ITC ILO
International Training Centre

THE POTENTIAL IMPACT OF MEDICAL BIOTECHNOLOGY ON THE FUTURE OF ADULT LEARNING

FINDINGS FROM ACTION RESEARCH

THE POTENTIAL IMPACT OF MEDICAL BIOTECHNOLOGY ON THE FUTURE OF ADULT LEARNING

FINDINGS FROM ACTION RESEARCH

TABLE OF CONTENTS

EXECUTIVE SUMMARY

ITCILO context for this report

ITCILO has a mandate to monitor emerging technologies and investigate opportunities for innovation that can enhance learning, training, and capacity-building. This mandate builds on ITCILO's longstanding track record of early engagement with transformative technologies in the context of large-scale training and workforce development. Within that mandate, the present workstream focuses on refining ITCILO's taxonomy of emerging technologies as a practical tool for guiding research activities, specifically with respect to biotechnology and its expanding impact across multiple sectors. Our workstream operates with a 2030-time horizon and remains aligned with broader ITCILO priorities related to decent work, sustainability, inclusion, and social justice. Strengthening biotechnology literacy, skills readiness, and workforce resilience are central themes of this report.

The methodology for this report integrates analysis of secondary data sources with insights gathered from key informant interviews. Secondary sources include national and regional biotechnology strategies (see Appendix 1), corporate roadmaps from leading biotechnology, pharmaceutical, and life-science companies, multiple international technology taxonomies, markets and foresight reports and additional online resources, academic publications, policy briefs and industry analyses cited throughout the document.

Biotechnology and Adult Learning in the ITCILO Mandate

ITCILO recognizes biotechnology as a strategic domain shaping the future of work, health systems, and national sovereignty. As part of its mission to anticipate emerging skills and promote social justice, this Action Research examines how medical biotechnology - strengthened by AI, data infrastructures, and personalized health technologies - will redefine adult-learning ecosystems through 2030. This report refines ITCILO's taxonomy for biotechnology, identifying technologies with the greatest learning potential and the most pressing implications for inclusion, equity, digital skills, and governance.

To fully realize the benefits of biotechnology in education, while avoiding the amplification of risks, this action research emphasizes the need for evidence-based foundations, rigorous biosafety and ethical norms, and strong pedagogical frameworks.

Summary of Modifications to the ITCILO Biotechnology Taxonomy

We revised the original ITCILO taxonomy to make it more accurate, future-oriented, and aligned to learning and workforce development needs. Our proposal moved away from a narrow discipline-based categorization (i.e. "Medical biotechnology") to a functional and transversal framework reflecting how biotechnology is used across sectors. The new taxonomy better reflects how biotechnology is developed, governed, taught, and used in society, enabling ITCILO to support the future workforce in a rapidly evolving bioeconomy.

Biotechnology Innovations for Restoring Cognitive Health and Learning Capacity

Advances in biotechnology are transforming how we understand, treat, and potentially cure diseases that impair learning and cognition. Through gene therapy, genome editing, RNA-based medicines, and cell-based interventions, scientists can now target the underlying molecular causes of neurodevelopmental and neurodegenerative disorders rather than only managing symptoms. For example, precision editing technologies such as CRISPR may correct pathogenic variants associated with intellectual disabilities, while gene regulation therapies are being investigated to mitigate the effects of chromosomal abnormalities like those in Down Syndrome. In parallel, monoclonal antibodies, antisense oligonucleotides, and neuroprotective cell therapies are showing promise in slowing or reversing cognitive decline in conditions such as Alzheimer's disease and other dementias. Novel drugs aim to improve attention, executive function, and impulse control with fewer side effects and lower dependency for the treatment of several learning related conditions, moving beyond traditional stimulant medications toward more precise and personalized interventions. These breakthroughs open new possibilities for enhancing synaptic function, promoting brain plasticity, and improving memory, attention, and communication abilities - ultimately expanding opportunities for learning, inclusion, and lifelong participation in society.

Biotechnology as an Engine for Digital Scientific Literacy

Technological convergence across genomics, gene therapies, RNA therapeutics, microbiome science, and AI-enabled drug discovery makes biological information accessible to individuals outside laboratory environments. As genetic risk testing, microbiome profiling, and mobile diagnostics expand, adults increasingly encounter probabilistic risk reports and personalized health data requiring interpretation skills. Strengthening biotechnology literacy is therefore a public-empowerment and misinformation-resilience priority.

