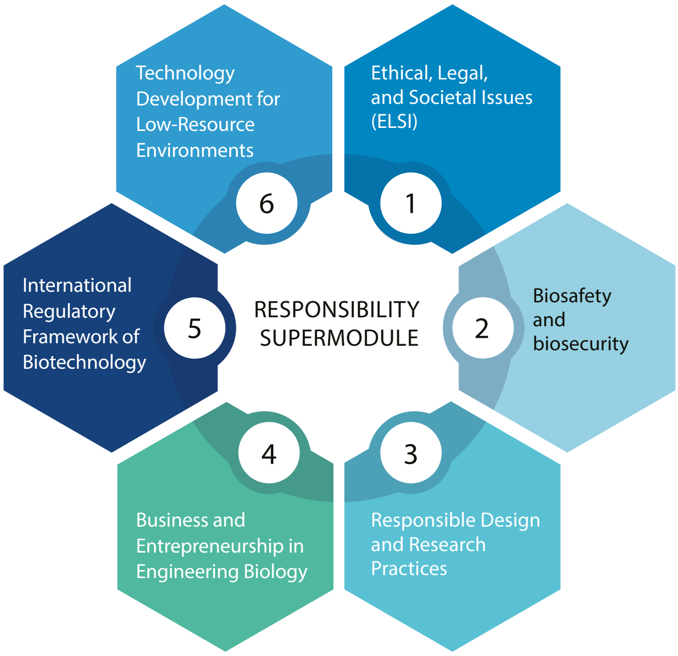


Figure 9: Show an illustration of each supermodule. Different colors will be used for each supermodule. © NXPO

◆ Ethical, Legal, and Societal Issues (ELSI)

This module is intended for teaching graduate students in Engineering Biology on a non-technical side of the emerging technology involving Ethical, Legal, and Societal Issues (ELSI). Upon finishing this course, students are expected to be capable of evaluating the ELSI angle of Engineering Biology research and communicate the concern to the broader public. Such information on international regulations and standards can be matched to publications from global-facing organizations e.g. CBD Technical Series [2022 report] and EBRC Roadmap on Technical Standards [2024 Technical Roadmap].

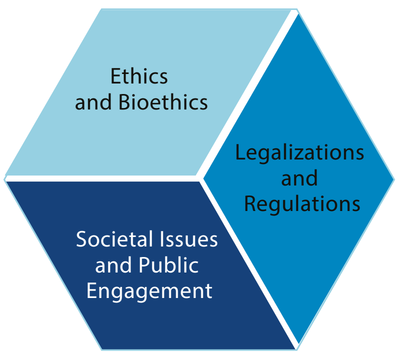


Figure 10: Each module is represented as a hexagon, subdivided into sections corresponding to key topics. Each segment of the hexagon is labeled with a topic title to illustrate the internal structure of the module. © NXPO

Sub-Module 1:

Ethics and Bioethics

Ethical considerations in Engineering Biology and relevant topics

Principle of Ethics and Bioethics

Introduction of Ethics/Bioethics in the context of Engineering Biology.

- Definition of ethics
- Framework for ethical analysis
- Ethical dilemma in Engineering Biology
- Beneficence and non-maleficence
- History of Bioethics overview of case studies

Biosafety and Biosecurity

Discussion surrounding safety and security in the biological technologies and products

- Dual-use of biological research
- Malice Analysis
- Biological Containment

Sub-Module 2:

Legalizations and Regulations

Introduction and case studies on legal and regulatory processes in engineering biology

Intellectual Property in Biotechnology

What is the definition of intellectual property in engineered biological systems

- Patentability in Biological Research
- Commercialization workflow

Case study on commercialized Engineering Biology

Case studies in commercialized products with relevance in Engineering Biology disciplines

- CRISPR IP dispute
- Gene therapy
- Engineered Crop Seeds

Regulatory Frameworks

Examples of regulatory frameworks at international and regional levels

- International Regulations
  - Cartagena Protocol, Nagoya Protocol, etc.
- Local/Regional Regulations
  - US, EU, etc.
- Different regulatory sections
  - Food
  - Drugs
  - Agriculture
  - Industrial biochemicals

Sub-Module 3:

Societal Issues and Public Engagement

Background on public engagement and societal aspects of engineering biology

Public Perception and Communication

Scientific communication and media utilization involving biotechnological research

- Communicating science to public audience
- Addressing positive impact versus risk management
- Misinformation versus Disinformation

Accessibility and Equity in Engineering Biology

Discussion surrounding technological access and transfer between communities

- Open Science and Knowledge Sharing
- Implications of Engineering Biology in Underserved Communities
- International and Regional Barriers in Biological Research

Future Trends and Emerging Challenges in Engineering Biology

Prospective trends and emerging applications of engineering biology technologies

- Emerging global regulation as a single framework
- Adaptation to rapid development in Engineering Biology

- Environmental impact of Engineering Biology deployment
- Diversity conservation versus novel strains development
- Special Topics: Biology in Space Exploration

◆ Biosafety and biosecurity

Biosafety and biosecurity in engineering biology

Teach students the importance of having effective regulatory and technological frameworks to manage biosafety, biosecurity, and ethical risks in engineering biology

- Definition and Distinction of biosafety and biosecurity
- Concerns relating to biosafety and biosecurity risks of engineering biology
- History of biosafety and biosecurity in research and industry
- Genetic safeguard measures
- Examples of regulations and practices in the Global North vs the Global South

Regulatory Frameworks and International Standards

Familiarize students with global biosafety and biosecurity regulations

- International guidelines: WHO, FAO, and the Cartagena Protocol
- National biosafety laws and regulations (e.g., NIH, CDC, FDA, and OSHA)
- Institutional biosafety committees (IBCs) and their role in research oversight
- Reviewing risk assessments, containment protocols, and safety procedures

Laboratory and Environmental Biosafety and Containment Strategy

Teach students about laboratory-level biosafety procedures

- Designing biosafe laboratory spaces and protocols (Biosafety Levels 1–4)
- Handling genetically modified organisms and containment strategies
- Personal protective equipment (PPE) and safety equipment in synthetic biology labs
- Use of biosafety cabinets, biological waste management, and decontamination procedures
- Consideration for engineering biology deployments beyond biocontainment

◆ Responsible Design and Research Practices

This module focuses on ethical decision-making, responsible innovation, and the implementation of best practices throughout the lifecycle of biological engineering projects. Topics in this module ensure that translational impact proceeds alongside long-term sustainability and public trust. This module complements existing frameworks like Responsible Research and Innovation (RRI) from European Union [EU] and other leading organizations [UKRI].

Introduction to Responsible Research Practices

Define responsible research and the ethical responsibilities of scientists

- The ethical obligations of researchers in synthetic biology and bioengineering
- Research integrity: avoiding misconduct, plagiarism, and falsification of data
- Responsible conduct of research (RCR) and research ethics education
- Environmental and social considerations in biotechnological advancements

Environmental Impact and Sustainability

Teach students to assess the environmental sustainability of engineered systems

- Evaluating ecological risks: impact on biodiversity, ecosystems, and natural resources
- Life cycle assessment (LCA) and sustainability metrics for biotechnology
- Designing for sustainability in metabolic engineering and biomanufacturing
- Circular bioeconomy and waste reduction in synthetic biology

Equity, Access, and Inclusivity

Focus on promoting equity and inclusivity in biotechnology

- Ensuring equitable access to synthetic biology innovations globally
- Addressing health disparities and the social implications of biotechnology
- Promoting diversity and inclusion in research and development teams

- Engaging marginalized communities in the decision-making process

Public and Stakeholder Engagement

Teach effective communication of responsible research to the public

- Communicating risks, benefits, and ethical considerations of synthetic biology
- Engaging with policymakers, scientists, and the public in dialogue about emerging technologies
- Building trust through transparency and responsible governance
- Understanding the role of public perception in shaping regulatory policies

Business and Entrepreneurship in Engineering Biology

This module introduces students to the intersection of synthetic biology and business, providing foundational knowledge and practical tools for entrepreneurial thinking in Engineering Biology. Upon completing this course, students will be able to evaluate market opportunities, navigate business models, understand startup ecosystems, and develop translational strategies for engineered biological technologies. Examples and case studies can be drawn from startups in the field.

Business Models in Biotech Industry and Entrepreneurial Mindset

Provide an overview of Business Industry in Biotech landscape

- Overview of business models: B2B, platform, service, licensing
- Intellectual Property transfer from institute/university to corporate
- Comparing hardware- and software-driven biotech models
- Lean startup principles and the iterative approach
- Identifying market gaps in Engineering Biology
- Case studies and trajectories of notable synthetic biology startups/companies e.g. Ginkgo Bioworks, Twist Bioscience, Benchling

Funding Landscape and Financial Strategy for Biotech Industry

Describe the distinct nature of Biotechnology Industry from that of other business environment

- Securing financial support for scaling bio-innovations
- Government grants applications
- Venture capital in Biotechnology
- Public-private partnerships

Product Development and Go-to-Market Strategy

Explore the processes involved in developing engineered biology products with real-world applications, and how to navigate product-market fit and regulatory alignment.

- Translating research into market-ready products based on timelines and milestones
- Aligning product development with regulatory requirements (examples from FDA and USDA)
- Customer discovery and market validation
- Supply chain design, manufacturing scale-up, and quality assurance
- Strategic positioning through partnership with biotech hubs/clusters e.g. Boston, Bay Area, London, Shenzhen

International Regulatory Framework of Biotechnology

This module provides students with a global view of biotechnology regulations, focusing on legalization, policy landscapes, and governance models related to products or processes in Engineering Biology. Students will learn how to interpret regulatory requirements across different jurisdictions, prepare for regulatory approval, and engage with governance bodies when necessary. Notable materials include the Cartagena [ref-CBD] and Nagoya Protocols [ref-CBD], WHO frameworks [WHO-Recommendations], and OECD reports.

Global Regulatory Systems and Organizations

Provide an overview of key international treaties and organizations relevant to Engineering Biology landscape.

- International Organizations: Convention on Biological Diversity (CBD), World Health Organization (WHO), etc.

- Multilateral Agreements and Protocols
  - Cartagena Protocol on Biosafety
  - Nagoya Protocol on Access and Benefit-Sharing
  - WHO Guidance on genome editing and biosurveillance
  - Notes from UNESCO International Bioethics Committee [ref]
- Notable Regional and National regulatory organizations
  - United States: USDA, FDA, EPA
  - European Unions: EFSA and EMA
  - Asia: Notable regulations from China, Japan, India, etc.
    - China's biosecurity laws
    - Korean Synthetic Biology Act

Cross-sectoral Regulatory Workflow

Describe several examples which require unique regulatory workflow due to cross-discipline nature of the innovations/systems.

- In-field Agricultural biotechnology
- Medical/therapeutic products
- Environmental biotechnology for conservation
- Gene drives for disease control and prevention

Challenges in International Regulation in Practice

Navigating regulatory frameworks in using real-world implemented projects as case studies

- Deploying genetically engineered products with transboundary potential
- Advance Cell Therapy regulations in limited resource environments, e.g. LMICs
- Engineered Coral for Climate Resilience and potential deployment in ocean environments
- Mosquito Gene Drive Trials for Malaria prevention

Technology Development for Low-Resource Environments

This module focuses on designing and developing biotechnological solutions tailored to low-resource and underserved environments.

Introduction to Low-resource Environments

Provide an overview of the challenges and opportunities in low-resource settings

- Defining low-resource environments: underdeveloped, remote, and disaster-stricken regions
- Challenges in infrastructure, access to resources, and affordability
- Opportunities for technological development in these settings
- The importance of culturally and locally relevant solutions

Designing for Accessibility and Affordability

Teach students to design biotechnology systems that are accessible and affordable

- Frugal Sciences for low-resource technology
- Approaches to reducing costs in biotechnology development (materials, processes, labor)
- Open-source and low-cost biotechnology solutions
- Low-cost diagnostics, vaccines, and therapeutics for resource-limited areas
- Designing for scalability and adaptability in diverse environments

Fieldwork and Adaptation of Technologies

Explore the adaptation of biotechnologies for field applications in low-resource settings

- Techniques for field testing and prototyping in developing regions
- Challenges in maintaining and scaling biotechnologies in remote areas
- Collaborating with local communities to develop appropriate solutions
- Examples of successful field applications in healthcare, agriculture, and energy

Enabling technology resources for the Global South

Provide tools which improve accessibility to enabling technologies for Engineering Biology to researchers in the Global South

- Importance in establishing enabling technology capability in the Global South; highlight globally important research questions in the Global South
- Open-source designs for lab equipment
- 3D-printing as enabling technology for experimental science
- Initiatives toward Findability, accessibility, interoperability, and reusability (FAIR) of data
- Open Science practices and infrastructures
- Open Science initiatives in the Global South (Africa, Latin America, South/Southeast Asia)

Legal and Commercial Strategy for LMICs

Develop legal, regulatory, and commercialization strategies that enable equitable participation of low- and middle-income countries (LMICs) in the global bioeconomy

- Importance of locally relevant regulatory frameworks for biotechnology and engineering biology in LMICs
- Intellectual property (IP) strategies, including open licensing, patent pools, and technology transfer mechanisms
- Regulatory capacity building for biosafety, biosecurity, and clinical translation
- Public–private partnerships, international collaboration, and innovation ecosystems to support biotech startups in LMICs
- Market access, affordability, and equitable benefit-sharing frameworks (Nagoya protocol)
- Case studies of successful biotech commercialization and policy frameworks in LMICs (Africa, Latin America, South/Southeast Asia)

Biology Supermodule

This supermodule captures the essential biology knowledge necessary for engineering practice. It is composed of 6 modules organized by subject area that can be extensively expanded as individual coursework themselves but is encouraged to be adapted as a single course or combined with other modules for the Engineering Biology curriculum.

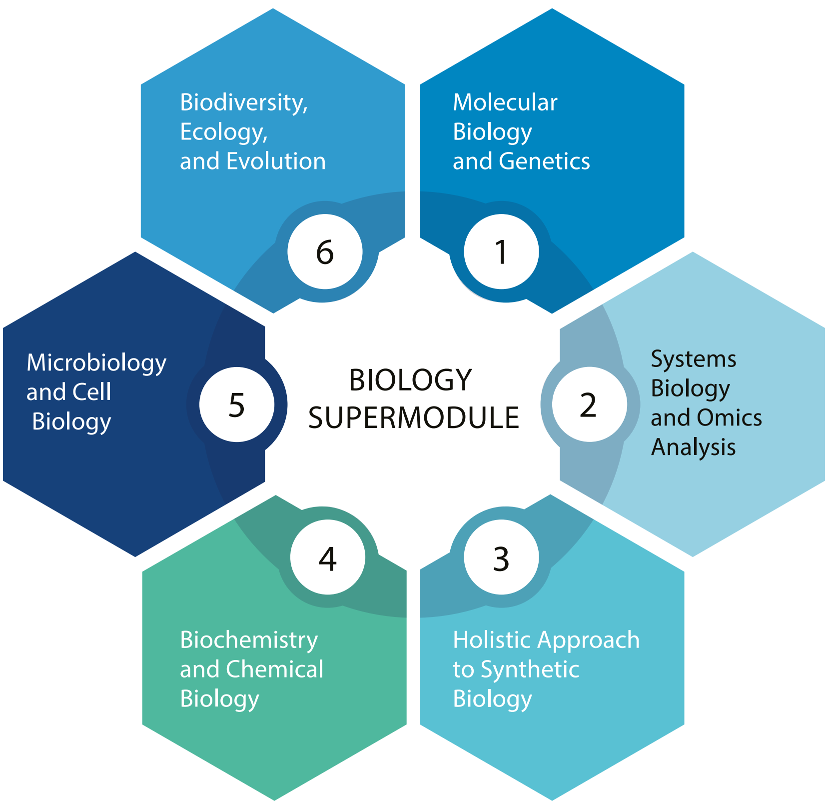


Figure 11: Each supermodule is presented as a distinct illustration, with a unique color assigned to differentiate among them. The content will be updated to reflect Biology Modules. © NXPO

◆ Molecular Biology and Genetics

This module provides an overview of basic molecular biology at molecular level crucial for understanding and further design of biological systems

Central Dogma of Molecular Biology

Describe the information flow in biological systems

- DNA replication, transcription, and translation
- Gene structure and regulatory elements
- RNA processing and modifications
- Protein biosynthesis and folding

Epigenetics and Gene Regulation

Introduce the concepts of gene regulation and heritable changes in gene expression beyond the DNA sequence

- Epigenetic mechanisms: DNA methylation, histone modification, chromatin remodeling
- Epigenetics in development and cellular differentiation
- Non-coding RNAs and gene regulation
- Environmental influence on epigenetic states
- Epigenetic tools and techniques in Engineering Biology
- Utilization of epigenetics in biotechnology and therapeutics

Molecular Cloning

Familiarize students with the principles, procedures, and applications of molecular cloning for engineering biology

- Overview of applications of molecular cloning
- Cloning vectors
- Genetic selection techniques and cloning strategies
- Enzymes for molecular cloning
- Polymerase chain reaction (PCR) and its variants
- DNA analysis and separation techniques
- Enabling technologies for synthetic biology
- Standardizations in molecular cloning

Gene and genome editing tools

Establish a foundational understanding of tools use to edit genes and genomes

- Basic genome engineering techniques
  - Restriction enzymes discovery and utilization
  - Homologous recombination
  - Transposon-based gene editing
- argeted Nuclease Technologies
  - Transcription Activator-Like Effector Nucleases (TALENs)
  - Zinc-Finger Nucleases (ZFNs)
- CRISPR-Cas system for gene editing
- Programmable recombination systems
  - Cre-lox and Flp-FRT systems

DNA synthesis and assembly techniques

Establish a basic understanding of tools used to synthesize and assemble DNA

- DNA structure and biosynthesis
- Polymerase Chain Reaction
- DNA synthesis technologies: Chemical Synthesis and Enzymatic Synthesis
- Historical context of recombinant DNA assembly
- DNA assembly beyond restriction ligation: Polymerase Cycling Assembly (PCA), Golden Gate, Gibson Assembly

◆ Systems Biology and Omics Analysis

Genomics, transcriptomics, and metagenomics

Teach students how to access, acquire and use data across the fields of genomics, transcriptomics, and metagenomics for Engineering Biology

- Functional and comparative genomics; genome-wide association studies
- Chromosome conformation capture techniques
- Gene expression analyses; annotation and gene ontology; gene set enrichment and overrepresentation analysis
- Gene expression atlas and single-cell gene expression atlas
- Gene co-expression network, ribosome profiling, SHAPE technologies
- Amplicon-based microbiome analysis
- Taxonomic and diversity analysis; microbiome network analysis