Adapting Advanced Biotechnologies into Safe Educational Tools

Cloud bioinformatics platforms, virtual and augmented laboratories, and AI-guided molecular exploration now allow learners to engage with real biological data without exposure to biosafety hazards. When grounded in strong ethical guidance, privacy protection, and teacher capacity-building, these tools can democratize access to genomics, structural biology, and computational drug discovery. They also provide a pathway for countries with restrictive direct-to-consumer genetic testing regulations, where simulated datasets can ensure equal participation.

Addressing Inequality, Misinformation, and Governance Challenges

Misinformation is critically increasing as biotechnology gains prominence in public discourse, particularly around GMOs, vaccines, gene editing, synthetic biology and pandemics. The technical complexity of biological concepts combined with the inherent uncertainty of scientific evidence creates fertile ground for misleading narratives that spread rapidly across digital platforms. Biotechnology topics are frequently appropriate for political agendas involving food sovereignty, immigration and disease transmission, biosecurity, national competitiveness and regulatory debates around reproductive or genetic technologies. This politicization fuels polarized public discussions, weakens trust in science and undermines the development of evidence-based policy. At the same time, commercial actors may contribute to misinformation by overstating the transformative potential of biotechnology or by disseminating fear-based and alarmist narratives, ranging from unsupported claims to exaggerated depictions.

Such dynamics distort societal understanding of what biotechnology can and cannot do. Building strong scientific literacy is therefore essential for democratic participation, for navigating complex information ecosystems, for interpreting biological data responsibly and for engaging meaningfully with bioethical questions. Embedding biotechnology education within learning systems is not only a technical or pedagogical objective: it is a broader societal resilience strategy that equips learners to identify misinformation, resist manipulation and participate responsibly in decisions shaping future health, food and environmental systems.

How AI Applied to Biotechnology Could Influence Adult Learning in the Near and Long Future

Artificial intelligence (AI) is now embedded across biotechnology, powering advances in genomics, protein engineering, drug discovery, metabolic modeling, and biomanufacturing-from genomics and protein engineering to metabolic modeling and biomanufacturing. Yet AI should be seen not only as a driver of scientific innovation, but also as a tool for learning biotechnology more effectively, most notably by enabling adaptive learning (AL) and by helping learners build meaningful connections across complex knowledge networks (Goh & Sze, 2019).

As these capabilities mature, AI does not only transform scientific practice; it reshapes how adults learn, what they must learn, and how societies prepare for biological complexity. The influence unfolds across two complementary time horizons.

A. Near Future (5–10 years): Acceleration, Access, and Foundational Competencies

AI tools make biotechnology understandable, interactive, safe, and broadly accessible. Adults learn faster, with less infrastructure, and gain resilience against misinformation.

A. Democratized access to biological analysis through AI tools

AI-driven platforms make once-specialized biological analyses accessible through simple interfaces. Adults-regardless of their background-will be able to:

- visualize protein structures,
- annotate genes,
- model pathways,
- simulate mutations,
- explore microbiome data,
- perform basic bioinformatics tasks.

This lowers entry barriers and transforms biotechnology into a subject that can be experienced, not merely taught.

B. AI-enabled virtual labs and autonomous experimentation

AI-powered virtual wet labs will allow adults to:

- design experiments,
- test hypotheses,
- run simulations of CRISPR edits or metabolic pathways,
- explore bioprocess engineering without physical equipment.

These tools support training for workers in regions with limited access to laboratory infrastructure, enabling equitable lifelong learning.

C. Strengthening scientific literacy and misinformation resilience

Because AI simplifies complex biology, it becomes a powerful tool to combat:

- misinformation about vaccines, GMOs, synthetic biology, etc.
- politically motivated narratives.
- market-driven exaggerations and alarmism.

Adults can use AI-guided explanations to understand biological evidence more clearly, reducing susceptibility to fake news and improving democratic participation.

D. New micro-credentials and reskilling pathways

AI-assisted biotechnology workflows will require new entry-level skills:

- digital biology literacy,
- AI-supported data interpretation,
- genomic and proteomic basics,
- regulatory and ethical awareness.