Proteomics and metabolomics

Teach students how to access, acquire and use data across the fields of proteomics and metabolomics for Engineering Biology

- Targeted and untargeted mass spectrometry-based proteomics
- Quantitative proteomics methods
- Chemical proteomics
- Proximity labeling technologies for interactome studies
- Targeted and untargeted mass spectrometry-based metabolomics
- Quantitative metabolomics methods
- Biomarker discoveries
- Applications to metabolic engineering
- Integrative multi-omics approaches

Data Integration and Modeling

Equip students with concepts and strategies to integrate and model multi-omics data for a systems-level understanding of biological functions

- Introduction to data integration in systems biology
- Concepts of network biology and biological interaction networks
- Modeling biological systems: stoichiometric models, constraint-based models (e.g., flux balance analysis)
- Model validation and predictive power in engineering applications
- Design and analysis of synthetic gene circuits using integrated omics

◆ Holistic Approach to Synthetic Biology

This module provides an overview of tools used for the design, modification and construction of biological systems

Foundation of Synthetic Biology

Familiarize students with the concept, scope, and significance of synthetic biology

- Definition and historical development of synthetic biology
- Integration of biology and engineering principles
- Role in biotechnology and engineering biology
- Examples of synthetic biology milestones which are of broad public interest
    - Production of artemisinin and opiates by yeast
    - Chemically synthesized and fully recoded bacterial genomes
    - Designer eukaryotic chromosomes

Synthetic biology parts

Establish a foundational understanding of genetic parts used in synthetic biology research

- DNA parts as biological entities
    - Synthetic Biology Open Language (SBOL)
- Promoter design and libraries
- Ribosome binding site design and libraries
- Terminator design and libraries
- Transcription factor and inducible promoters
- Dealing with context-dependent effect
- Genetic parts repository
    - iGEM database

Genetic circuits and gene regulation

Teach students how to design logical functions from biological parts

- Naturally occurring gene regulation and circuits
- Classical examples of synthetic gene circuits
    - Genetic oscillator
    - Toggle switch
    - Noise reduction
    - Boolean logic gates
- Recombinase-based logic gates and circuits
- Protein-based genetic circuits
- Multi-level control of gene expression
- Computer-Assisted Design of Genetic Circuits (e.g. CelloCAD)
- Considerations for complex genetic circuits
    - Stability
    - Orthogonality
    - Genetic and environmental contexts
    - Level-matching
    - Operation kinetics
    - Resource consumption

Standardizations in synthetic biology

Expose students to the process of establishing common standards and protocols to make it easier to engineer biology

- BioBricks as standardized and interchangeable parts
  - iGEM parts repository
- Standardization of plasmids
  - Standard European Vector Architecture (SEVA)
  - BglBrick
- Standardization of enzymes and biochemical reactions
  - Strenda
- Modular Cloning (MoClo) systems
- Data standards (genomic, enzymological, chemical) for natural product synthetic pathways
- Biosecurity and standardization in screening synthetic genes and customers

Precise gene editing and regulation

Establish a foundational understanding of tools use for precise editing of target genes and genomes

- Modular parts for DNA/RNA targeting systems
  - Transcription Activator-Like Effector Nucleases (TALENs)
  - Zinc Finger Nucleases (ZFNs)
  - CRISPR-Cas system
- CRISPR-Cas9 as a standard gene editing tool
- Other CRISPR-Cas systems for DNA and RNA editing
- Uses of CRISPR-Cas systems beyond editing
  - Transcriptional control
  - Genome and RNA imaging
- CRISPR-Cas-mediated base editing
- Next-generation genome editing:
  - Prime editing
  - Transposon-mediated editing
  - Integrase-mediated editing
- Modular detection
  - Nucleic acid-based biosensor systems
  - CRISPR genetic screens
- CRISPR gene therapy

DNA assembly tools and strategy towards

Establish a foundational understanding of tools used to assemble DNA at increasingly large scales

- DNA synthesis technologies recap
- DNA assembly beyond restriction ligation: Polymerase Cycling Assembly (PCA), Golden Gate, Gibson Assembly
- Considerations in scaling DNA assembly from genes to genomes: error correction; use of NGS to assess assembly fidelity
- Genome-wide codon replacement via MAGE/CAGE

Optogenetics

Teach students the principles, tools and applications of optogenetics

- Advantages of using light to control biological systems
  - High spatial and temporal resolution
  - High dosing precision
- Photoreceptors and the birth of optogenetics
- Improving properties and functions of photoreceptors
- Hardware for optogenetics
- Other photo-responsive parts commonly used in synthetic biology
  - Cryptochrome
  - LOV
  - Phytochromes
- Applications of photoreceptors
  - Neuroscience
  - Signaling pathway regulation
  - Cell movement control

Cell-free systems

Teach the principles of cell-free synthetic biology and bioengineering.

- Pros and cons of cell-free vs cell-based bioproduction
- Cell-free protein synthesis (natural and non-natural proteins)
- Cell-free metabolite production
- Cell-free biosensors

- Applications of cell-free systems linking to the Global South
  - Freeze-dried Cell-free systems
  - Field-deployable biosensors
  - Remote vaccine production

◆ Biochemistry and Chemical Biology

This module provides students with background on biomolecules and how chemical/biochemical tools could be implemented to study biological processes or to develop new technologies/products. The course is divided into two parts, (1) an overview of biomolecules and tools to study them and (2) applications of chemical biology for interrogation and manipulation of biomolecules.

Sub-Module 1:

Overview of biomolecules and tools to study them

Overview of biomolecules and tools for observing and manipulating them

Biomolecules and organic chemistry of life

Review on the basics of biomolecules and related chemical bonds and molecular interactions in biological systems

- Structures and functions of biomolecules
  - Proteins, nucleic acids, polysaccharides, lipids
- Post-translational/transcriptional modifications
  - Phosphorylation, ubiquitination, protein glycosylation, protein lipidation, DNA methylation
  - Enzymes and biochemical reactions
- Covalent and non-covalent interactions in biological systems

Transcriptomics and proteomics (Bulk, single cell, spatial)

Introduction to the techniques to study transcriptomics and proteomics at bulk, single-cell, and spatial levels

- Techniques for bulk and single cell RNA sequencing
  - Techniques in spatial transcriptomics
  - In situ hybridization (ISH)
- Single-molecule fluorescence in situ hybridization (smFISH)) --- High-Resource Topic
- Techniques in spatial proteomics (e.g. CODEX)

Bioorthogonal and bioconjugation chemistry

Introduction to the concept of biorthogonal chemistry, common chemical reactions employed in bioconjugation, and relevant applications

- Covalent chemistry
  - Carbodiimide chemistry
  - Michael addition (e.g. Thiol-Maleimide)
  - Alkyne-azide cycloaddition
  - Inverse electron-demand Diels–Alder reaction
  - Enzyme-mediated ligation (sortase, transglutaminase)
  - Staudinger ligation
  - Suzuki–Miyaura cross-coupling
  - Olefin metathesis (Stapled peptides)
  - HaloTag, SpyTag/SpyCatcher
  - Dynamic covalent bonds (disulfide, imine, oxime, hydrazine, and boronate)
  - Proximity labeling
- Non-covalent chemistry
  - Guest-host interactions (cyclodextrin, pillararene, and cucurbit[n]uril)

Sub-Module 2:

Applications of chemical biology for interrogation and manipulation of biomolecules

Reviews on chemical biology techniques to study or manipulate biomolecules with real-world applications

Engineering protein translation and biosynthetic gene clusters

Introduction to the basic of protein production and post-translational modifications. Production of proteins with non-natural amino acids. Introduction to biosynthetic gene clusters and how they could be employed to produce natural/synthetic compounds

- Expression and purification of recombinant proteins
- Circular permutation proteins, split proteins
- Genetic code expansion, genomically recoded organisms
- Engineering proteins with post-translational modifications (glycosylation, lipidation, phosphorylation)

- Engineering biosynthetic gene clusters (BGCs) for production of natural/synthetic compounds
- Ribosomally synthesized and post-translationally modified peptides (RiPPs), polyketides

Directed evolution approaches and computational protein structure prediction and designs

Introduction to the concepts and techniques for directed evolution of proteins as affinity agents or biocatalysts. Introduction to the concepts of computational protein designs and structure prediction

- Display screening technologies (Phage, yeast, and ribosome) to target binder identification and affinity maturation
- Directed evolution for biocatalysis
- Introduction to computational protein design and structure analysis

Chemical biology of nucleic acids

Introduction to the past and present technologies related to study, modification, and applications of nucleic acids

- DNAzyme and ribozyme
- SELEX for aptamer screening
- Gene editing technologies
- Expanded genetic alphabets
- DNA barcoding technologies
- DNA digital data storage

Chemical biology of glycans

Introduction to the past and present technologies related to study, modification, and applications of glycans

- Glycan profiling techniques (glycan arrays)
- Glycan aberration in diseases
- Glycan labeling and applications (e.g. pathogen identification)
- Modulation of glycan as therapeutics (e.g. antibody-sialidase conjugate)
- Engineering glycosylation of glycoproteins (e.g. defucosylated antibody)
- Enzymatic glycosylation for industrial applications

Chemical biology for drug discovery

Discussion on how techniques in chemical biology could be employed for drug discovery with focus on small molecules

- CRISPR screens for target identification
- Affinity/activity-based pull-down
- DNA-barcoded small molecule library
- Covalent and non-covalent inhibitors
- PROTACs/LYTAC

Chemical biology for design of biologic therapeutics [High-Resource Topic]

Discussion on the examples of protein and oligonucleotide therapeutics with novel mechanism of actions

- Engineered endolysins
- Antibody-drug conjugates, immunocytokine, bispecific antibody, bi-specific immune cell engager
- Protein nanoparticle vaccine (e.g. Icosavax)
- Extracellular targeted protein degradation
- mRNA vaccine/therapeutics

◆ Microbiology and Cell Biology

This module introduces core principles of microbiology and cell biology essential for understanding and engineering living systems.

Microbial Diversity and Classification

Introducing the diversity of microorganisms and their classification systems

- Bacterial, archaeal, and eukaryotic microorganisms
- Classification and phylogenetic tree construction using 16S/18S rRNA and whole-genome data
- Extremophiles and their biotechnological applications
- Virus and phage biology: life cycles and synthetic biology tools
- Characterization and cultivation of unculturable microbes

Cell Structure and Function

Explore the structural and functional components of prokaryotic and eukaryotic cells

- Cell walls, membranes, organelles, and compartments
- Protein targeting and trafficking

- Membrane dynamics and vesicular transport
- Cytoskeleton and cell motility
- Comparative cell biology of model organisms used in engineering biology

Microbial Physiology and Metabolism

Understand microbial life processes and their relevance to biotechnological applications

- Microbial growth kinetics and environmental responses
- Aerobic and anaerobic respiration; fermentation
- Central metabolic pathways (glycolysis, TCA cycle, pentose phosphate pathway)
- Microbial stress responses and adaptation
- Cross-feeding and microbial interactions

Cell Communication and Signaling

Introduce mechanisms of cellular communication and regulation

- Quorum sensing and microbial consortia
- Two-component systems and signal transduction pathways
- Crosstalk between signaling networks
- Engineering synthetic signaling systems

Tools and Applications in Microbiology

Explore laboratory and computational tools for microbiological analysis and engineering

- Culture-dependent and -independent microbial analysis
- Microscopy, flow cytometry, and live-cell imaging
- Bioreactors and continuous culture systems
- Applications of microbiology in health, agriculture, and industry

◆ Biodiversity, Ecology, and Evolution

This module provides an integrated view of biodiversity, ecological systems, and evolutionary processes.

Principles of Biodiversity and Taxonomy

- Explore the scope of biological diversity and the methods used to classify life
- Defining species and levels of biodiversity (genetic, species, ecosystem)
- Taxonomic classification and systematics
- Phylogenetics and molecular barcoding
- Global biodiversity hotspots and conservation efforts
- Impact of synthetic biology on biodiversity

Ecological Principles and Interactions

Introduce basic ecological concepts and species interactions within ecosystems

- Population dynamics, community structure, and ecosystem functions
- Symbiosis: mutualism, commensalism, and parasitism
- Nutrient cycling and energy flow
- Microbial ecology and engineered microbiomes
- Ecological succession and resilience

Evolutionary Biology and Mechanisms

Understand the mechanisms driving evolution and diversification of life

- Natural selection, genetic drift, gene flow, and mutation
- Molecular evolution and evolutionary constraints
- Experimental evolution and laboratory evolution techniques
- Evolution of multicellularity, cooperation, and complex traits
- Evolutionary engineering and directed evolution

Synthetic Biology in Ecological and Evolutionary Contexts

Reflect on the interplay between engineering biology and natural systems

- Gene drives, horizontal gene transfer, and ecological risk assessment
- Co-evolution and synthetic mutualisms
- Design of biosensors and organisms for environmental remediation
- Ethical, legal, and social implications (ELSI) of releasing engineered organisms
- Evolution-informed design of robust synthetic circuits

Tools for Biodiversity and Ecosystem Analysis

Introduce technologies and data sources to study biodiversity and ecosystems

- Field sampling methods and remote sensing
- Environmental DNA (eDNA) and metagenomic analyses
- Biodiversity databases and ecological modeling tools
- Statistical approaches to ecological data
- Citizen science and participatory biodiversity monitoring

Engineering Supermodule

This supermodule captures the essential engineering principles necessary for engineering biological systems. It is composed of 6 modules organized by subject area that can be considered a degree themselves but is encouraged to be adapted as a single course or combined with other modules for the Engineering Biology curriculum.

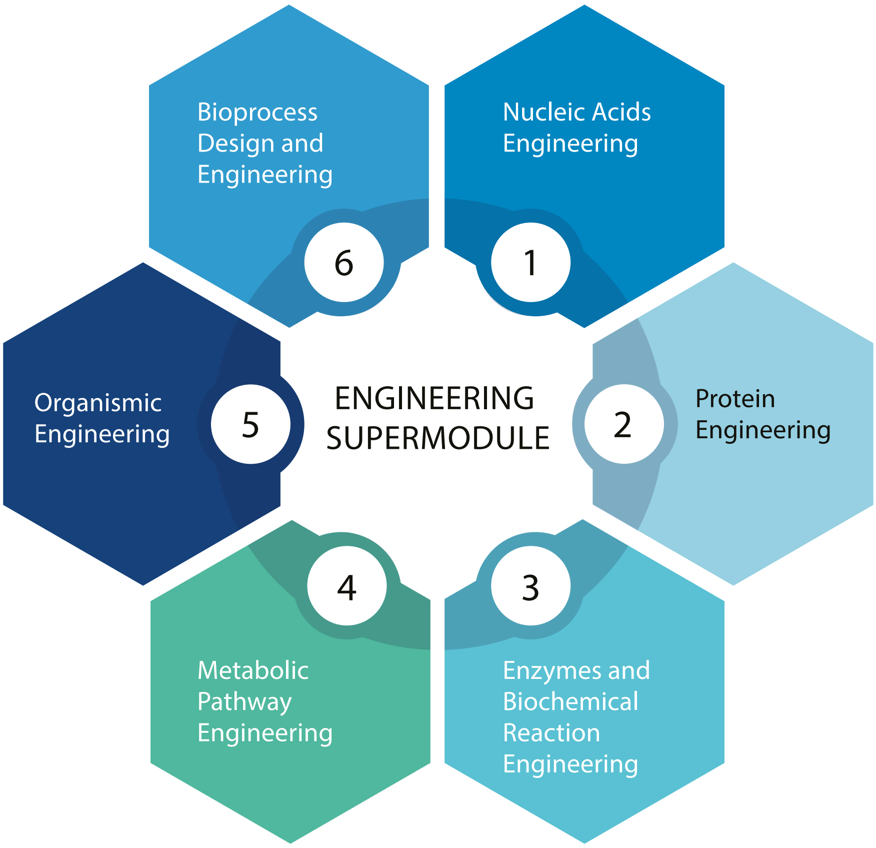


Figure 12: Each supermodule is presented as a distinct illustration, with a unique color assigned to differentiate among them. The content will be updated to reflect Engineering Modules. © NXPO

◆ Nucleic Acids Engineering

Nucleic Acid Structure and Function

Introduce the biochemical and biophysical properties of DNA and RNA

- Nucleotide chemistry, base-pairing rules, secondary and tertiary structures
- Thermodynamics of nucleic acid hybridization
- RNA folding and structural motifs (e.g., hairpins, pseudoknots, ribozymes)
- Nucleic acid stability and chemical modifications

Design and Synthesis of Nucleic Acids

Explore strategies for creating synthetic DNA and RNA molecules

- De novo DNA synthesis and error correction
- Custom oligonucleotide and gene synthesis
- Enzymatic synthesis and novel nucleic acid chemistries (e.g., XNA)
- Computational tools for sequence design and optimization

RNA Engineering and Functional Devices

Establish a foundational understanding of RNA-based tools in synthetic biology beyond CRISPR-Cas systems

- Riboswitches and small regulatory RNAs
    - Modulation of transcription and translation
- RNA aptamers and their selection (SELEX)
    - Utility as multiplexed biosensors
- Ribozymes for gene expression control

DNA Nanotechnology and Structural Design

Explore nucleic acids as programmable biomaterials

- DNA origami and nanostructure assembly
- Dynamic DNA devices and strand displacement systems
- Applications in biosensing, drug delivery, and synthetic cells

◆ Protein Engineering

This module covers the principles and techniques for designing, modifying, and evolving proteins with new or improved functions.

Protein Structure and Function Fundamentals

Build foundational understanding of protein biochemistry

- Amino acid properties and protein folding
- Primary to quaternary structure hierarchy
- Structure-function relationships in enzymes, receptors, and scaffolds
- Protein stability and dynamics

Rational Design of Proteins

Introduce structure-guided and computational methods for engineering proteins

- In silico protein modeling and design (e.g., Rosetta, AlphaFold)
- Site-directed mutagenesis and domain swapping
- Stabilizing proteins and enhancing solubility
- Design of synthetic protein scaffolds

De novo design of proteins [Move to Data Science and Modelling or new Generative/Design module]

Highlight protein design capabilities with current technologies such as Rosetta and deep learning methods

- Introduction to protein design and Rosetta
- Parametric design of backbones
- Sidechain design using ProteinMPNN and AlphaFold
- Protein design with RFDiffusion

Directed Evolution and Combinatorial Approaches

Teach experimental strategies to evolve new protein functions

- Error-prone PCR, DNA shuffling, and saturation mutagenesis
- Library construction and high-throughput screening
- In vitro vs in vivo evolution systems
- Case studies in industrial and therapeutic enzyme engineering

Engineering Protein Functionality

Explore engineering of catalytic, binding, and structural properties

- Enzyme kinetics and catalytic mechanisms
- Allosteric regulation and conformational switching
- Affinity and specificity tuning in antibodies and receptors
- Design of fusion proteins, biosensors, and synthetic enzymes

◆ Enzymes and Biochemical Reaction Engineering

This course aims to provide students with current state of knowledge for performing efficient engineering of enzymes and biochemical reactions to obtain desired biocatalytic systems.

Sub-Module 1:

Enzyme Catalysis

Knowledge required to understand principle and fundamental of enzyme catalysis

Overview of Enzyme Catalysis

Familiarize students with principles of enzyme catalysis and tools for investigating enzyme reactions and mechanisms. Before performing enzyme engineering, students need to understand capability and principles underlying different enzyme types.

- Enzyme classes and general reaction mechanisms associated with cofactor-dependent and cofactor-independent enzyme systems
- Examples of cofactor-independent enzymatic reactions
- Examples of cofactor-dependent enzymatic reactions
- Kinetics and thermodynamics of enzymatic reactions
- Use of AlphaFold and AlphaFill to analyze enzyme and ligand interactions

Mechanistic tools for investigating enzymatic reactions

Provide students with in-depth principles necessary for investigating enzyme mechanisms and functions. The knowledge is generally useful for understanding and comparing characteristics of native and engineered biocatalysts and to explain insights into the engineering improvement.

- Transient kinetics and use of kinetic data to identify a bottleneck in an enzyme reaction
- Advanced spectroscopies for investigating metal-dependent enzymes (EPR, Mössbauer, etc.)
- Kinetic isotope and pH-dependent effects as mechanistic probes.
- Use of Quantum mechanics (DFT) for investigating enzymatic reactions
- Use of Molecular Dynamics (MD) simulations to investigate enzyme and ligand dynamics

Sub-Module 2:

Enzyme engineering

Current state-of-knowledge in performing enzyme engineering

Enzyme engineering tools

Familiarize students with well-established and available engineering tools to improve enzyme properties

- Methodology in enzyme engineering (directed evolution, rational design and semi-rational design)
- Computational tools for improving enzyme thermostability (PROSS, FireProt, B-Fitter and Disulfide-by-Design)
- Examples of enzyme engineering cases with improved performance
- Examples of active site and Loop engineering for modulating enzyme activities

Bioinformatic tools to aid in selecting and improving enzymes for biocatalysis

Explain to students currently available bioinformatic tools for selecting and shortlisting enzyme candidates for performing biocatalysis. Several tools are currently available for helping researchers to select their enzymes of interest for performing biocatalytic applications.

- Use of Enzyme Function Initiation (EFI) to evaluate diversity of enzymes within their families
- Use of EnzymeMiner to identify enzymes of interest and evaluate their structure and function relationship
- Use of computational tools for predicting enzyme solubility
- Use of bioinformatic tools such as docking software to evaluate capability of selected biocatalysts

Current and emerging topics in enzyme engineering

Provide students with up-to-date information of current and emerging topics in enzyme engineering. These methodologies are not well settled but under fast development.

- De novo enzyme design: principles, methodology and examples
- Ancestral sequence reconstruction: principles, methodology and examples
- AI-assisted enzyme engineering: examples of enzyme engineering using machine-learning approach

Sub-Module 3:

Biocatalysis

Use of enzymes for synthesizing target compounds

Familiarize students with knowledge related to catalytic potential of enzymes and whole cells for production of useful compounds. Students should be aware of important parameters which should be selected to achieve successful biocatalytic reactions.

- Overview of biocatalysis process design
- Use of biocatalysts in bioconversion process
- Important parameters for scaling up
- Reproducibility and data cataloguing in biocatalysis
- Use of STRENDA platform in reporting biocatalysis projects

◆ Metabolic Pathway Engineering

This module introduces strategies for designing and optimizing metabolic pathways to produce valuable compounds, fuels, materials, and therapeutics.

Fundamentals of Metabolic Pathways

Understand how cellular metabolism operates as a network of biochemical reactions

- Central carbon metabolism (glycolysis, TCA cycle, PPP)
- Anabolic and catabolic pathways
- Cofactor balance and energy metabolism
- Flux distribution and metabolic bottlenecks

Pathway Design and Construction

Learn to design synthetic and semi-synthetic metabolic routes

- Retrosynthetic pathway design
- Enzyme selection and orthogonal pathway integration
- Modular pathway construction and standardization
- Toolkits for multi-gene operon assembly

Dynamic Regulation and Control of Pathways

Introduce concepts of controlling pathways in real time

- Metabolic burden and toxicity mitigation
- Biosensors and feedback regulation
- Inducible and repressible promoter systems
- CRISPRi/a and RNA-based regulation

Computational Tools and Modeling

Use computational frameworks to design and analyze pathways

- Stoichiometric modeling and flux balance analysis (FBA)
- Constraint-based modeling and pathway optimization
- Machine learning and AI-assisted pathway prediction
- Case studies: production of biofuels, pharmaceuticals, and bioplastics
- Genome-scale models to design metabolic engineering strategies

Engineering by Evolution: Adaptive Laboratory Evolution (ALE)

Harness evolution to improve pathway performance and host adaptability

- Principles of laboratory evolution and evolutionary selection pressures
- Design of ALE experiments for growth rate, stress tolerance, and metabolic productivity
- Coupling pathway performance to fitness
- Combining ALE with rational design and genome sequencing
- Case studies of evolved strains for biofuel, amino acid, and organic acid production

◆ Organismic Engineering

This module focuses on selecting and modifying microbial or eukaryotic hosts to support synthetic circuits, metabolic pathways, or genome-scale design.

Microbial Host Selection and Design

- Introduce the concept of engineering biological chassis
- Characteristics of ideal host organisms
- Model organisms (e.g., E. coli, S. cerevisiae, B. subtilis)
- Non-model and extremophilic hosts
- Minimal genome organisms and synthetic cells

Eukaryotic cell engineering

Introduce toolsets for the engineering of eukaryotic cells

- Basic principles of cell science and cell engineering
- Tools for reporting, transgenes, knock-ins, knock-outs, Cre-lox, barcoding methods for monitoring and regulating cell behavior
- Genetic control of cell fate and behavior
- Cell-cycle engineering: comparison of somatic, stem, cancer cells; checkpoints and control
- Overview of current approved engineered cell therapies (e.g. gene-edited hematopoietic stem cells (HSCs) and chimeric antigen receptor (CAR) T cells)
- Examples of recent advances in engineered cell therapies and engineered organ transplants

Genome Engineering for Host Optimization

Learn tools to reprogram host genomes

- CRISPR-based genome editing
- Multiplex Automated Genome Engineering (MAGE)
- Genome-scale deletions and insertions
- Recoding genomes and synthetic chromosomes

Strain Engineering for Robustness and Performance

Enhance host traits for stability and productivity

- Tolerance to solvents, pH, temperature, and oxidative stress
- Engineering global transcription factors and sigma factors
- Controlling resource allocation and minimizing burden
- Population control and biocontainment strategies

Orthogonality and Compatibility in Host Systems

Ensure stable function of engineered parts and circuits

- Use of orthogonal transcription/translation systems
- Compartmentalization strategies (e.g., bacterial microcompartments, organelles)
- Host-circuit interactions and evolutionary stability
- Heterologous expression and codon optimization

◆ Bioprocess Design and Engineering

This course covers fundamental and advanced concepts of bioprocess engineering to develop efficient biomanufacturing systems.

Introduction to Bioprocess Engineering

Familiarize students with the principles, scope, and applications of bioprocess engineering.

- Overview of bioprocess engineering principles
- Applications in pharmaceuticals, biofuels, and environmental biotechnology
- Integration of biology and engineering for production systems

Fundamental Concepts in Bioprocess Engineering

Establish a foundational understanding of microbial kinetics, bioreactor design, and downstream processing.

- Microbial kinetics and growth models
- Bioreactor design and operational parameters
- Downstream processing techniques and product recovery

Process Optimization and Scale-Up

Equip students with the knowledge and skills to optimize and scale up bioprocesses for industrial applications.

- Strategies for scaling-up bioprocesses
- Process modeling and optimization techniques
- Automation and control systems for bioprocess industries
- Scaling-down process for design purposes

Sustainability and Emerging Technologies

Highlight the importance of sustainability and explore recent advancements in bioprocess technology.

- Sustainable bioprocessing and environmental impact
- Advances in synthetic biology and bioprocess modeling
- AI and machine learning applications in bioprocess engineering

Practical Applications and Case Studies

Bridge theoretical knowledge with real-world applications through hands-on learning and case studies.

- Hands-on laboratory experiments in microbial growth and bioreactor operation
- Simulation-based exercises in bioprocess modeling and optimization
- Industrial case studies on enzyme production and bioreactor optimization
- Pilot-scale bioprocess demonstrations and troubleshooting techniques
- Preparation for careers in bioprocess industries and research

Frontier-Technology Supermodule

The Frontier-Technology Supermodule is where things can really shine in terms of showcasing cutting-edge tools and concepts pushing the boundaries of Engineering Biology. It covers 6 modules specifically for technological vignette that are relevant to students learning.

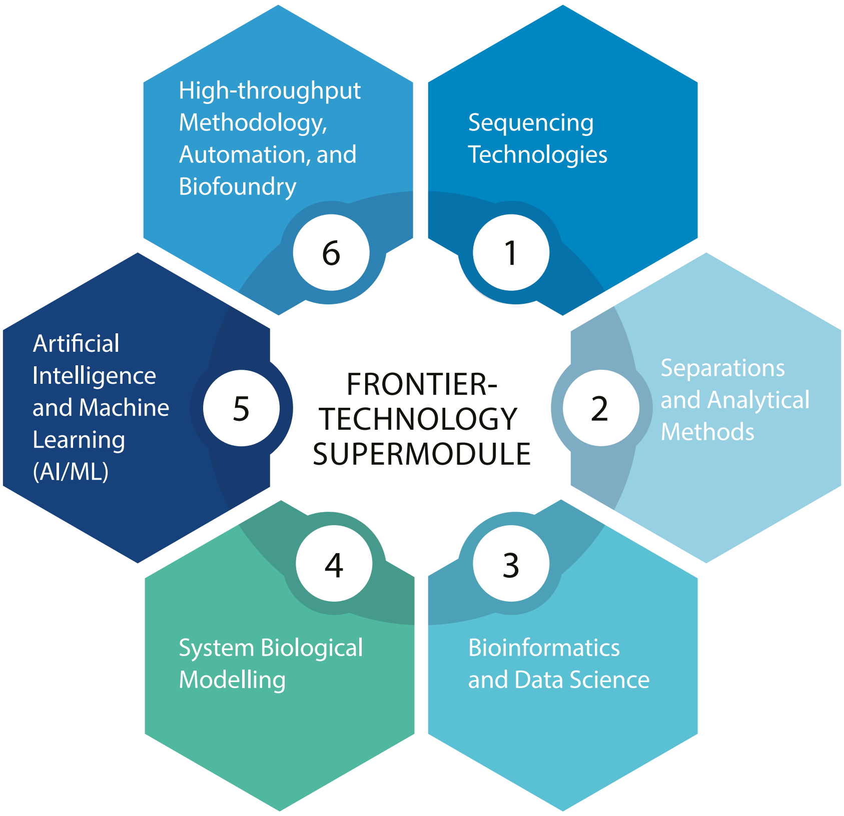


Figure 13: Each supermodule is presented as a distinct illustration, with a unique color assigned to differentiate among them. The content will be updated to reflect Frontier-Tech Modules. © NXPO

◆ Sequencing Technologies

Nucleic acid sequencing technologies

Establish a foundational understanding of traditional and next-generation nucleic acid sequencing technologies

- Principles behind traditional DNA sequencing (Maxam-Gilbert, different variants of Sanger sequencing)
- Automation- and capillary-assisted Sanger sequencing, which drove sequencing of genomes
- Principles behind key short-read sequencing technologies (pyrosequencing, Illumina, Solid sequencing)
- Principles behind key long-read sequencing technologies (SMRT, Nanopore)

- Comparative parameters of different sequencing technologies
- Application examples where sequencing and NGS drove inventions in Engineering Biology

Sequencing Data Analysis and Interpretation

Enable students to analyze, interpret, and use sequencing data

- Read alignment, variant calling, and genome assembly
- Transcriptome profiling and differential expression analysis
- Barcode-based lineage tracing and multiplexing strategies
- Metagenomics and microbiome sequencing workflows

Protein Identification and Sequencing

Introduce foundational and emerging protein sequencing tools

- Edman degradation and classical methods
- Mass spectrometry-based proteomics (MS/MS, bottom-up and top-down)
- Single-molecule protein sequencing technologies
- Post-translational modification (PTM) mapping

Separations and Analytical Methods

Principles of Molecular Separation

Introduce core concepts underlying separation techniques

- Physical and chemical basis of separation
- Resolution, efficiency, selectivity, and sensitivity
- Preparative vs analytical separations
- Chromatographic methods and phase interactions

Chromatography and separation technologies

Teach principles of chromatography and separation techniques used in biological and engineering biology research

- Affinity chromatography
- Ion exchange chromatography
- Gel filtration chromatography
- Hydrophobic interaction chromatography
- High-performance liquid chromatography
- Electrophoretic separation of biomolecules

Electrophoresis and Gel-Based Methods

Introduce gel and capillary-based techniques for biomolecular analysis

- Agarose and polyacrylamide gel electrophoresis (PAGE)
- 2D-PAGE for proteomics
- Capillary electrophoresis and microfluidics-based separations
- Western blotting and imaging-based detection

Molecular imaging tools for Engineering Biology

Introduction to various tools to image and study biomolecules, microorganisms, and tissue at the cellular level.

- Basic microscopy
- Principles of fluorescence spectroscopy
- Chromophores and Fluorophores for biological research
- Biomolecular labeling tools
- Different microscope setups and techniques for biological imaging
  - Optical clearing and expansion microscopy
- Imaging flow cytometry
- CryoEM and SEM
- Advanced imaging modalities such as single-molecule and super-resolution microscopy
- Applications to highlight the use of fluorescence microscopy to engineer biology

Spectroscopy and Quantification Techniques

Explore optical and mass-based methods for molecular detection

- UV-Vis, fluorescence, and circular dichroism (CD) spectroscopy
- Mass spectrometry for metabolite and protein analysis
- NMR spectroscopy in metabolic flux analysis
- Qubit, Nanodrop, and fluorometric quantification tools

Mass spectrometry for biomolecules

Establish a fundamental understanding of mass spectrometry and its use for Engineering Biology

- Instrumentation; ion optics; resolution and mass accuracy
- Applications to proteomics; post-translational modifications
- Applications to metabolomics for metabolic engineering
- Informatics for mass spectrometry
- Quantification methods for mass spectrometry

◆ Bioinformatics and Data Science

This module focuses on computational tools and statistical methods used to analyze and interpret large-scale biological data. Since computational works can be conducted remotely, this module is encouraged for the low-resource setting curriculum.

Tools and Technologies for Biological Data Manipulation

Gain knowledge of essential tools and technologies in biological engineering, including genetic design, computational tools, high-throughput screening, and sequencing technologies.

- Genetic design tools: CRISPR-Cas systems, Gibson Assembly.
- Computer-aided tools: Benchling, Geneious.
- Simulations and modeling: Python packages, COBRA Toolbox.
- Automated screening platforms.
- Analysis and interpretation of high-throughput data.
- Applications in drug discovery and genomics.
- Sequencing: principles and platforms.
- Data analysis for sequencing technologies.
- Introduction to Linux commands, file systems, and running bioinformatics tools.

Bioinformatics Tools and Computational Methods

Provide basic understanding how one can use bioinformatics to facilitate engineering biology

- Introduction to biological databases and high-throughput data sources
  - Accessing public databases: NCBI, EMBL-EBI, Ensembl, KEGG, UniProt, GEO, SRA, etc.
- DNA and protein sequence alignment, analyses of sequence patterns and motifs
  - Sequence alignment and assembly tools (e.g., BLAST, Bowtie, BWA, SPAdes)
- Phylogenetic analyses of different species
- Transcriptomics pipelines: FASTQ processing, differential expression
- Metagenomics and microbiome analysis platforms
- Protein structures: alignment, analyses and prediction
- Microarray data analyses
- Biological networks

Data Preprocessing and Quality Control

Teach techniques for data cleaning and preparation

- Preprocessing sequencing data (quality trimming, error correction)
- Handling raw data from next-generation sequencing platforms (NGS)
- Normalization and standardization of datasets
- Removing batch effects and controlling for confounding variables

Statistical Methods in Bioinformatics

Cover statistical tools and approaches for biological data analysis

- Basic statistics for bioinformatics (t-tests, ANOVA, regression analysis)
- Multi-dimensional scaling (MDS) and principle component analysis (PCA)
- Identification of differentially expressed genes and metabolites
- Advanced statistical modeling for omics data integration

◆ System Biological Modelling

Machine Learning in Bioinformatics

Introduce machine learning methods for biological data interpretation

- Classification and regression algorithms (SVM, decision trees, random forests)
- Clustering algorithms for gene expression and protein interaction data
- Dimensionality reduction techniques (PCA, t-SNE, UMAP)

- Applications in predicting biological outcomes and gene function

Data structure prior to Modeling

Equip students with concepts and strategies to integrate and model multi-omics data for a system-level understanding of biological functions

- Data structure for biological modelling
- Concepts of network biology and biological interaction networks
- Frameworks for omics data integration
- Dynamic modeling using ordinary differential equations (ODEs)
- Bayesian and machine learning approaches for systems modeling
- Model validation and predictive power in engineering applications
- Design and analysis of synthetic gene circuits using integrated omics

Modelling Metabolic Pathways

Teach students principles and practical aspects of metabolic modelling methods

- Introduction to metabolic networks
- Kinetics of metabolic reactions and networks
- Metabolic networks in steady-state; applications to flux balance analysis
- Tools for modelling time-series data
- Advances in model-assisted metabolic engineering

De novo design of proteins

Highlight protein design capabilities with current technologies such as Rosetta and deep learning methods

- Introduction to protein design and Rosetta
- Parametric design of backbones
- Sidechain design using ProteinMPNN and AlphaFold
- Protein design with RFDiffusion

◆ Artificial Intelligence and Machine Learning (AI/ML)

This module introduces artificial intelligence and machine learning techniques that are transforming the field of engineering biology.