Adult education providers will introduce short, modular programs linking AI and biotech (e.g., AI-for-genomics; AI-for-bioeconomy).

E. Improved accessibility for learners with disabilities

AI systems can translate complex biological data into:

- audio descriptions,
- simplified visualizations,
- step-by-step guidance,
- cognitive-accessible explanations.

Biotechnology has become more inclusive, supporting learners with diverse needs.

B. Long Future (10–25 years): Transformation of Learning Systems and Workforce Identities

AI and biotechnology co-evolve, creating new professions, new ethical frameworks, and new learning architectures. Adult learning becomes interdisciplinary, continuous, and essential for participating in a bio-driven society and economy.

A. AI-bio design reshaping the architecture skill of work

As AI becomes a co-designer of biological systems ("BioGPTs", generative protein models, automated biomanufacturing), adults will require:

- hybrid biology–computation skills,
- the ability to evaluate AI-generated biological outputs,
- competencies in biosecurity, ethics, and data governance,
- systems-thinking across ecology, engineering, and digital infrastructures.

Lifelong learning becomes continuous, interdisciplinary, and dynamic.

B. Emergence of the "Bio-AI workforce"

AI-integrated biotechnology will create new professions in:

- automated laboratory operations,
- computational strain design,
- in-silico clinical trial simulation,
- AI-monitored biomanufacturing plants,
- digital biosecurity,
- gene therapy logistics and data stewardship.

Adult learners will need long-term upskilling cycles to remain employable in a fast-evolving bioeconomy.

C. Bioethics, governance, and citizen-literacy as core societal skills

The expansion of AI in biology raises critical questions about:

- genetic privacy,
- AI-generated biological risks,
- biosurveillance,

- equitable access to engineered therapies,
- algorithmic bias in clinical genomics.

Adults will require structured learning on bioethics, regulatory frameworks, and rights, making ethical literacy a central component of future education.

D. Personalized learning informed by biological and behavioral data

In privacy-preserving, ethically governed systems, long-term future applications may include:

- AI-driven learning recommendations based on metabolic or cognitive profiles,
- individually tailored training pathways informed by biomarkers,
- adaptive learning tools that respond to stress, attention, or cognitive load.

Biotechnology and AI combine to create holistic lifelong learning ecosystems.

E. Environmental and planetary literacy shaped by bio-AI modeling

AI-accelerated biology will decentralize knowledge about:

- climate biotechnology,
- bio-based materials,
- carbon-sequestration microbes,
- synthetic ecologies.

Adults will need new literacy around bio-based sustainability, linking bioeconomy, ecology, and green transitions.

Conclusion

Biotechnology is no longer a niche scientific domain; it is increasingly embedded in everyday life, healthcare systems, labour markets, and democratic participation. As these transformations accelerate, ensuring that they advance social justice will be critical. In this context, ITCILO has a strategic role to play in shaping inclusive, future-ready learning systems that empower workers, institutions, and policymakers to engage with the emerging bioeconomy responsibly, confidently, and equitably.

Within the domains highlighted in Part III, this report underscores how recent breakthroughs in precision genome editing, RNA-based therapeutics, and cell-based interventions are beginning to restore cognitive function, improve quality of life, preserve cognitive and motor abilities, and reduce long-term disability in central nervous system (CNS) disorders. These advances carry

significant implications for social justice, social protection, and labour-market inclusion. By mitigating cognitive impairment, a larger share of individuals can access mainstream education, participate in skills development, and enter the workforce. At the same time, fewer workers are forced out of employment due to neurological decline, supporting income security and sustained economic participation.

Preserving memory and cognitive capacity is also closely aligned with broader labour-market challenges linked to demographic change. As populations age, enabling longer, healthier working lives become essential to economic resilience and social protection sustainability. Neuro-protective and restorative biotechnologies therefore offer not only health benefits, but also a pathway to reducing premature retirement, long-term dependency, and the societal costs associated with care and exclusion.

However, biotechnology innovation remains heavily concentrated in the Global North, where research capacity, investment flows, and regulatory infrastructures are most developed. This geographic concentration poses clear risks for widening global inequalities in access to innovation and its benefits. Limited research, training, and manufacturing capacity in low- and middle-income countries constrains the opportunities identified in this report. Addressing these gaps underscores the urgency of inclusive industrial, skills, and innovation policies. Strategic investment in training pathways, research fellowships, regional innovation ecosystems, and international knowledge-sharing mechanisms will be essential to ensure that emerging biotechnologies strengthen equitable access to education, employment, income security, and social protection across regions.

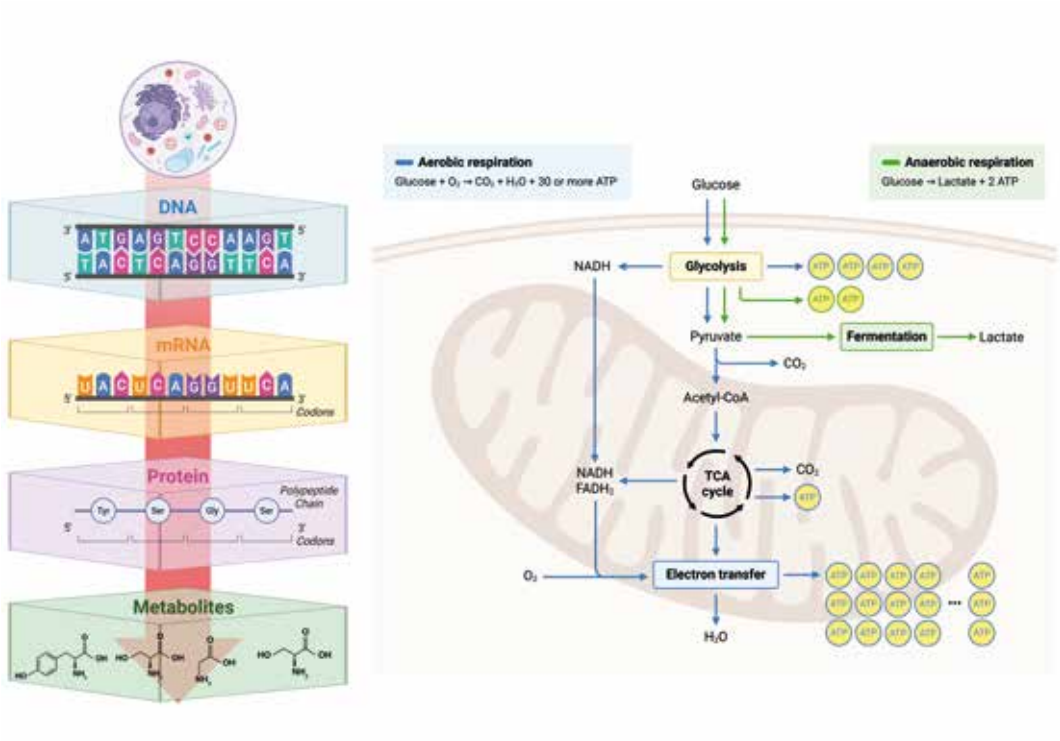
INTRODUCTION. HORIZON SCANNING OF EMERGING AND ENABLING INNOVATIONS FOR THE FIELD OF BIOTECHNOLOGY

A. The compounding impact of technologies in Biotechnology

As a scene-setting preliminary consideration, it is essential to establish that interfacing with living systems requires a detailed molecular and functional understanding of life itself. The biological world is extraordinarily complex and efficient: the human genome alone encodes more than 20,000 genes, expressed and regulated through intricate networks of proteins, metabolites, and signaling pathways that sustain all forms of life. Each human cell contains approximately 3 billion base pairs of DNA, capable of orchestrating countless biochemical reactions every second through finely tuned molecular machinery. Figure 1 illustrates this complexity.

Figure 1.

Overview of molecular information flow and cellular metabolism. The left panel illustrates the central dogma, showing how DNA is transcribed into mRNA and translated into proteins that shape cellular metabolite profiles. The right panel depicts major metabolic pathways, including glycolysis, the TCA cycle, electron transport, and fermentation, highlighting how cells generate ATP under aerobic and anaerobic conditions.



Biotechnology operates at the intersection of biology, chemistry, physics and engineering, where bioprocesses translate molecular knowledge into tangible applications. These bioprocesses encompass the design, optimization and scaling of biological reactions, whether enzymatic, microbial, or cellular, into controlled systems capable of producing therapeutic proteins, biofuels, vaccines or high-value chemicals. The integration of chemical kinetics, thermodynamics, and fluid dynamics with cell biology and genetic engineering enables scientists to transform living organisms into efficient biofactories. From fermentation to downstream purification, bioprocesses represent the critical bridge between fundamental biological discovery and industrial production, embodying the union of life sciences with the quantitative precision of the physical sciences.