Introduction to AI and Machine Learning in Biology

Introduce the fundamentals of AI/ML and their relevance to synthetic biology

- Overview of AI and machine learning principles (supervised, unsupervised, reinforcement learning)
- AI applications in bioinformatics, genomics, and systems biology
- The role of AI in automating biological design and analysis
- Challenges and ethical considerations in AI for biology

Machine Learning in Bioinformatics

Introduce machine learning methods for biological data interpretation

- Classification and regression algorithms (SVM, decision trees, random forests)
- Clustering algorithms for gene expression and protein interaction data
- Dimensionality reduction techniques (PCA, t-SNE, UMAP)
- Applications in predicting biological outcomes and gene function

AI for Predictive Biology and Simulation

Introduce AI techniques for simulating biological systems and predicting their behavior AI in pathway prediction and gene regulatory network design

- Simulating cellular behavior using AI-enhanced agent-based models
- Optimization of biotechnological processes using AI-based decision-making
- Applications in metabolic engineering, microbial consortia, and tissue engineering

Future Directions and Challenges in AI/ML for Biology

Explore the emerging trends and challenges for AI/ML in synthetic biology

- AI in gene editing and gene therapy predictions
- Challenges in dataset bias, interpretability, and explainability of AI models
- The role of AI in developing bioinspired algorithms and biologically aware machine learning techniques
- Interdisciplinary collaborations in AI and synthetic biology

◆ High-throughput Methodology, Automation, and Biofoundry

High-throughput technologies and biofoundry

Provide basic and advanced principles of high-throughput technologies used to accelerate discoveries in Engineering Biology

- Flow cytometry
- High-content imaging and screening platforms
- Automation systems specialized for Engineering Biology
- Biofoundry for automated biomanufacturing
- Applications of high-throughput technologies to Engineering Biology

Technologies for High-throughput Screening and Assays

Learn the technologies behind high-throughput methodologies in synthetic biology

- High-throughput PCR, cloning, and sequencing platforms
- Automated liquid handling and microarray systems
- Single-cell analysis and high-throughput flow cytometry
- High-content screening (HCS) and multiplexed assays for metabolic engineering

Robotics and Automation in Biofoundries

Explore the role of robotics and automation in scaling up synthetic biology experiments

- Robotic systems for automated cloning, plasmid construction, and transformation
- Automated liquid handling platforms for media preparation and cell culture
- Automated high-throughput data acquisition and analysis
- Integration of robotics in biofoundry workflows for system-level engineering

Biofoundry Design and Optimization

- Dive deeper into the design and operation of biofoundries
- Overview of biofoundry design principles (modular, scalable, and flexible systems) Tools and platforms for automated gene synthesis and pathway assembly Automation of design-build-test-learn (DBTL) cycles for metabolic engineering Scale-up from laboratory automation to industrial biofoundries

Data Management and Integration in Biofoundries

Introduce concepts of data integration, management, and analysis in biofoundry settings Managing large-scale data generated by high-throughput platforms

- Integration of biological data with engineering data (process variables, system metrics)
- Real-time feedback and data-driven decision-making for biofoundry workflows
- Use of cloud computing, LIMS (Laboratory Information Management Systems), and other software platforms in biofoundries

Special Topics for Engineering Biology Curriculum

Draft a visual description of what special topics module are --- they're technically an expansion of a subset of essential module but is more appropriate for the institutional context, thus should be elaborated on a dedicated course

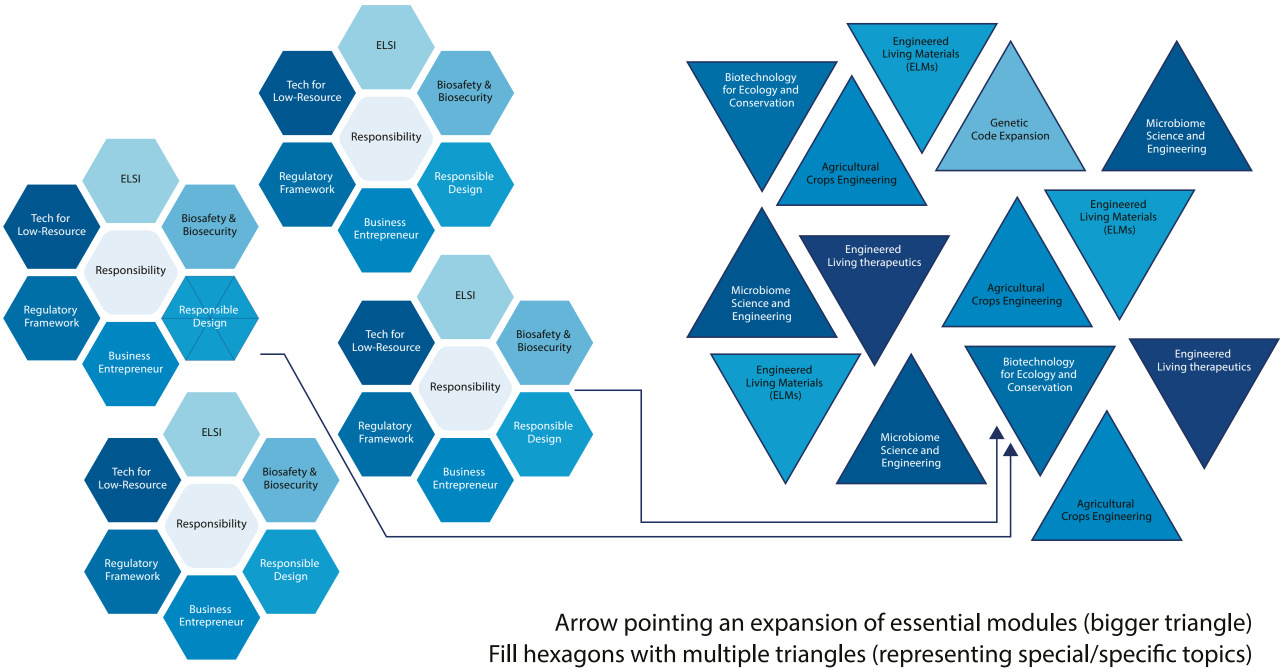


Figure 14: Drafted visual description of what Special Topics Modules are — they are technically an expansion of a subset of Essential Modules but are more appropriate for the institutional context, and thus should be elaborated as dedicated courses. © NXPO

Special Topics modules are dedicated to emerging areas of Engineering Biology that can be used to frame a standalone course or mix with other essential or special topics into a new course. Most modules were briefly described rather than detailed narration to be aware of regional/national focus or institutional expertise. A few special topics modules relevant to LMICs ecosystem such as Thailand are fully narrated as examples. A new special topic based on instructors' expertise can be developed using this section as a guideline.

A list of Special Topics modules and sub-modules—in bullet points—is outlined below with loose categorization by placing them closely. Suggested contents are provided for six selected modules i) Genetic Code Expansion, ii) Engineered Living Materials, iii) Agricultural Crops Engineering, iv) Biotechnology for Ecology and Conservation, v) Microbiome Science and Engineering, and vi) Engineered Living Therapeutics. Other Special Topics modules were listed with brief information per existing interests in the field.

Detailed Examples of Special Topic Modules

- Genetic Code Expansion
- Engineered Living Materials (ELMs)
- Agricultural Crops Engineering
- Biotechnology for Ecology and Conservation
- Microbiome Science and Engineering
- Engineered Living therapeutics

Expanded list of Special Topic Modules

- Multi-cellular Biology and Tissue Engineering
- Synthetic Genome and Synthetic Cell
- De Novo Computational Protein Design
- Drug discovery and developments
- Antimicrobial Resistance
- Engineering Food and Livestock
- Biological Materials for Textile

Detailed Examples of Special Topic Modules

◆ Genetic Code Expansion

This module introduces students to the strategies and technologies used to reprogram the genetic code surrounding the non-canonical amino acids (ncAAs) and non-canonical nucleic acids (XNA).

Redefining the Genetic Code

- The structure and universality of the standard genetic code
- Limitations in natural amino acid diversity
- Historical perspectives and landmark discoveries in code expansion

Codon Reassignment Strategies

- Stop codon suppression (e.g., UAG reassignment)
- Use of quadruplet codons and synthetic codon systems
- Recoding of genomes to create "blank" codons

Engineered Translation Systems

- Orthogonal tRNA/synthetase pairs
- Engineering aminoacyl-tRNA synthetases (aaRS)
- Directed evolution of translation components

Non-canonical Amino Acids (ncAAs)

- Chemical structures and functional categories of ncAAs
- Applications: site-specific labeling, photocrosslinking, post-translational mimicry
- In vivo versus in vitro expression platforms

Non-canonical Nucleic Acids (XNAs)

- Chemical structures and base pairing of XNAs
- Synthesis, biosynthesis, and polymerization of XNAs
- Read, write, and edit of XNAs
- Emerging technologies from XNAs

Applications and Implications

- Expanding protein functionality in materials and therapeutics
- Biocontainment strategies using unnatural amino acids
- Ethical and safety considerations in genetic code manipulation

◆ Engineered Living Materials (ELMs)

This module explores the concept and development of biologically active materials that grow and respond to environmental stimuli, created through the integration of engineering biology with materials science.

Concept and Design of ELMs

- Definition and core principles of ELMs
- Comparison with traditional biomaterials and synthetic materials

Biological Components in ELMs

- Microbial chassis used in ELMs (e.g., E. coli, Bacillus subtilis, Shewanella, fungi)
- Use of extracellular matrix, curli fibers, and biofilm engineering
- Engineered cell–cell communication in materials

Functional Properties and Applications

- Self-healing and responsive materials
- Biosensing and signaling interfaces
- Programmable shape and mechanical properties
- Applications in construction, soft robotics, and environmental sensing

Design and Fabrication Techniques

- Patterning and 3D printing with living cells
- Material–biology interfaces
- Challenges in scalability, durability, and reproducibility

◆ Agricultural Crops Engineering

This module covered Engineering Biology Agricultural crops with expanded interests in Plant Biology and Plant Engineering.

Sub-Module 1:

Plant Biology

Basic knowledge in plant biology necessary for downstream engineering

Plant Diversity and Relevant Agricultural Crops

Discuss the diversity of plants

- Classification of plants
- Regional and climate specificity
- Agricultural crops relevant to bioeconomy

Molecular Biology of Plants

Introduction of Plant Biology in the molecular biology context

- Cellular structure of plants compared to microbial and animal cells
- Model organisms
- Gene expression in plant
- Genome architecture and polyploidy

Sub-Module 2:

Plant Engineering

Basic knowledge in plant biology necessary for downstream engineering

Conventional Breeding

Background of selective breeding for crops

- Case studies of plant breeding
- Comparison of breeding and genetic engineering outcome

Plant Engineering Techniques

State-of-the-art technologies in plant engineering

- Plant tissue culture in laboratory set-up
- Introduction of transgene
- Engineering secondary metabolites for pharmaceuticals and flavors
- Compartmentalization and regulatory tuning in plants

Plant Synthetic Biology

Approaches in plant synthetic biology

- Plant Synthetic Biology
- Metabolic Engineering in Plants

Plant Symbionts and Soil Microbiome

Current knowledge of microbiota residing in plant and soil environments

- Plant-microbe interactions
- Microbial signaling in soil ecosystems

Outstanding Applications for Plant Engineering

Notable applications relevant to Engineered Plants

- Engineered plants as food products and climate resilience
- Medicinal plants and engineering processes
- Engineered plants for bioenergy
- Plant-based Sustainable technology

Regulation of Agricultural Crops

Specific regulations of plant species distinct from general engineering biology products

- History of plant strains regulation
- Different genetic engineering approaches on distinct regulatory criteria
- Case studies on foreign species invasion

◆ Biotechnology for Ecology and Conservation

This module explores the use of synthetic biology and biotechnology to address ecological challenges, support conservation, and manage biodiversity.

Ecological Monitoring and Biosensing

- Environmental biosensors for pollutants, pathogens, and stressors
- Engineered organisms for in situ detection of ecological parameters
- CRISPR-based diagnostics for environmental DNA (eDNA)

Biocontrol and Invasive Species Management

- Gene drives for population control (e.g., mosquitoes, rodents)
- Precision pest control with engineered microbes
- Ecological risk assessment and containment strategies

Bioremediation and Ecosystem Restoration

- Engineering microbes for pollutant degradation (e.g., hydrocarbons, plastics, heavy metals)
- Phytoremediation and plant-microbe consortia
- Bioreactor designs for environmental cleanup

Biodiversity and Synthetic Ecology

- Engineering keystone species and synthetic microbial ecosystems
- Assisted evolution for endangered species adaptation
- Use of synthetic biology to bolster coral reef and forest resilience

Species conservation and de-extinction

- Genetic engineering approaches for resilience enhancement of species
- Synthetic biology approaches for species de-extinction

Ethics, Policy, and Governance

- Risks of ecosystem disruption and unintended consequences
- Community and indigenous engagement in conservation biotechnology
- Conservation priorities and equitable application of technologies

◆ Microbiome Science and Engineering

This module delves into the engineering of microbial communities in diverse contexts—from human health to agriculture and environmental systems.

Understanding Microbiomes

- Structure and dynamics of microbial communities
- Human, soil, marine, and plant-associated microbiomes
- Role of microbiomes in health, productivity, and ecosystem functions

Tools and Techniques for Microbiome Analysis

- Metagenomics, metatranscriptomics, and amplicon sequencing
- Metabolic modeling and community dynamics
- High-throughput culturing and synthetic community construction

Engineering Microbiomes

- Strain-level engineering within microbial consortia
- Designing and introducing synthetic consortia
- Prebiotics, probiotics, and postbiotics in engineered interventions

Applications in Health and Agriculture

- Microbiome-targeted therapies and diagnostics
- Soil microbiome optimization for crop productivity
  - Nitrogen-fixing microbiome
- Microbiome modulation in livestock and aquaculture

◆ Engineered Living Therapeutics

This module introduces strategies to design, develop, and deliver living organisms as therapeutic agents for treating disease.

Foundations of Living Therapeutics

- Definition and scope of engineered living therapeutics
- Microbial chassis: E. coli Nissle, Lactococcus lactis, yeast, etc.
- Tissue- and organ-specific delivery strategies

Synthetic Gene Circuits in Therapeutics

- Logic gates and environmental sensing modules
- Inducible expression systems and secretion pathways
- Kill switches and control mechanisms for in vivo use

Applications in Human Health

- Treatment of metabolic disorders, inflammation, and infections
- Cancer-targeting microbial therapeutics
- Oral, topical, and injectable delivery approaches

Design and Development Challenges

- Pharmacokinetics and pharmacodynamics of living systems
- Biomanufacturing and stability of therapeutic strains
- Host-microbe interactions and immune considerations

Expanded list of Special Topic Modules

Multi-cellular Biology and Tissue Engineering

Introduce the design and engineering of structured, multi-cellular biological systems for regenerative medicine and biofabrication.

- Principles of cell–cell communication and tissue morphogenesis
- Stem cells and induced pluripotent stem cells (iPSCs)
- Scaffolds, biomaterials, and extracellular matrix engineering
- 3D bioprinting and organoids
- Applications in regenerative medicine, disease models, and bioart

Synthetic Genome and Synthetic Cell

Explore bottom-up approaches to constructing genomes and synthetic cells with programmable functions.

- Minimal genome design (e.g., Mycoplasma experiments)
- DNA synthesis and genome assembly methods
- Whole-genome transplantation and rebooting cells
- Protocells and artificial cell-like systems
- Ethical, biosafety, and philosophical implications

De Novo Computational Protein Design

Introduce strategies to design entirely new proteins using computational tools for novel functions.

- Protein structure prediction and modeling (AlphaFold, Rosetta)
- AI/ML-based protein design (ProteinMPNN, RFdiffusion)
- Design algorithms for binding sites, scaffolds, and enzymes
- In silico screening and stability assessments
- Experimental validation via directed evolution or assays
- Applications in catalysis, therapeutics, and biosensing

Drug Discovery and Developments

Provide an overview of the drug discovery pipeline with emphasis on modern biotech and synthetic biology tools.

- Target identification and validation
- High-throughput screening and AI-aided compound discovery
- Synthetic biology for natural product biosynthesis
- Preclinical testing and optimization
- Regulatory processes and translational pathways

Antimicrobial Resistance (AMR)

Understand the growing challenge of AMR and how engineering biology can help address it.

- Mechanisms of resistance: efflux pumps, target mutation, degradation enzymes
- Surveillance technologies (genomics, diagnostics)
- Synthetic antimicrobials and bacteriophage therapy
- Engineered microbial competition and CRISPR-based approaches
- Global health and policy dimensions of AMR

Engineering Food and Livestock

Explore how synthetic biology and biotechnology are shaping the future of food production and animal health.

- Cultured meat and cellular agriculture
- Engineering animal microbiomes for health and sustainability
- Synthetic flavors, fragrances, and food additives
- Precision breeding and genome editing in livestock
- Regulatory and societal acceptance of bioengineered foods

Biological Materials for Textile

Examine how engineered biological systems are being used to develop sustainable and functional textiles.

- Microbial production of silk, cellulose, and other fibers
- Engineering fungi and yeast for textile dyes and colors
- Biodegradable and responsive materials
- Biofabrication techniques for textiles
- Sustainability, scalability, and fashion industry adoption

Practical modules

Figure 15: Structure of the Three Training Tracks — Lab, Research, and Internship. © NXPO

Practical modules are key elements to novel curriculum especially in the age of AI and automation which necessitate unique learning outcome beyond knowledge gain. Therefore, several routes to establish practical training are necessary. In this curriculum framework, three instances of practical training tracks are encouraged as part of the courses or as a dedicated training course.

Three practical training tracks are

1. **Laboratory and technical skills training**
2. **Project-based research based on given problem statements**
3. **Internship program with partnership outside academic institutions**

Out of these three tracks, the laboratory training for technical skills is the most straightforward as they can be constructed on top of the knowledge-based module and dedicated certain class time for practical training. Some lab practicals are listed below based on knowledge-based essential modules.

On the other hand, project-based training and internship programs require thorough planning both within and outside the institutions. Examples are also provided for each track.

Laboratory and Technical Skill Track

Holistic Approach to Synthetic Biology

Lab Practical: Basic Molecular Cloning

Students will perform a simple molecular cloning experiment by inserting a gene of interest into a plasmid vector. They will use restriction enzymes to digest both the plasmid and the gene, followed by ligation to create recombinant DNA. Transformation into bacterial cells will be followed by antibiotic selection to identify successful clones. Students will verify the presence of the insert using PCR and gel electrophoresis. This hands-on exercise will familiarize them with cloning vectors, genetic selection techniques, PCR, and DNA analysis, demonstrating the core principles of molecular cloning and its applications in synthetic biology.

Lab Practical: DNA assembly reactions

Students can perform a DNA assembly reaction (Gibson, Golden Gate, etc.) and transform the assembled products into E. coli. While successful assembly can be verified via gel electrophoresis, the instructors can consider using visible gene products such as chromoproteins or fluorescent proteins as a part of their DNA assembly, so students can see successful assembly in cells (i.e. via production of bacterial colonies containing the right color)

Lab practical: CRISPR for gene editing and detection

Students can learn how to design guide RNAs for commonly used CRISPR-Cas systems (Cas9, Cas12, Cas13). Lab activities can involve testing such designs in E. coli, where students can compare gene editing activities of their different designs. For gene insertion, a comparison of Cas9-mediated insertion vs Prime editing could illustrate different design principles, off-target effects, and editing efficiencies of different methods. See further reading at [CRISPRpedia - Innovative Genomics Institute (IGI)]

Lab practical: Bioproduction of color and light

Students can characterize bioproduction of color compounds (violacein, beta-carotene, lycopene) by transformation of E. coli with expression plasmids for pigment-producing enzymes. Light-producing compounds such as luciferin produced by bacterial or fungal luciferases may also be used.

Separations and Analytical Methods

Lab Practical: Introduction to Chromatography and Separation Techniques

There are several practical activities for students to perform here. They can perform affinity chromatography to isolate protein using a specific ligand. If available, they can also use ion exchange chromatography, gel filtration chromatography or hydrophobic interaction chromatography to separate proteins based on charge, size, or hydrophobicity. Students can conduct HPLC to separate a mixture of small molecules, or electrophoretic separation (e.g., SDS-PAGE) to analyze protein purity.

Lab Practical: High-throughput Technologies

Students can learn how to design lab automation protocols to set up easy experiments such as cell growth measurements under different antibiotic concentrations. If a lab automation system is not locally available, students may still get to test their protocols remotely via collaboration with centers or labs who host automation systems for educational purposes.

Metabolic Pathway Engineering

Lab Practical: Design and Optimization of a Biomanufacturing Pathway

This section focuses on the end-to-end design of a microbial production strain. Students will select a simple metabolic product (e.g., lycopene or lactic acid) and map out the biosynthetic pathway using tools like KEGG, Biocyc, or MetaCyc. They will design a modular genetic construct to express the enzymes needed for the pathway, simulate its flux using selected predictive tools, and predict potential bottlenecks. If computational tools are available, they will perform Flux Balance Analysis (FBA) to optimize pathway yield. Finally, students will design a plan for chassis strain selection, promoter tuning, and basic scale-up conditions in shake flasks.

Bioinformatics and Data Science

Lab Practical: Bioinformatics and Data Analysis of Genomic Datasets

In this practical, students will perform basic bioinformatics workflows to analyze DNA sequencing data from engineered systems. Using publicly available datasets (e.g., NCBI SRA or iGEM Registry), students will conduct quality control with tools like FastQC, align reads with Bowtie2 or BWA, and visualize gene expression using IGV or similar tools. They will perform differential expression analysis with DESeq2 in R or Galaxy, and explore gene ontology enrichment. A secondary task involves annotation of a plasmid or synthetic construct using SnapGene, Geneious, or Benchling. Through this, students will learn how to interpret biological meaning from sequencing data and explore how design intent aligns with observed data.

Lab Practical: Computational Modeling of Genetic Circuits

Students will learn how to construct and simulate mathematical models of synthetic gene circuits using differential equations and network-based tools. The activity begins with simple toggle switch and oscillator models (e.g., repressilator), implemented using software such as MATLAB, COPASI, or other tools of instructor's expertise. Students will adjust parameters like promoter strength, degradation rate, and feedback loop strength to observe system dynamics. They will compare deterministic (ODE-based) vs stochastic models (e.g., Gillespie algorithm) to understand biological noise. Students will design a genetic logic gate and simulate its behavior under varying inputs. This exercise introduces the foundational concepts of systems biology, feedback, stability, and circuit behavior essential for predictive design in synthetic biology.

Of note, computational approaches should be implemented whenever possible to improve practical training effectiveness, which is not limited to computational focus modules. Molecular Cloning, DNA Assembly, and Genome Engineering lab practicals can be assisted with computational analysis and walkthrough. In the low-resource settings where instruments and laboratory reagents are costly, virtual laboratory style can improve students' preparation prior to actual laboratory procedures which can significantly reduce the cost needed to run teaching labs. Moreover, DIY instruments and low-cost reagent sharing should also be emphasized for sustainable training within the institution. These activities that enhance learning capacity are also beneficial to the larger community and public engagement through outreach to college or high school students should also be an option for technical training. Teaching outreach is undeniably useful training for students with interest in academic sector.

Research Project Training Track

Anticipating that some Engineering Biology students will be working in the research and development sector, conducting research projects is a holy grail for self-taught experience with appropriate mentoring. Research training should equate to that of conventional training of graduate students working toward a **thesis** but a few concerns for Engineering Biology should be encouraged. Whenever appropriate, the research project training can also start earlier in the degree timeline as a **capstone project** course irrelevant of a degree-conferring thesis.

- **Emphasize cross-team collaboration:** Since Engineering Biology is an umbrella field covering various biology and engineering disciplines, it is nearly impossible to work alone toward a breakthrough project. Therefore, training in a collaborative environment should be encouraged.
- **Partnership with non-academic institutions:** Technological advancement of the field usually gets initiated in a small academic team but requires a proper incubation environment to grow properly. Therefore, partnering with institutions beyond academic research groups can enlighten students on different methodologies and questions framing in their research project.
- **Addressing regional or local problems:** The research project, especially in Engineering Biology, usually takes time. It is important that the students immerse themselves in a real-world problem, especially ones imminent in the region. Tackling regional or even local issues can also ensure their engagement with stakeholders beyond the academic community, increasing their experience in other skill sets beyond technicality.

Scenario: Engineering a Modular Biosensor Platform for Arsenic Detection in Groundwater

As an example, scenario in this research project training track, a team of Engineering Biology students was asked to collaboratively design a modular, field-deployable biosensor system for detecting arsenic contamination in groundwater—a critical and ongoing public health issue in several regions, including parts of South and Southeast Asia.

The project begins in the second semester of the curriculum as a capstone course, where students from diverse backgrounds or interests—molecular biology, chemical engineering, computational biology, and hardware design—form interdisciplinary teams. Early on, they are introduced to stakeholders from a local environmental health agency, a water utility NGO, and a startup working on portable diagnostics, providing real-world context and use-case feedback.

Students are mentored by both academic researchers and a startup partner with expertise in cell-free systems. Throughout their capstone, they design the biosensor based on cell-free transcription-translation (TX-TL) reactions, embedded on paper-based devices, engineered to detect arsenic ions via regulatory RNA switches. Even though the basic concept of this work is not entirely new from scratch, the device fabrication and context-aware design are prominent for their capstone. These devices should produce a visual colorimetric output when activated. A subset of the team will work on optimizing the detection threshold and response time, while another subgroup will design a smartphone-based reader app for quantitative data capture and cloud integration.

Throughout the project, planned to span across the 4-5 months semester, the team holds biweekly cross-team meetings, sharing data, troubleshooting challenges, and refining design goals. They will learn to manage roles dynamically balancing wet lab work, software development, field testing logistics, and stakeholder communication. The startup partner supports the prototyping process and provides access to a semi-automated lab environment simulating real biofoundry operations.

By the end of the project, the team might be able to present a working prototype to test in-field. Additionally, they can also conduct community engagement workshop in a high-risk village area, helping them understand the broader ethical, regulatory, and user-centered design challenges involved in engineering biology solutions for real-world problems.

Internship Program Track

The internship program is not common in the engineering biology field due to the nature of the research which requires longer training time. With that, the curriculum designers need to put extra work into coordinating with other companies or institutions to enable these internship opportunities for students in the program. Internship-style training is encouraged to give trainees exposure to a real working environment in the field which cannot be learned in the regular academic set-up. The timing of internship can be adjusted based on organizational preferences. However, the longer internship time, at least 2-3 months long, will be more beneficial over the short ones due to conventionally steep learning curve in engineering biology practice. Of note, internship training at the private company or even a start-up can put students into the working environment prior to joining the job market and most of the time even increase their potential as a candidate. If an industry job is not students' career path, interning at the research institution such as national laboratories or research institutes can also provide experience in the research and development sector or even government-related tasks not available in the classroom. While the internship can be pursued alone by individual student, it is also plausible to conduct a capstone project style for an agile student working group (less than 6 members). This small team practice will be an important steppingstone especially for students with interest in entrepreneurial space. Furthermore, the internship should not be limited to only technical STEM training. Training for policy and governance section is also meaningful especially in the community where these frontier technologies are relatively new. Workforce in non-STEM tracks are necessary comparable to highly technical human resource. While this Internship Program Track is beneficial for such Graduate Degree Curricula, it should be applicable to specialized undergraduate program track as well. See Chapter 5 for further elaboration.

Scenario: Three-Month Internship at a Synthetic Biology Start-Up Focused on Biomanufacturing of Sustainable Fragrances

During the summer of their master's degree, a group of Engineering Biology students is matched with a growing synthetic biology start-up that engineers' microbial platforms to produce sustainable fragrance molecules, replacing petrochemical or animal-derived sources in the flavor and fragrance industry. The internship is coordinated by the university's engineering biology program office, which has built a partnership pipeline with emerging biotech companies. The selected students undergo a short pre-internship bootcamp to prepare for industry-standard lab protocols, regulatory expectations, and project documentation practices.

During their three-month full-time internship, students are integrated directly into project teams. One student joins the **Strain Engineering Team**, working on optimizing yeast chassis for higher product titers using iterative rounds of CRISPR editing and metabolic flux balancing through plasmid DNA design and genome editing campaigns. Another is embedded in the **Analytical Chemistry Team**, developing LC-MS workflows to quantify product yield and detect byproducts. A third intern supports the **Automation and Data Engineering Team**, helping build data pipelines and dashboard tools that analyze real-time fermentation results from bioreactors. Each intern is paired with a company mentor and attends biweekly R&D meetings. They contribute to actual company milestones, such as strain validation before scale-up or QC development for downstream processing. They also attend training on intellectual property management, quality control, and GMP readiness, which are rarely covered in academic environments.

Midway through, interns participate in a company-wide design sprint, pitching ideas for improving productivity or sustainability in their workflows. By the end, they produce a technical report and give a presentation to both the company and university partners, reflecting on what they learned and how it fits their future goals. One student decides to pursue a career in industrial strain engineering, while another becomes interested in regulatory policy for biotech and later interns with a national biosafety authority. In this scenario, the internship doesn't just enhance technical competency—it also deepens the students' understanding of team-based R&D, business timelines, and the market impact of engineered biology.

Exemplary Curriculum Assembled from Framework Modules

As a complete guideline on how to effectively use the provided framework to design a new Engineering Biology curriculum, this section serves as an exemplary curriculum for a semester-style 2-year master's degree training program at a small research institute in LMICs set-up. This curriculum takes limited instructors pool into consideration and points out notable parts which can benefit from external educators in the form of adjunct faculty members and invited lecturers.

◆ Exemplary Curriculum based on an Institution in Thailand

Given that Thailand contains rich biomass resources, possess broad agricultural landscapes, and establish itself as a medical tourism hub, the curriculum should contain relevant trainings based on the strength of the country/region. Key modules on industrial biotechnology, agricultural applications, and medical technology (especially for tropical diseases) should be included. The whole curriculum is expected to have 30-36 credits across 2 years of Master's degree:

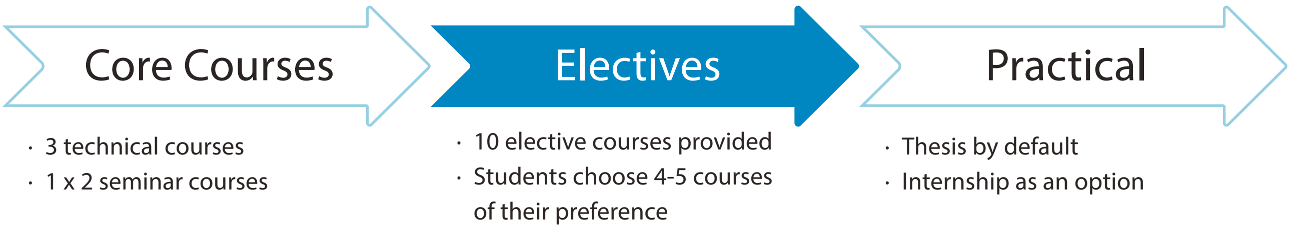


Figure 16: Needs an Illustration for This Section

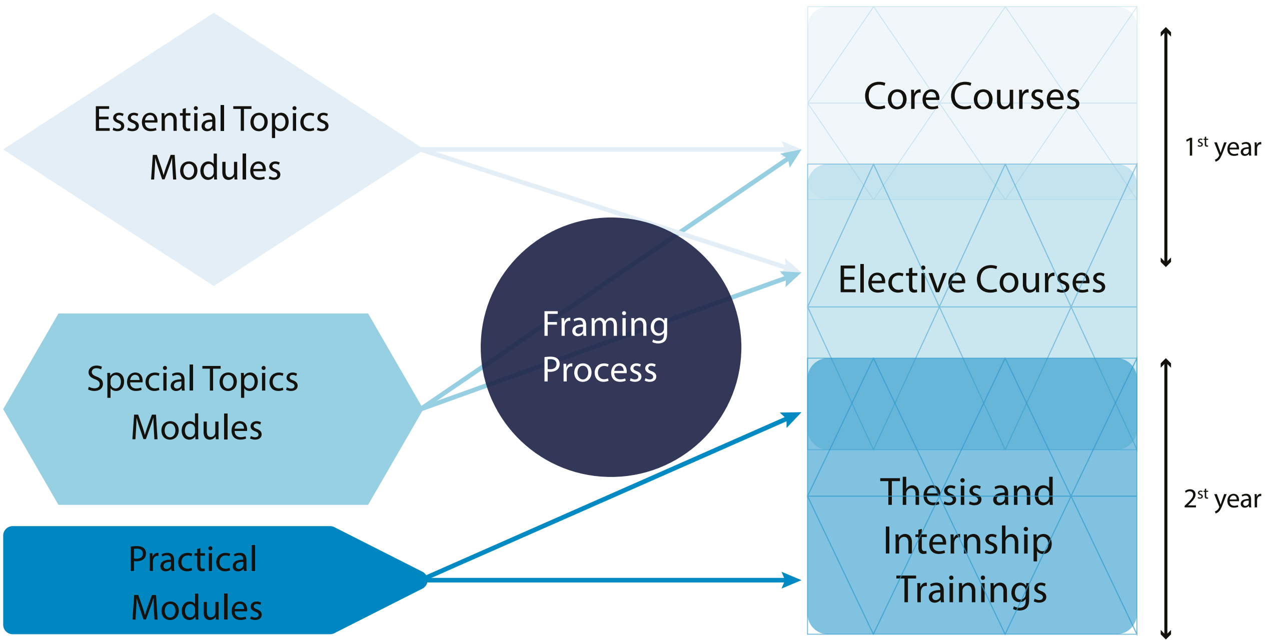


Figure 17: Another illustration showing how Framework Contents were selected for each course. Structured similarly to a fund flow diagram — with modules (Essential above Special) on the left, flowing into different courses on the right. The right side is divided into Core and Elective courses. © NXPO

◆ Core Courses (12 credits)

All students are required to take these core courses, 12 credits (may varied depending on national/regional recommendations) so that they are sufficiently equipped with basic knowledge in Engineering Biology. Contents in Responsibility Supermodule are incorporated into core courses accordingly.

1. **Fundamentals in Engineering Biology I** – covers pre-requisite contents and selected portions of Biology Supermodule
   - 4 credits for the 1st semester
2. **Fundamentals in Engineering Biology II** – covers Responsibility Supermodule and selected portions of Engineering Supermodule
   - 3 credits for the 1st semester
3. **Frontier Technology and Instrumental Techniques** – covers selected portions of Frontier Technology Supermodule
   - 3 credits for the 2nd semester
4. **Seminar on Engineering Biology** – covers some special topics with relevance to national/institutional context
   - 1 credit each for the 2nd and 3rd semesters

◆ Elective Courses (12 credits)

All students are required to take 12 credits (may vary depending on national/regional recommendations) from provided elective courses on their selections to shape their specific expertise in Engineering Biology. Given that each course has different credits allocation, students are encouraged to take 1-3 courses in the first 3 semesters prior to diving into practical training period.

1. **Effective communications in Biotechnology context** – covers parts of Entrepreneurship module
   - 2 credits for the 2nd semester
2. **Systems and Synthetic Biology** – covers Molecular Biology, Systems Biology, and Synthetic Biology modules plus some special topics modules
   - 3 credits for the 2nd semester
3. **Biomass Valorization and Precision Fermentation** – covers Biochemical Reaction, Metabolic Pathway, Organismic Engineering, and Bioprocess Design modules
   - 3 credits for the 2nd semester
4. **Bioconjugate Chemistry for Biologics Production** – covers Chemical Biology, Biochemical Engineering, and High-throughput Methodology modules
   - 2 credits for the 2nd semester
5. **Biosensors Development for Clinical Applications** – covers Sequencing Technologies, Separations and Analytical Methods, and High-throughput Methodology modules
   - 2 credits for the 2nd semester
   - Emphasis on the biosensing of tropical diseases
6. **Frugal Science and Accessible Technology** – covers Technology development for Low-resource module
   - 2 credits for the 2nd or 3rd semester
7. **Agricultural Crops Engineering** – covers Organismic Engineering, Ecology, and Regulatory Framework modules together with the dedicated special topic module
   - 2 credits for the 2nd or 3rd semester
8. **De Novo design for new-to-nature biological materials** – covers Nucleic Acids and Protein Engineering modules with dedicated special topics modules on Genetic Code Expansion and De Novo Protein Design
   - 2 credits for the 2nd or 3rd semester
9. **AI Tools in Biological Systems Modelling** – covers Bioinformatics, AI/ML, and Biological Modelling modules with dedicated special topics modules
   - 2 credits for the 2nd or 3rd semester
   - Requires an invited instructor from Computer Science departments within the institute to co-lead the course
10. **Advance Techniques in Biomolecule Characterizations** – covers Analytical Methods and High-throughput & Automation modules
    - 2 credits for the 2nd or 3rd semester
    - Requires an invited instructor from Analytical Chemistry or Structural Biology departments to assist in the specialized lectures

◆ Practical Trainings

Offer practical training in the form of a Master Thesis or Internship Program which covers Practical Modules with an option to conduct research within the institute or conduct an internship program externally. The practical training should total to 12 credits to emphasize the practical industry-relevant training appropriate to Thailand's growing Engineering Biology job market.

Master Thesis

Continuous training in a research group within the institute/ university for 2-3 semesters equivalent to 4-6 credits and total to 8-12 credits. This trajectory should be offered as a default option with an option to scale down the thesis work if internship option is incorporated into the degree-conferring requirement.