Therefore, one of the most fundamental research strands of biotechnology is to lay the groundwork for decoding, manipulating, and redesigning biological processes at multiple scales, from genes and enzymes to entire ecosystems. This effort has been driven over the last half-century by the convergence of molecular biology, genetic engineering and bioinformatics, enabling humans to read, write, and edit the code of life. Techniques such as recombinant DNA, genome sequencing and CRISPR-based editing, have established the experimental and conceptual foundations for a new generation of technologies that harness and reprogram biological systems.

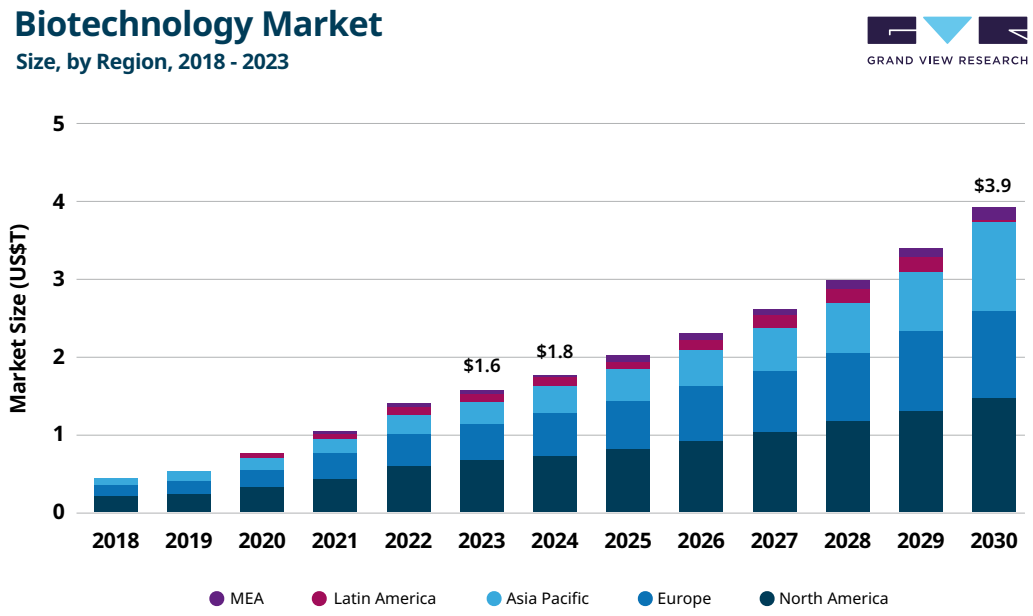
Hence, a technology that collects, interprets, and modifies biological information, whether to produce therapeutics, engineer resilient crops, or synthesize sustainable materials, requires a preliminary and profound understanding of the living systems it manipulates. The last two decades of academic and industrial research in genomics, synthetic biology, and systems biology have been laying the ground for an increasingly precise and predictable manipulation of biological functions, which today represents the first and main enabler of the biotechnology industry. Its latest developments in areas such as mRNA therapeutics, gene editing, and AI-driven protein design have proven remarkably successful in redefining how we diagnose diseases, produce energy, and sustain life on a global scale.

B. Biotechnology: From Fundamental Research to Industrial and Societal Translation

Over the past two decades, the biotechnology sector has evolved from a niche scientific endeavor into a multi-trillion-dollar driver of the global economy, spanning pharmaceuticals, agriculture, and industrial processing. The global biotechnology market, valued at USD 1.55 trillion in 2023, is projected to reach USD 3.88 trillion by 2030, expanding to a CAGR of 13.9% (Grand View Research, 2023) (Figure 2).

Figure 2.

Global biotechnology market size by region from 2018 to 2030. The graph illustrates steady market growth across all regions, with North America and Asia-Pacific representing the largest contributions. The market is projected to increase from USD 1.6 trillion in 2023 to USD 3.9 trillion by 2030. (Source: Grand View Research, 2023).