Internship Program

An optional 3-month or 6-month internship equivalent to 4-8 credits can be formulated in partnership with an external institute or a private company. Depending on career trajectory, students can explore research-oriented internship at a national laboratory or conduct policy development work at a public organization. Alternatively, students can dedicate their internship time to working in a private company which prompts them with skills needed in the industry or entrepreneurial job sectors.

◆ Exemplary Curriculum based on an Institution in Uganda

This proposed curriculum is designed based on accessible educational courses executed through SynBio4ALL Africa, officially Synthetic Biology Initiative Africa limited. The key emphasis in Africa covers the rich biodiversity utilization, the potential for alternative agricultural development, and nature conservational approaches to protect endangered species.

◆ Core Courses (12 credits)

All students are required to take these core courses (credit distribution may vary depending on institutional/ national guidelines). Responsibility Supermodule content is incorporated throughout.

1. **Fundamentals in Engineering Biology I** – covers pre-requisite contents and selected portions of Biology Supermodule
   - 4 credits for the 1st semester
2. **Fundamentals in Engineering Biology II** – covers Responsibility Supermodule and selected portions of Engineering Supermodule
   - 3 credits for the 1st semester
3. **Accessible Technology and Techniques for Low-Resource Settings** – selected portions of Frontier Technology Supermodule, emphasis on accessible tools for low-resource settings
   - 3 credits for the 2nd semester
4. **Seminar on Engineering Biology** – special topics relevant to Uganda/African context: conservation biotechnology, One Health, Nile ecosystem sustainability
   - 1 credit each for the 2nd and 3rd semesters

◆ Elective Courses (9–12 credits)

Students choose electives to specialize, typically starting in the 2nd semester. The elective courses provided should focus on regional interests, especially in Nature Conservation, Agricultural Technologies, and Frugal Science approach.

1. **Biodiversity and Conservation Biotechnology – genome editing, population genetics, and** ecological engineering applied to conservation of African species/ecosystems
   - 3 credits (2nd or 3rd semester)
2. **Biological Engineering for Food and Agriculture** – crop biotechnology, soil microbiomes, precision agriculture, and climate-resilient crops
   - 3 credits (2nd semester)
3. **Frontier Systems and Synthetic Biology in Africa** – foundations plus African use cases in various industry of Systems Biology and Synthetic Biology technologies
   - 3 credits (2nd semester)
4. **Frugal Science and Accessible Technology** – low-cost biosensors, DIY equipment, mobile diagnostics (focus on low-resource settings)
   - 2 credits (2nd or 3rd semester)
5. **Bioremediation Technology** – recent applications of Engineering Biology in remediation of industrial and agricultural waste in the land and water body. Focus on deployable technologies in Africa within the regulatory framework.
   - 2 credits (2nd or 3rd semester)
6. **Bioprospecting and Natural Products Engineering** – valorization of medicinal plants, secondary metabolites, and local resources in a sustainable and ethical framework
   - 2 credits (2nd semester)

7. **Biotechnology for Public Health** – biosensors, vaccines, and diagnostics for infectious and understudied tropical diseases
   - 2 credits (2nd or 3rd semester)
8. **Bioprocessing and Industrial Biotechnology** – fermentation and bioproduction for energy, food, and pharmaceuticals
   - 3 credits (2nd semester)
9. **AI and Bioinformatics in Resource-Constrained Contexts** – AI/ML and bioinformatics tools for biodiversity monitoring and biological systems modeling
   - 2 credits (2nd or 3rd semester)
   - Co-taught with computer science faculty
10. **Regulatory Science and Bio-Policy in Africa** – biosafety, conservation law, Nagoya Protocol, and community engagement in biotech innovation
    - 2 credits (2nd or 3rd semester)

◆ Practical Training (6–12 credits)

Students can choose to work on a Master Thesis or explore opportunities through an Internship Program. Given that internship training opportunities might not be as diverse in the high-resource region, it is recommended that the university establish partnership with companies or organizations that have ongoing work within the region so that students can train on a real-world implementation of Engineering Biology practice. Given the regional establishment, partnership with European countries/ organizations are encouraged.

Master Thesis

Ccontinuous training in a research group in the curriculum providing school or partnering school/institutes (2–3 semesters, 12 credits).

Internship Program

Optional 3–6 month internship (4–8 credits). The internship can be conducted at National labs or conservation agencies (e.g., Uganda Wildlife Authority, National Agricultural Research Organization). Students can also explore training opportunities with NGOs in biodiversity, conservation, or One Health or private sector such as agricultural business or biotech branch within the area. Finally, it is also applicable to partner with the policy and regulatory bodies, e.g. biosafety councils, conservation ministries, to work on a policy topic unique to the African region.

◆ Exemplary Curriculum based on an Institution in Chile

This proposed curriculum is designed based on general interest of South America community which has various deployment of Engineering Biology technologies. For Chile specially, the rich basis in climate sciences (with diverse ecosystems in the region from Atacama Desert, the South Pacific Sea, to Patagonia Mountains) and astronomy excellence serves as outstanding examples on how to implement regional expertise into the emerging curriculum framing. The rich knowledge established by the indigenous community is also included as an emerging area for cross-discipline learning.

◆ Core Courses (12 credits)

All students are required to take core courses (credits may vary depending on national regulations). Responsibility Supermodule content is integrated into all courses.

1. **Fundamentals in Engineering Biology I** – biology and engineering prerequisites, with examples from desert and marine biology (Biology Supermodule)
   - 4 credits, 1st semester
2. **Fundamentals in Engineering Biology II** – ethics, responsibility, biosafety, and engineering tools for high-impact technologies (Responsibility + Engineering Supermodules)
   - 3 credits, 1st semester
3. **Frontier Technology and Instrumental Techniques** – genomics, remote sensing, and astronomical methods applied to biology (Frontier Technology Supermodule)
   - 3 credits, 2nd semester
4. **Seminar on Engineering Biology** – rotating topics relevant to Chile: astrobiology, desert adaptation, marine ecosystems, biotech for mining waste remediation
   - 1 credit each, 2nd & 3rd semesters

◆ Elective Courses (9–12 credits)

Students choose electives to specialize, typically starting in the 2nd semester. The elective courses provided should focus on regional interests, especially in Climate Science and Astrobiology-relevant topics.

1. **Astrobiology and Extremophile Biotechnology** – studying life in extreme environments (Atacama

Desert, Antarctic sites) as models for planetary biology

- 3 credits, 2nd semester

2. **Marine Biotechnology and Conservation** – engineering marine organisms for aquaculture, climate monitoring, and biodiversity conservation
   - 3 credits, 2nd or 3rd semester
3. **Sustainable Mining Biotechnology** – bioremediation, biomining, and environmental monitoring in extractive industries
   - 3 credits, 2nd semester
4. **Agricultural Biotechnology in Diverse Climates** – grapevine genomics, crop engineering for arid zones, plant-microbe interactions
   - 2 credits, 2nd semester
5. **Synthetic Biology and Genetic Systems Design** – genetic circuits, microbial engineering, and systems approaches for industrial and research applications
   - 3 credits, 2nd semester
6. **Frugal and Remote Sensing Technologies** – integrating astronomy-derived imaging, satellite data, and biotech for ecosystem monitoring
   - 2 credits, 2nd or 3rd semester
7. **Natural Products and Bioeconomy** – valorization of Chile's biodiversity, including marine-derived compounds and desert microbiome products
   - 2 credits, 2nd or 3rd semester
8. **Indegenious Knowledge for Biotechnology** – leverage the knowledge accumulated through millennials by indigenous people for adaptation to modern biotechnology. Emphasis on the land-use and rights of technological deployment in nature.
   - 2 credits, 2nd or 3rd semester
9. **AI and Big Data in Biology**– machine learning for biological systems modeling, drawing parallels with astroinformatics
   - 2 credits, 2nd or 3rd semester
   - Co-taught with physics/astronomy faculty
10. **Regulatory Frameworks and International Bio-Policy** – biosafety, biodiversity treaties, intellectual property for bioproducts in South America. Focus on safe implementation benefit sharing.
    - 2 credits, 2nd or 3rd semester

◆ Practical Training (12 credits total)

Students can choose to work on a Master Thesis or explore opportunities through an Internship Program. It is also possible to partner with institutions in the North America for knowledge transfer especially with the organization that actively invest in translational Engineering Biology technology from the North to South America.

Master Thesis

Continuous lab/research group training in the curriculum providing school or partnering school/institutes (12 credits, 2–3 semesters).

Internship Program

3–6 months (4–8 credits). The internship can in partnership with National observatories or astrobiology research centers (linking biology with astronomy), Marine institutes and aquaculture companies, or Mining industries for environmental sustainability projects. It is also plausible to work with NGOs or government agencies with focus on conservation, climate, and biodiversity. Additionally, partnering with private international biotech companies is also encouraged.

Assessment Guidelines & Quality Assurance of the Curriculum

Engineering Biology is established as an interdisciplinary field that applies engineering concepts to understand, design, modify, and control biological systems for achieving desired outcomes. Effective education in Engineering Biology should encompass essential knowledge (K), practical skills (S), and competencies (C) across three core domains: biology (B), engineering (E), and technology (T), along with a strong understanding of ethics and safety. These domains help students develop the ability to solve problems in healthcare, environmental sustainability, bio-manufacturing, ethics, and safety. The potential LOs should include the following elements.

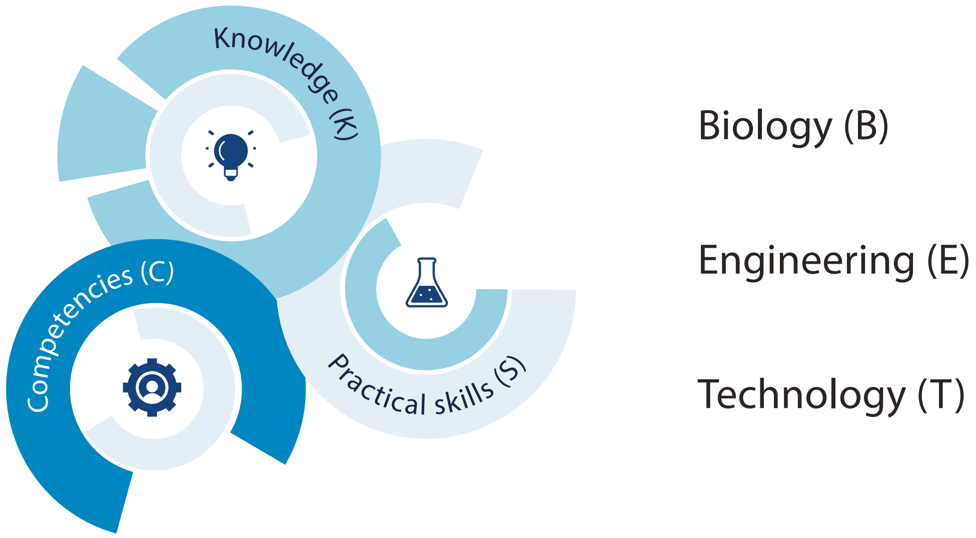


Figure 18: A figure/diagram needs to be re-drafted for this section to illustrate the described structure and relationships. © NXPO

◆ Potential Learning Outcomes (LOs)

1. Essential Knowledge Foundations (K)

- **Biological Systems (K-B):** be able to apply fundamental principles of biological systems—including cellular structure, genetic mechanisms, protein functions, and metabolic networks—to design biological systems for specific applications; be able to think quantitatively about biological systems and biological phenomena. *This section should be evaluated based on the coverage of essential modules under Biology Supermodule in the designed curriculum.*
- **Molecular Biology** (K-B): be able to utilize molecular biology principles to effectively engineer biological systems to achieve targeted outcomes. *This section should be evaluated based on the coverage of essential modules under **Biology** Supermodule in the designed curriculum.*
- **Engineering Principles** (K-E): be able to integrate core engineering principles (e.g., thermodynamics, circuit control) within biological contexts to optimize performance and ensure standardization. *This part should be evaluated based on the coverage of essential modules under **Engineering** Supermodule in the designed curriculum.*
- Emerging Technologies (K-T): be able to understand emerging (high-throughput) technologies and their measured data, which will enhance in-depth comprehension of complex biological systems and contribute to future systems engineering. *This part should be evaluated based on the coverage of essential modules under **Frontier-Technology** Supermodule in the designed curriculum.*

2. Practical/Technical Skills (S)

- **Critical Planning** (S-B/S-E): Be able to design Engineering Biology workflow to optimize processes in the given time frame and resources. *This section should be evaluated based on the design and execution of **Practical** Modules, particularly on the Research Project part.*

- **Molecular Engineering** (S-B): Be able to perform molecular manipulation techniques, including CRISPR, gene cloning, and synthetic biology approaches. *This section should be evaluated based on the design and execution of* ***Practical*** *Modules, particularly on the* ***Laboratory and Technical*** *part.*
- **Bioinformatics & Data Analysis** (S-T): be able to analyze large biological datasets using high-throughput technology to extract meaningful insights. *This section should be evaluated based on the design and execution of* ***Practical*** *Modules.*
- **Computational Modeling** (S-E): be able to develop models to predict biological behavior and optimize engineering designs; be able to use the models for guiding effective experimental designs. *This section should be evaluated based on the design and execution of Practical Modules.*
- **Design & Innovation** (S-E): Be able to create, optimize, and scale biological systems for synthetic biology, biotechnology, and bio-manufacturing applications. *This section should be evaluated based on the design and execution of* ***Practical*** *Modules, particularly on the* ***Laboratory and Technical part***.

3. Competencies (C)

Students should develop:

- Problem-Solving Skills for tackling complex biological engineering challenges.
- Critical Thinking Abilities to analyze data and design solutions effectively.
- Communication & Teamwork skills to collaborate in interdisciplinary settings.
- Responsible decision-making ability to justify choices with clear rationale and take accountability for outcomes, ensuring responsible action in diverse situations

4. Ethics & Safety

- Ethical & Social Considerations: Understand the societal, legal, and environmental implications of genetic engineering, synthetic biology, and biotechnology.
- Safety Protocols: Follow biosafety standards when handling biological materials, including genetically modified organisms (GMOs) and hazardous agents.

These learning outcomes (LOs) serve as foundational elements for cultivating student skills and competencies within the Engineering Biology program. Additional LOs may be incorporated to support specialization areas that reflect the unique attributes of each individual program. The development of required learning outcomes (LOs) is effectively supported through active learning, problem-based learning approaches, and a well-structured series of assessments.

◆ Assessment Strategies for Engineering Biology Curriculum

To achieve the learning outcomes in Engineering Biology curriculum, effective measures of student learning and feedback activities should be established to ensure continuous improvement. Data analytics may be employed to track student performance trends, identify at-risk students, and provide targeted interventions. Additionally, it can help assess whether the learning outcomes are being effectively met. The assessment strategy should be diverse, incorporating various formats to evaluate different skill sets. Strategies narrated in this section should be adapted to any courses provided in the Engineering Biology curriculum designed using this framework.

1. Formative Assessments (Ongoing Evaluations)

These assessment track student progress and provide feedback for improvement:

- Weekly quizzes
- Laboratory reports
- Peer reviews of quizzes and reports
- Conceptual exercises and case studies

2. Summative Assessments (Final Evaluations)

These assess overall competency and understanding:

- Comprehensive exams (both theoretical and practical)
- Capstone projects or thesis work demonstrating real-world application
- Presentations and defense of project results

3. Performance-Based Assessments

Students apply their skills in practical settings:

- Design Challenges (e.g., synthetic biology solutions, bioprocess development)
- Lab-Based Assessments, including troubleshooting experiments and prototyping biological systems

4. Portfolios & Self-Assessment

- Learning Portfolios: Encourage students to document their work and progress over time.
- Peer & Self-Assessments: Develop self-reflection and collaboration skills.

5. Continuous Feedback & Improvement Mechanisms

To ensure learning effectiveness, continuous feedback must be integrated:

- Timely Feedback: Provide constructive responses on exams, assignments, and projects.
- Feedback Mechanisms: Gather student input via evaluations, focus groups, and industry advisory boards.
- Program Review: Regularly assessing the curriculum, adopting new technologies and addressing knowledge gaps.

◆ Quality Assurance in Engineering Biology Education

Quality assurance in Engineering Biology education ensures that students not only acquire the necessary technical skills but also develop essential competencies such as critical thinking and problem-solving. These guidelines emphasize maintaining academic standards, fostering continuous improvement, and aligning educational outcomes with industry and societal demands. To implement effective quality assurance in Engineering Biology education, the following strategies should be adopted.

1. Curriculum Design & Alignment

- Clear Learning Outcomes: Define measurable goals aligned with industry standards.
- Interdisciplinary Integration: Ensure seamless incorporation of biology, engineering, and computational sciences.
- Active Learning: Use project-based learning, lab experiments, and case studies to enhance student engagement.
- Stakeholder Involvement: Consult industry experts and accrediting bodies regularly to ensure relevance; expand scope of stakeholders to involve potential end-users of technologies, government and regulatory agencies, etc.

2. Quality Assurance Mechanisms

Accreditation & Standards Compliance: Adhere to recognized accreditation frameworks (e.g., ABET) and industry regulations (e.g., FDA).

- Instructor Qualifications & Development: Ensure faculty possess academic and practical expertise, with continuous professional development encouraged.
- Monitoring Learning Outcomes: Evaluate student success through surveys, alumni feedback, and employment tracking.
- External Peer Review: Engage industry and academic experts to refine teaching methods and curriculum effectiveness.
- Benchmarking: Compare program quality against peer institutions and industry best practices

Engineering Biology Accreditation Checklist

This checklist defines the minimum quantitative and engineering competencies expected for graduates of Engineering Biology programs. It ensures that graduates are equipped in biological sciences and also engineering capacities including predictive design, quantitative reasoning, and systems-level engineering, consistent with the interdisciplinary vision of engineering biology. Particularly, graduates are expected to adapt descriptive biology with Design–Build–Test–Learn (DBTL) cycles grounded in quantitative processes.

◆ Competency Domains

1. Quantitative Modeling of Biological Systems

- Ability to construct and analyze mathematical models of biological processes

2. Data-Driven and Computational Skills

- Ability to Process biological datasets (omics, sequencing, phenotypic data)
- Apply statistical inference and basic machine learning
- Integrate experimental and computational workflows

3. Predictive Design and Engineering Thinking

- Application of forward engineering approaches: Model → Design → Implementation → Validation
- Standardization frameworks (e.g., modular parts, abstraction hierarchies)

4. Systems Integration Across Scales

- Ability to connect models across biological scales: Molecular → Cellular → Population → Bioprocess

5. Measurement, Validation, and Uncertainty Quantification

- Competence in Experimental design for model validation
- Competence in Quantitative measurement techniques (e.g., fluorescence, sequencing)

◆ Accreditation Criteria (Checklist)

- ❑ Integration of mathematics, computation, and biology across curricula
- ❑ At least one project-based course requiring predictive modeling
- ❑ Evidence of closed-loop DBTL training
- ❑ Use of real-world datasets and experimental validation
- ❑ Assessment of quantitative reasoning
- ❑ Inclusion of uncertainty, risk, and reproducibility analysis
- ❑ Accessibility, inclusivity, and responsibility in research design practice

Goals and Objectives of the Curriculum

Engineering Biology is established as an interdisciplinary field that applies engineering concepts to understand, design, modify, and control biological systems for achieving desired

Figure 19: Sustainable Development Goals (SDGs) with Highlights. © NXPO

◆ Equip Educators and Students with UN Sustainable Development Goals (SDGs)

Engineering Biology curriculum is fitting for incorporation of the United Nations Sustainable Development Goals (SDGs) to ensure that students and educators are not only developing cutting-edge biotechnological solutions but are also aligning their contributions with global priorities for people, planet, and prosperity. Engineering Biology has the potential to contribute meaningfully to various SDGs including SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), SDGs 14 & SDG 15 (Life Below Water & Life on Land).

For Educators:

- Integration of SDG-relevant challenges into course design, laboratory exercises, and capstone projects encourages interdisciplinary thinking of the curriculum designing teams.
- Use project-based learning and real-world case studies to link technical content with societal impact: e.g., designing biosensors for environmental monitoring (SDG 6) or developing engineered probiotics for malnutrition (SDG 2).
- Emphasize systems thinking and ethical reasoning to address trade-offs, unintended consequences, and equity considerations embedded in sustainable development.

For Students:

- Cultivate the mindset of engineering for global benefits, recognizing the broader implications of their research and design choices.
- Embed sustainability goals into research training tracks, such as engineering biodegradable materials, optimizing microbial consortia for climate resilience, or designing low-cost diagnostics for underserved communities.
- By embedding the SDGs throughout the Engineering Biology curriculum, students not only advance scientific literacy but also cultivate responsible, future-ready innovations for building a more equitable and sustainable world.
- Learn to map project outcomes against specific SDG targets and indicators, preparing them for impact-driven careers in academia, industry, and public policy. See Job Opportunities and Career Prospects below.

◆ Job Opportunities and Career Prospects in Food and Agriculture

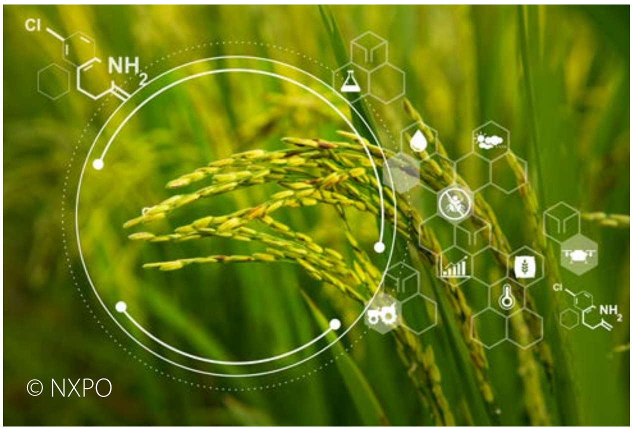


Figure 20: Illustrative Images Representing Food and Agriculture in Thailand

The field of engineering biology presents promising career opportunities for individuals interested in sustainable food production, regenerative and sustainable agriculture, and microbial fermentation technologies. With the rise of biotechnology startups focusing on alternative proteins, precision agriculture, and bio-based solutions, graduates in engineering biology have opportunities to play a crucial role in developing sustainable and innovative food and agricultural systems. In addition, many global and lead companies in these sectors have developed innovative technologies to create new business opportunities based on engineering biology principles to. As technologies developed within companies are generally not revealed to the public, we thus focus discussion of job opportunities for engineering biology graduates based on technological development by startups. Specific technology job sectors which would value high skilled workforce trained in engineering biology are listed below.

1. Alternative proteins and sustainable food production

Graduates in engineering biology can pursue careers in research and development, process optimization, and product formulation in companies developing technologies in alternative proteins and sustainable food production such as Promyc, Solar Foods, Air Protein, and Nature's Fynd. These companies are pioneering in the production of novel protein sources through microbial fermentation and gas fermentation. Roles such as fermentation scientists, metabolic engineers, and food process engineers are highly sought after in these companies. Experts can help optimize microbial strains, improve fermentation yields, and scale up sustainable protein production. Additionally, there are opportunities in job sectors related to regulatory affairs, quality control, and sustainability. Trainee in engineering biology can work as consultants to ensure that alternative protein products meet safety standards, and their production process are commercially viable.

2. Regenerative and precision agriculture

Startups such as Pivot Bio and Provivi offer career prospects in sustainable agriculture, focusing on reducing reliance on synthetic fertilizers and chemical pesticides. Engineering biology graduates can work as microbial ecologists, agronomists, and bioinformatics specialists to design and optimize beneficial microbial strains that enhance soil fertility and plant growth. Opportunities exist in an R&D sector to innovate precision pest control strategies (e.g. vaccine and bacteriophage) and molecular diagnostics for field deployment. An example is the Thailand ShrimpGuard project, funded by the International Development Research Centre (IDRC) of Canada, which was aimed to formulate phage cocktails against antimicrobial-resistant vibriosis in shrimp farming in ASEAN. In addition, there are roles in field application research, where professionals test and validate biofertilizer and biopesticide efficacy and employ on-site pathogen/contaminant diagnostics under real-world agricultural conditions. Careers in regulatory science and intellectual property management are also relevant, as these companies navigate complex agricultural regulations and patents related to microbial innovations.

3. Fermentation and synthetic biology for agriculture

Companies such as Kinnva are driving innovations in synthetic biology and fermentation to create sustainable feeds and biomaterials from greenhouse gas. Graduates with expertise in metabolic engineering, strain development, and bioprocess optimization can work as bioprocess engineers, synthetic biologists, or fermentation specialists. These professionals focus on engineering microbial systems to convert greenhouse gases such as methane into valuable products such as feed-grade proteins and bio-based chemicals. Additionally, career opportunities are also available in downstream processing, quality assurance, and techno-economic analysis, where experts evaluate the cost-effectiveness and scalability of bio-based solutions for global agricultural markets.

Overall, engineering biology graduates entering the food and agriculture industry can contribute to solving pressing global challenges such as food security, climate change, and resource efficiency. With the demand for sustainable and bio-based solutions rising, professionals in this field can expect diverse career paths spanning research, manufacturing, regulatory affairs, and entrepreneurship. By leveraging their expertise in microbial engineering, fermentation, and process development, graduates can drive innovation and create a more resilient and sustainable agricultural ecosystem.

◆ Job Opportunities and Career Prospects for Energy and the Circular Economy

Figure 21: Images Representing Energy and Circular Economy in Thailand (e.g., Suzdee Startup)

The intersection of engineering biology with energy production and the circular economy presents a wide array of career opportunities for graduates with expertise in synthetic biology, bioprocessing, and sustainable materials. As industries shift towards reducing carbon footprints and enhancing waste utilization, biotechnology startups play a crucial role in developing innovative solutions that transform waste gases, organic residues, and renewable feedstocks into valuable bio-based products. Graduates in this field can contribute to the development of sustainable fuels, biodegradable plastics, and novel biomaterials, ensuring a cleaner and more resource-efficient future. Specific technology job sectors which would offer jobs for highly skilled workforce trained in engineering biology are listed below.

1. Carbon recycling and synthetic biology for energy

Startups such as LanzaTech, Kiverdi, and Mojia Biotech are pioneering the transformation of carbon emissions and renewable feedstocks into biofuels, chemicals, and sustainable materials. Engineering biology graduates can pursue roles as metabolic engineers, fermentation scientists, and process engineers, where they work on optimizing microbial strains and fermentation processes for the efficient conversion of carbon rich waste gases into ethanol, bioplastics, or specialty chemicals. Additionally, careers in bioprocess development and scale-up engineering offer opportunities to bridge the gap between laboratory research and industrial-scale production. Hiring workforce with such skillsets would ensure the feasibility and efficiency of biomanufacturing processes. Professionals in this field also have opportunities to work in job sectors related to regulatory affairs and sustainability analysis, ensuring that these novel bioproducts meet global environmental and industry standards.

2. Waste utilization and the circular economy

With increasing demand for sustainable materials and waste-to-value technologies, companies such as Genecis and C16 Biosciences develop technology to utilize organic waste and renewable feedstocks to produce biodegradable plastics and alternative oils. Graduates with expertise in microbial engineering, synthetic biology, and bio-based material science can find employment as biopolymer researchers, fermentation specialists, and sustainability consultants. These roles involve designing microbial consortia to convert food waste into biopolymers like PHAs, optimizing microbes to produce bio-based oils in replacement for production by traditional palm oil industries. Such companies would integrate synthetic biology tools to enhance product yield and performance.

3. Cross-disciplinary roles and future prospects

Beyond core R&D and production roles, engineering biology graduates can also explore career paths in data science for biotechnology, bioinformatics, AI-driven enzyme engineering and metabolic modeling. Many of these companies rely on computational tools to optimize fermentation processes, predict microbial performance, and enhance enzyme and strain performance. Moreover, professionals with skills in business development, venture capital, and intellectual property management are in demand to help biotech startups commercialize their innovations and navigate regulatory landscapes.

Currently, the use of artificial intelligence (AI) technology in design or decision-making in synthetic biology is becoming increasingly popular. This is because it can reduce research time and processes, as well as save losses in unnecessary research budgets by predicting parameters or variables that are not important, which can lead to unsuccessful experiments. This results in a reduction or elimination of some testing steps in laboratory settings. Therefore, skilled personnel in the Engineering Biology industries should promptly improve their skills in artificial intelligence technology to facilitate rapid advancements in the field.

As global industries transition toward bio-based solutions, engineering biology graduates have the potential to drive sustainability initiatives and create breakthrough technologies in energy and the circular economy. Whether in research, production, or commercialization, the skills acquired in microbial engineering, synthetic biology, and fermentation technology will be instrumental in shaping the future of clean energy and sustainable materials.

◆ Job Opportunities and Career Prospects by Job Sectors

Since Engineering Biology is a rapidly growing field that intersects biology, engineering, and other interdisciplinary subjects to address global challenges, graduates equipped with Engineering Biology competencies will be highly competitive across a range of sectors. This section outlines typical job roles and opportunities across four key sectors: Academia, Industry, Government, and Entrepreneurship. These job opportunities listed serve as examples and are not intended to limit the prospect of individuals career path.

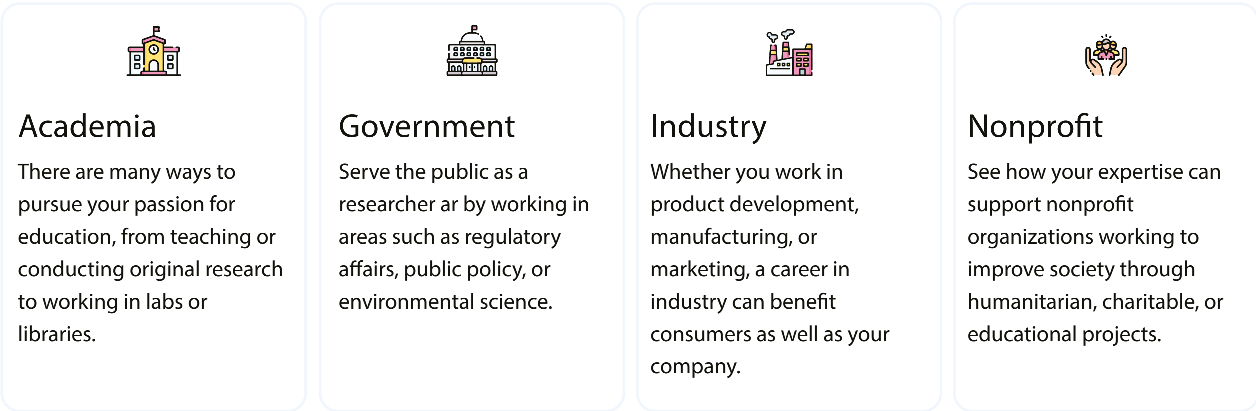


Figure 22: Diagram Showing Four Plausible Job Sectors in Engineering Biology (ACS-style). © NXPO

Academia and Research Institutes

Engineering Biology graduates will play critical roles in shaping the future of scientific discovery and education. Academic institutions and research centers increasingly demand interdisciplinary researchers and educators who can drive innovation across traditional boundaries.

Common Roles:

- Postdoctoral Researcher or Research Fellow
- Principal Investigator or Group Leader (after advanced training)
- Lecturer or Professor in Synthetic Biology, Bioengineering, or Biotechnology
- Core Facility Scientist (e.g., Biofoundry or Genomics Center)
- Educational Program Designer or Curriculum Developer

Industry and Biomanufacturing

The industrial sector offers diverse roles for Engineering Biology professionals in sectors like biopharmaceuticals, bio-based chemicals, food tech, and green manufacturing. Companies seek talent in strain development, fermentation, analytical methods, and product innovation.

Common Roles:

- Synthetic Biologist or Metabolic Engineer
- Bioprocess Engineer or Fermentation Scientist
- R&D Scientist (e.g., enzyme engineering, precision fermentation)
- Regulatory Affairs Associate (bio-based products, GMOs)
- Product Development Specialist (e.g., bio-based materials, diagnostics)
- Application Scientist or Technical Consultant

Government, Policy, and Public Sector

Engineering Biology is increasingly relevant in public policy, national bioeconomy strategy, and biosafety oversight. Government agencies, science councils, and intergovernmental organizations seek professionals who can bridge science and governance.

Common Roles:

- Scientific Advisor for Bioeconomy or Biotech Policy
- Regulatory Scientist or Biosafety Specialist
- Program Manager (Science Funding or International Collaboration)
- Science Communicator or Outreach Coordinator
- Analyst or Policy Fellow in Biosecurity and Ethics

Entrepreneurship and Startups

With the rise of the bioeconomy, Engineering Biology graduates are increasingly founding or joining startups. Entrepreneurial careers can range from building novel biotech platforms to solving local problems through engineered biological solutions.

Common Roles:

- Startup Founder or CTO (synthetic biology, biomanufacturing, diagnostics)
- Technical Co-Founder (R&D and IP strategy)
- Venture Lab or Incubator Fellow
- Innovation Officer in Tech Transfer Offices
- Business Development Analyst (bio-based ventures)

◆ Barriers and Solutions in Thailand's Bioeconomy Development

National and Local Challenges

Thailand's bioeconomy faces structural issues stemming from political instability and bureaucratic inefficiencies. The country's frequent government transitions and changes in investment directions have caused inconsistent policy directions, affecting long-term scientific and economic planning. This instability hinders stable research funding, disrupts public-private collaborations, and delays regulatory reforms.

At the smaller scale in different regions of the country, Thailand's bioeconomy ambitions are hampered by uneven regional development. While Bangkok and the Eastern Economic Corridor (EEC) received significant infrastructure and investment in the past decade, other regions lag behind in research capacity, technology access, and skilled workforce availability. This creates disparities in bioeconomy implementation and limits the nationwide impact.

Possible solutions that are applicable to Thailand's bioeconomy and countries of similar issues include:

- Establishing independent scientific advisory bodies to ensure continuity in bioeconomy policies, even during political shifts. This is partly done through the establishment of BCG model but can be improved with continuity of workforce behind the policy enactment.
- Implementing legally binding research and innovation roadmaps that remain consistent across administrations.
- Strengthening regional bioeconomy hubs with tailored research and development funding and infrastructure support beyond major cities.
- Encouraging technology transfer and workforce training programs across provinces.

Misconception Management

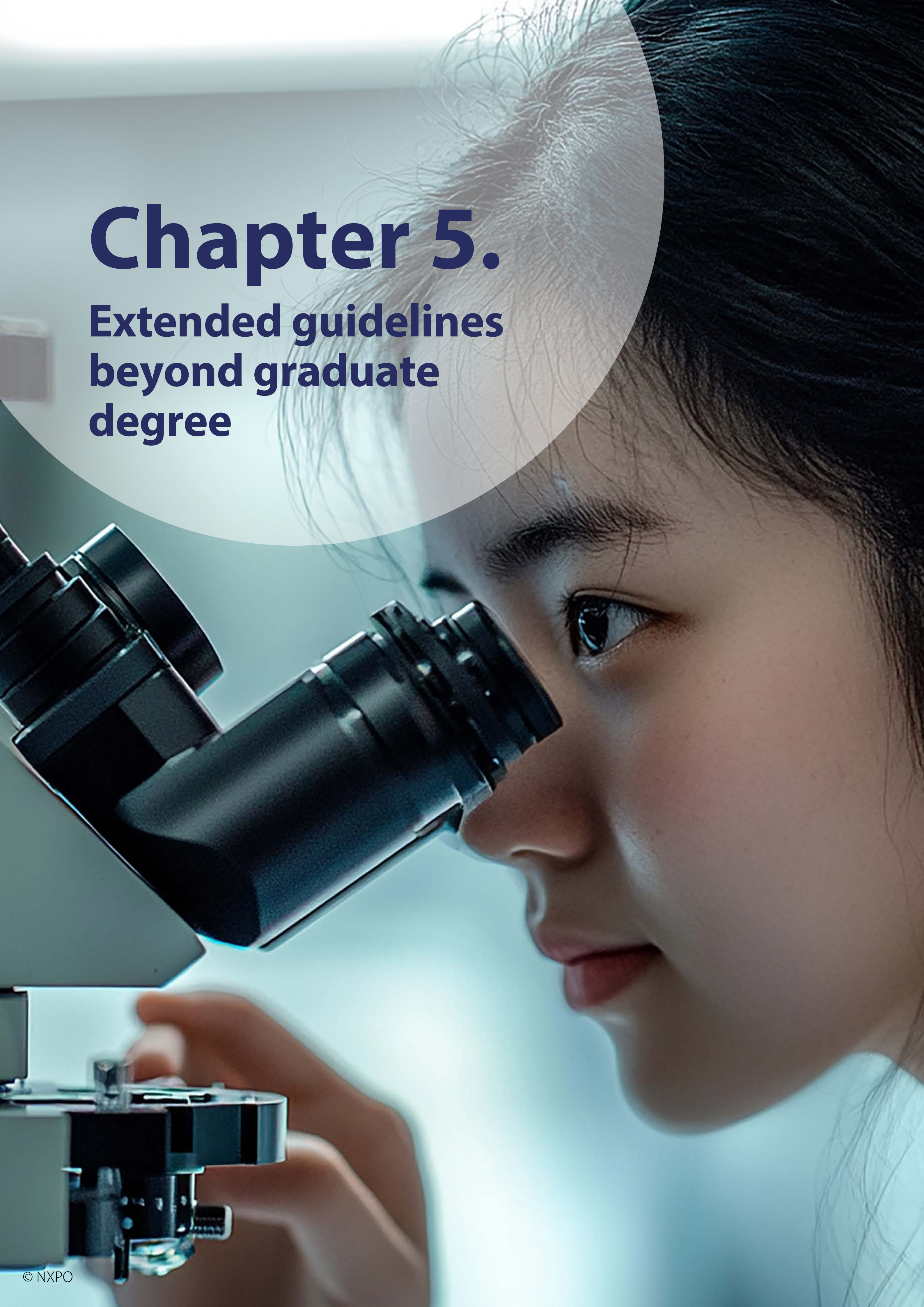
Public and stakeholder misconceptions regarding bioeconomy risks and benefits can impede policy adoption and public trust, thus affecting the success of curriculum framework execution as well. Concerns over environmental risks, exploitation of natural resources, and scientific transparency fuel skepticism in the developing countries like Thailand. Misconceptions surrounding Synthetic Biology and Genetic Engineering technologies can be demystified if the students trained under this curriculum framework join the workforce and public, supporting sustainable development of the bioeconomy both directly as the workforce and indirectly as part of the public.