Biotechnology encompasses a diverse range of technological platforms, including recombinant DNA, CRISPR gene editing, cell and gene therapy, synthetic biology, and bioinformatics. The accelerated translation of fundamental research into applied biotechnology has been fueled by advances in genomics, AI-driven drug discoveries, and high-throughput biomanufacturing. The global cell & gene therapy market was estimated at USD 7.2 billion in 2023 and is projected to reach USD 23.3 billion by 2028 (CAGR ~26.4 %) while the renewable chemicals segment, which overlaps significantly with industrial biotechnology, including biofuels, enzymes and bioplastics, was estimated at US$ 80.2 billion in 2022, with growth to US$ 195.6 billion by 2030, driven by the circular-economy transition (BBC 2024; Global Industry Analysts 2025).

Importantly, private and governmental investments have played a key role in consolidating biotechnology as a pillar of national innovation agendas. According to EY, venture financing in the biotechnology sector totaled approximately USD 18.9 billion in 2023, below the five-year pre-pandemic average of USD 47.5 billion, with North America and Europe continuing to dominate global biotech investment activity (Ernst & Young (EY) 2024). Public R&D investments in large-scale programs such as the NIH Human Genome Project which received approximately USD 3.8 billion in federal funding between 1990 and 2003 (National Human Genome Research Institute (NHGRI) 2023), the European Union's Horizon Europe framework with a budget of EUR 93.5 billion for 2021–2027 (European Commission, 2024) and China's National Biotechnology Development and Bioeconomy Plans (National Development and Reform Commission, 2022) have collectively mobilized tens of billions of dollars, establishing robust ecosystems for translational and innovation-driven research.

The biopharmaceutical segment continues to dominate the global biotechnology market, representing approximately 60% of total revenues (DataHorizzon Research 2024). Meanwhile, agrobiotechnology, encompassing innovations such as biofertilizers and gene-edited crops, is expanding rapidly with the agricultural biotechnology market projected to surpass USD 100 billion by 2031 (Consegic Business Intelligence 2024). These trends underscore the increasing convergence between biotechnology, data analytics, and sustainable agriculture.

In summary, biotechnology has transitioned from fundamental biological research to a strategic industrial sector with profound implications for health, food systems and the environment. Supported by large-scale R&D funding, rapid innovation in genomics and bioprocessing and expanding consumer markets, the biotechnology industry exemplifies how science-driven innovation can deliver scalable solutions to 21st-century challenges, from pandemic preparedness to decarbonization.

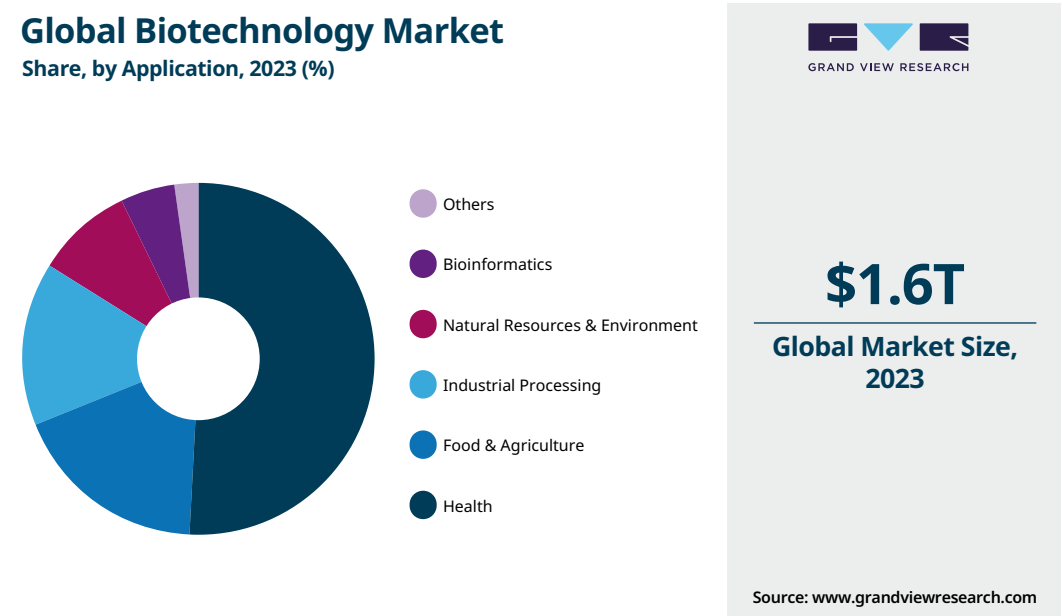
C. Biotechnology: Addressing Global Health, Sustainability, and Industrial Transitions

Modern biotechnology development and deployment are primarily driven by the urgent need to respond to global health crises, antimicrobial resistance, climate change, and the rising cost of chronic diseases. The biotechnology industry serves as a major driver of global biomedical innovation, contributing to the development of around 30% of all new drugs approved annually by the U.S. Food and Drug Administration (FDA) (SelectUSA 2023).

From a healthcare perspective, biotechnological therapies, including monoclonal antibodies, gene therapies, RNA-based vaccines, and biosimilars, represent a paradigm shift in medicine. The World Health Organization (WHO 2022) reports that noncommunicable diseases such as cancer, diabetes and cardiovascular disorders account for 74% of global deaths, creating an urgent need for biotechnological interventions that enable precision diagnostics, targeted treatments, and sustainable production systems.

Figure 3.

Percentage distribution of the global biotechnology market by application in 2023. The health sector dominates the market, followed by food & agriculture, industrial processing, natural resources & environment, bioinformatics and other applications. The estimated total global market size in 2023 was USD 1.6 trillion. (Source: Grand View Research, 2023).



In recent years, biopharmaceuticals have continued to dominate the biotechnology landscape, representing nearly half of the global biotechnology market (Mordor Intelligence 2024). The COVID-19 pandemic accelerated innovation in mRNA-based platforms, triggering a surge of global investment in vaccine, diagnostic, and therapeutic technologies (McKinsey & Company 2024). As shown in Figure 3, the biotechnology innovation landscape is dominated by therapeutic biotechnologies, followed by industrial biotechnology, which leverages biological systems for sustainable production, and agrobiotechnology, addressing food security and resilience.

In industrial and environmental contexts, biomanufacturing has emerged as one of the fastest-growing segments of the biotechnology industry, driven by advances in synthetic biology and the global shift toward low-carbon and circular bioeconomies. The global next-generation biomanufacturing market is projected to reach USD 43.3 billion by 2030, expanding at a compound annual growth rate of over 10% (Virtue Market Research 2024). Between 2000 and 2023, global patent-application filings increased consistently, filings reached approximately 3.55 million in 2023, representing sustained growth in innovation activity (World Intellectual Property Organization (WIPO) 2024). At the same time, although venture-capital investment in biotechnology showed strong growth in the 2010s, recent data indicate a pull-back, with the global total deal value for biotech falling to about USD 18.1 billion in 2023 (S&P Global Market Intelligence 2024). These trends reflect the evolving interplay between biotech innovation, patenting activity and investment flows in the era of converging AI, automation and biological design.

In summary, the expanding biotechnological sector is not only addressing unmet therapeutic needs but also transforming food systems and manufacturing to be more resilient and sustainable. The escalating R&D investment and intellectual property growth reflect global confidence in biotechnology as a transformative general-purpose technology, one that will be instrumental in building health resilience, mitigating climate change, and driving equitable access to innovation.