Regulatory Guidelines

The lack of cohesive guidelines and regulatory frameworks for bioeconomy practices leads to fragmented governance and thus hindering the ability of trained professionals in the system. The vaguely described policy and inconsistent enforcement will reduce international/external investment and slow down the pace of innovation. Thus, the national standards and best practices should be established including clear regulatory protocols for synthetic biology research, biomanufacturing industry, and biological data management. There are various international standards from UN-CBD, OECD, and WHO that can be harmonized with the nationally crafted one which will also promote cross-border collaborations with countries/institutions that share the same regulatory framework.

Chapter 5.

Extended guidelines beyond graduate degree



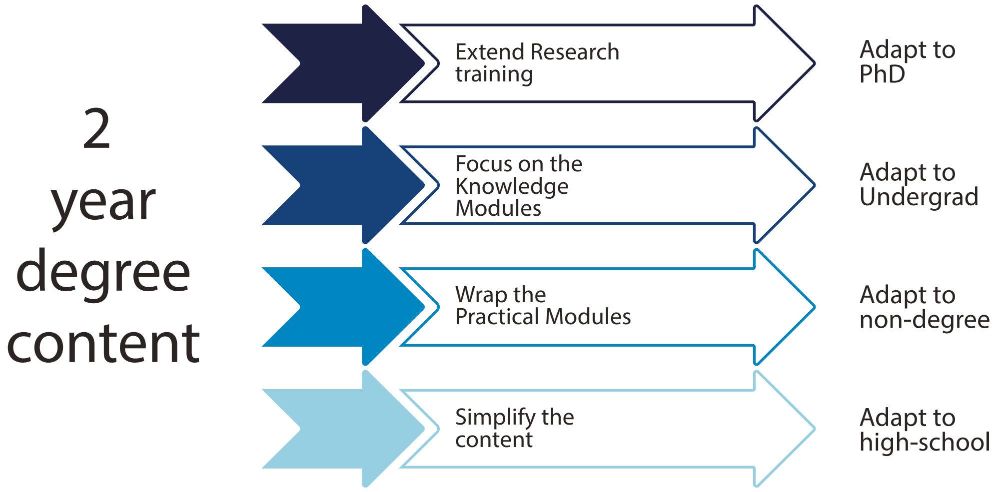


Figure 23: Pending Diagram Showing Repurposing of the Master Framework Across Educational Levels. © NXPO

Brief Guideline for PhD Curriculum

Doctoral programs in Engineering Biology or related programs should emphasize original research while cultivating technical depth, interdisciplinary fluency, and translational vision. There are various PhD programs offering Engineering Biology relevant programs already established in the high-resource ecosystems. The PhD program is a huge investment with slower return to the LMICs ecosystems. However, a strong PhD curriculum is obligatory to advance national research infrastructure to be globally competitive. Thus, this curriculum framework suggested that the PhD program in Engineering Biology, if were to be provided, should offer:

- **Foundational Core Courses:** Equivalent of the master's program courses listed in Chapter 4 of this framework.
- **Research-Driven Training:** Students should focus majority of their time to the individual research project. To consider providing a PhD option, the host institute should be aware of necessary infrastructure, e.g. permission to conduct biosafety research and waste management, and sufficient resources and long-term research funding.**Professional Development:** Include training in research proposal writing, public communication, and entrepreneurship training to prepare students for leadership roles post-graduation.
- **Collaboration and Global Outlook:** PhD students should be encouraged to participate in interdisciplinary consortia (e.g., EBRC SPA, SynBioCDT, IBISBA) or regional community and pursue collaborations or internships across sectors.

A typical PhD pathway would span 4–6 years, integrating coursework, teaching assistantships, and a dissertation contributing novel research to the field. Institutions in LMICs may partner with international research networks to offer remote mentorship, data access, or shared research platforms.

Brief Guideline for Undergraduate Curriculum

Due to extensive pre-requisite of Engineering Biology knowledge narrated in this curriculum framework, it may not be optimal for designing a standalone undergraduate curriculum alone. However, as the bachelor's degree should be designed to excite, engage, and equip students with core knowledge, it might be possible to offer the graduate courses already provided for master's students to enthusiastic undergraduate students as is. To ensure that the breadth and adaptability remain, key components to be considered for an undergraduate track include:

- **Introductory Engineering Biology:** An introductory course listed in Chapter 4 should be a pre-requisite prior to enrolling into specific courses unless other courses have sufficiently prepared students for that core course.

- **Foundational Core Courses:** Equivalent of the master's program courses listed in Chapter 4 of this framework.
- **Interdisciplinary Electives:** Options such as ethics, environmental applications, AI for biology, or bioeconomy entrepreneurship should be provided for undergraduate curriculum. This is equivalent to special topics modules described in Chapter 4.
- **Capstone Projects or Research Experiences:** Students should be encouraged to conduct hands-on research by applying what they've learned to resolve real-world or regionally relevant challenges. Furthermore, an internship option as described in Chapter 4 can also be adapted for undergraduate research training.

Institutions without the ability to offer a full major can integrate an Engineering Biology track within biology, chemistry, or bioengineering degrees, or offer it as a certificate or minor. Partnerships with research institutes or companies can enrich learning through internships, competitions (e.g., iGEM or other local leagues), or innovation challenges.

Brief Guideline for Professional Training (Non-Degree Certificate Programs)

Professional training programs serve current workers, career-switchers, or lifelong learners who seek to gain technical proficiency or domain-specific knowledge in Engineering Biology. These programs can be designed as short courses (<12 weeks) or long certificate programs (>3 months).

◆ Short Courses (2–12 weeks)

A short training can be offered to individuals with background in research and development work sector where they can train new skills on emerging ground-breaking techniques such as

- CRISPR and genome editing
- Microbial strain engineering
- Biomanufacturing and biofoundries

◆ Certificate Programs (3–6 months)

A long certificate program can culminate in a project or applied practicum during the training. It is also possible to partner with organizations in need of workforce expansion so that they can train their new workers or re-train their existing workforce to be equipped with Engineering Biology skill sets. Target audiences should be inclusive to:

- Industry technicians needing upskilling
- Government or NGO professionals working on biosafety or bioeconomy policies
- Educators or science communicators
- Entrepreneurs exploring biotech ventures

Programs should be modular and adaptable to regional industry needs, and may be hosted at universities, research centers, or through industry-academic collaborations. Use of Open Educational Resources (OER) and virtual labs can broaden access and support scalability across LMICs.

Brief Guideline for Pre-College Content (High School and Earlier)

Inspiring the next generation of Engineering Biology practitioners requires engagement at the high-school level, with age-appropriate content that builds curiosity, foundational science knowledge, and ethical awareness. Recommended elements include:

◆ Main High School Curriculum

- Modular units on genetics, synthetic biology basics, and sustainability themes.
- Integration with national science standards and inclusion in biology or STEM electives.
- Project-based modules (e.g., simple DNA extraction, genetic switch modeling, bio-art).

◆ Extracurricular Programs

Participation in iGEM High School, bio-maker clubs, or science fairs focused on bioengineering.

- Summer camps and virtual bootcamps with guest scientists and global peers.

◆ Teacher Training and Curriculum Toolkits

- Provide high school teachers with modules, hands-on protocols, and access to biosafety guidelines.
- Develop context-specific case studies (e.g., synthetic biology for clean water or crop resilience in Southeast Asia).

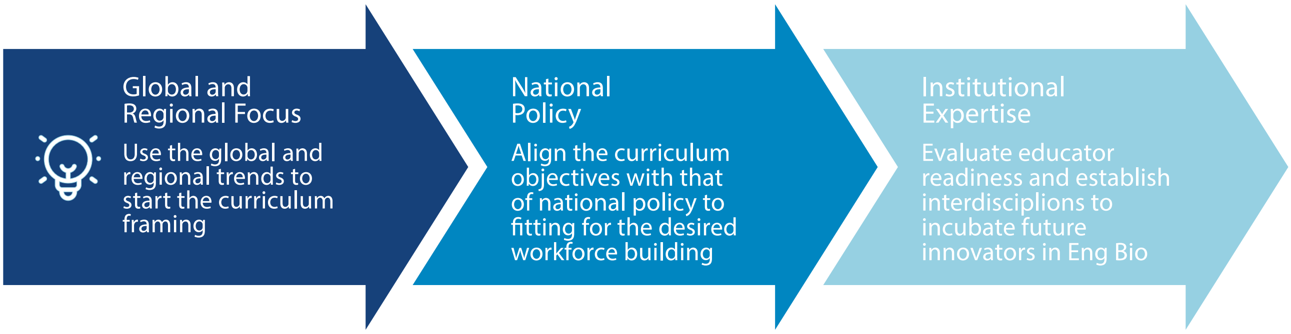
◆ Outreach and Awareness

- Introduce societal themes: What is a GMO? Can biology solve plastic pollution?
- Use storytelling, games, and arts to bridge science and society from an early age.

By establishing these foundational layers early, Engineering Biology becomes more inclusive, equitable, and relevant to diverse global communities and future workforce demands.

Concluding Remarks

This framework is crafted to ensure global readiness on workforce preparation in Engineering Biology research, industry, and relevant sectors. This document starts by reviewing the importance of Engineering Biology through its historical meaning and policy stance, navigates the existing initiatives at the regional and national level through the institutional modules widespread in the resource-abundant community, the readers of this framework are expected to repurpose the information provided to design the curriculum that best fits the regional and institutional context. It is important that the student background and educator expertise are taken into consideration for the new curriculum design. External collaboration with local and global stakeholders is encouraged for workforce-limited institutions. The later half of this document is a collection of relevant topics in Engineering Biology which were categorized by essentiality with further grouping by disciplines. Using a small research institute in Thailand as a representative context, the narrative for framing a new curriculum for Southeast Asian community is showcased.



Appendices

Notable references from the Spirit of Asilomar meeting

- 5.3 Broadening Science Education within Existing Structures
- 6.2 Accessible Biotech Education

General Resources from Entreaty 5.3

- Community Partnerships Playbook: How to Create Equitable Partnerships
- between Technical and Community Experts (Cutler et al., 2024)

- A Pedagogical Model for Team-Based, Problem-Focused Interdisciplinary Doctoral Education (Bosque-Pérez et al., 2016)
- Broadening Horizons: How STEM-in-Society Programs Train Socially Responsible Scientists, Engineers, and Policy Leaders (Burkett, 2025)
- Deconstructing synthetic biology across scales: a conceptual approach for training synthetic biologists (Karim et al., 2024)
- External Review of Ethical, Legal, Environmental, Safety, Security, and Societal Issues of Engineering Biology Research and Development (In progress)
- National Informal STEM Education Network (NISE Net)
- NASA Ames Life Science Data Archive - Open Science Data Repository
- National Institutes of Standards and Technology (NIST) BioRespository
- DIYBio.org
- European Synthetic Biology Society
- SynBio4ALL Africa
- Synthetic Biology Africa (SBA)
- SynBio Alliance
- The Key Attributes Employers Are Looking for on Graduates' Resumes (Gray and Koncz, 2024)
- The Career-Ready Graduate: What Employers Say about the Difference College Makes (Finley, 2023)

Networks, organizations, and initiatives directory relevant to Open Education

- **HTGAA from MIT Media Lab** | Website - 2025. htgaa.org

'How to Grow (Almost) Anything,' abbreviated as HTGAA, is an MIT, Harvard, and global synthetic biology course that instructs students on concepts and skills that are both foundational and at the cutting edge of bioengineering. The course is provided in-person to students at MIT and Harvard students but also to a global classroom of virtual students. Additionally, there is a growing network of HTGAA 'nodes' around the world where students can join in-person regionally, or learn with a virtual cohort in the same time-zone. The instructor team comprises both global and MIT/Harvard teaching assistants working with students in their region, in recent years increasingly leveraging the power of automation and robotics for distance-learning.

- **SynBio4ALL Africa** | Website - SynBio4ALL Africa

SynBio4ALL Africa is a non-profit organization spearheading collaborative, community-driven education by offering free and accessible synthetic biology learning opportunities tailored to the African context. Their virtual courses are designed to provide foundational knowledge through context-aware lectureship and hands-on, project-based modules. Since 2023, the initiative has engaged learners from various African countries (and other low-resource regions) and continues to grow through regional partnerships and mentorship networks.

- **iBiology** | Website - www.ibiology.org

iBiology is a nonprofit science communication platform—in partnership with Science Communication Lab—that provides free, world-class biology education through video lectures and talks by leading scientists. Its content spans cutting-edge research topics, career development, and scientific thinking, making it a widely used resource for students, educators, and life science professionals worldwide. The initiative is grounded in values of open access, inclusion, and lifelong learning.

- **iGEM (International Genetically Engineered Machine) Foundation** | Website - https://igem.org/

iGEM is a global synthetic biology competition and education platform that brings together students from high schools, universities, and community labs to design, build, and test synthetic biology projects addressing real-world challenges. Participants gain hands-on experience in molecular biology, bioethics, safety, and entrepreneurship, culminating in the annual Grand Jamboree. Many teams go on to publish their work, launch startups, or lead national synthetic biology efforts. iGEM provides various educational resources for students of different learning stages and accessibility levels.

- **Gogec (Global Open Genetic Engineering Competition)** | Website: www.gogecconference.org

GOGEC is an open, inclusive international competition that empowers individuals and teams—from high school students to independent researchers—to design and share innovative genetic engineering projects. Unlike traditional competitions, GOGEC emphasizes accessibility, open science, and low-cost participation, aiming to lower barriers for global engagement in synthetic biology. The program encourages interdisciplinary collaboration and creativity, with a focus on community impact, education, and scalable solutions. Participants share their work openly and are supported by a global network of mentors and reviewers.

- **Brazilian SynBio Olympiad (OBBS)**

The Brazilian Synthetic Biology Olympiad (OBBS) is a national competition that introduces high school students to synthetic biology through engaging challenges and educational content. Organized by SynBioBR with support from the Vertere Institute, OBBS aims to democratize access to science and foster interest in biotechnology among youth across all regions of Brazil.In its 2024 edition, OBBS reached a record 3,794 participants from every Brazilian state, with a majority coming from public schools for the first time. With 59% of registrants identifying as female and strong representation from the North and Northeast, OBBS continues to break barriers in STEM education, promoting gender equity and regional inclusion in the synthetic biology community.

- **Build-a-Cell** | Website: www.buildacell.org/

Build-a-Cell is an international collaborative research and education initiative focused on the ambitious goal of building synthetic cells from the bottom up. It brings together scientists, engineers, and educators to explore the fundamental principles of life by constructing artificial systems that mimic the behavior of living cells. Build-a-Cell hosts workshops and seminar series providing open-source introduction into synthetic cell research.

- **BioBuilder Educational Foundation** | Website: https://biobuilder.org/

BioBuilder combines classroom teaching with laboratory experimentation to introduce synthetic biology to middle school, high school, and undergraduate students. Based in Boston and operating internationally, BioBuilder offers curriculum kits, teacher training programs, and student innovation challenges, making engineering biology accessible and exciting. Their approach merges biotechnology with design thinking and entrepreneurship, empowering the next generation of bioengineers.

- **Gathering for Open Science Hardware (GOSH)** | Website: https://openhardware.science/

GOSH is a global community committed to making science hardware open, accessible, and collaborative. By connecting scientists, technologists, educators, and artists, GOSH fosters the development of low-cost, open-source lab tools and instrumentation. Through various events and initiatives, they promote equitable access to scientific research and education across geographic and socioeconomic boundaries.

- **FreeGenes** | Website: https://stanford.freegenes.org/

FreeGenes is an open-access platform hosted by Stanford that facilitates the distribution of standardized, editable genetic parts. Aimed at democratizing synthetic biology, FreeGenes provides free-to-access DNA and supports community-driven design and assembly efforts. It enables educators, students, and researchers to collaborate in developing and sharing biological tools while advancing synthetic biology as a more inclusive and distributed discipline.

- **Hackteria community** | Website: https://www.hackteria.org/

Hackteria is an international, open-source bioart and biohacking community that merges science, art, and DIY biology. The network runs workshops, residencies, and online resources to support experimental, interdisciplinary exploration of living systems and biotechnologies. Rooted in accessible and speculative design, Hackteria helps create spaces where cultural critique and biological experimentation intersect.

- **Science Centers** - public engagement and designing learning experiences, professional development workshops, teaching and learning tools for science teachers including
  - American Natural History Museum, NY | Human Origin Educational Lab
  - Cold Spring Harbor | DNA Learning Center, NY
  - The Tech, CA | Biodesign Studio and BioTinkering Lab
  - Exploratorium, CA

  i. DNA Files - Radio program and workshop materials

  ii. K-12 Science Leader Network
- Other Open Educational Resources (OER) sites providing educational materials such as
  - MIT OpenCourseWare | https://ocw.mit.edu/
  - Stanford Intro to BioE Course | https://introbioe.stanford.edu/
  - Khan Academy | https://www.khanacademy.org/
  - OpenStax | https://openstax.org/
  - Addgene | https://www.addgene.org/

unesco

ENGINEERING BIOLOGY

International guidelines for constructing higher education curricula

Designed under the visionary of UNESCO's International Basic Sciences Programme, the Engineering Biology Curriculum Framework equips learners with interdisciplinary skills in biodesign, biomanufacturing, bioinformatics, and AI-driven biological engineering while embedding ethics, biosafety, and sustainability throughout its structure.

Using Low- and Middle-Income Countries as a representative model, the framework offers a scalable template that bridges local systemic needs with global bioeconomy advancement.

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