D. Biotechnology as a Pillar of National Sovereignty

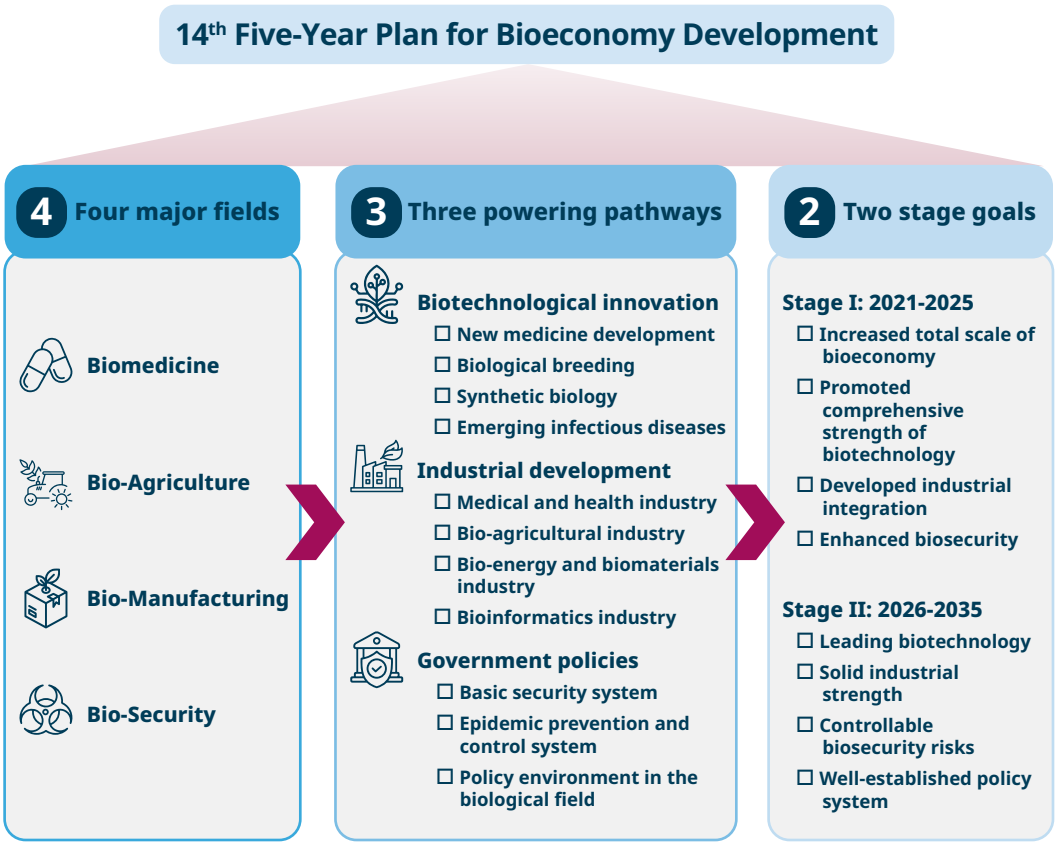
Biotechnology has become a strategic pillar for national sovereignty in the twenty-first century (Proestou et al., 2025). As countries confront increasingly complex challenges, ranging from public health crises and food insecurity to climate adaptation and energy transition, the capacity to understand, engineer, and deploy biological systems determines not only scientific leadership but also geopolitical resilience. Nations with strong biotechnological infrastructures can develop vaccines and therapeutics locally, engineer climate-resilient crops, secure sustainable sources of energy and materials, and reduce dependence on foreign supply chains in critical sectors, a central theme in contemporary bioeconomy analyses (Gardossi et al., 2023). Moreover, sovereignty in the bioeconomy era requires more than access to biological resources; it demands the ability to interpret biological data, innovate through synthetic and computational biology, and build robust regulatory and manufacturing capabilities. Countries

that cultivate these competencies gain greater autonomy in health, agriculture, environment, and industry, while those without them risk technological dependency and reduced national resilience (Papadopoulou et al., 2022).

In this sense, biotechnology should be viewed not simply as a scientific discipline, but as a form of strategic infrastructure, foundational to economic competitiveness, social well-being, and national security (Buchman & Kovak, 2025). Strengthening biotechnological capacity is therefore essential for safeguarding national sovereignty in an increasingly interconnected and biologically driven world. Across leading economies, national biotechnology and bioeconomy strategies reveal a shared recognition of biotechnology as a strategic driver of sustainability, competitiveness, and sovereign resilience (Appendix I). Canada, France, Germany, Italy, and Japan articulate comprehensive bioeconomy roadmaps centered on sustainable production, circular bio-based industries, and alignment with agricultural and environmental goals. China's 14th Five-Year Bioeconomy Plan and long-term 2035 vision frame biotechnology as a pillar of national security and industrial modernization, emphasizing domestic innovation capacity and biomanufacturing (Zhang et al., 2022), illustrated in Figure 4.

Figure 4.

Overview of the 14th Five-Year Plan for Bioeconomy Development. The scheme outlines four major fields (biomedicine, bio-agriculture, bio-manufacturing, and biosecurity), three strategic pathways (biotechnological innovation, industrial development, and government policies), and the two implementation stages spanning 2021–2025 and 2026–2035. (Source: Zhang et al., 2022).



The United Kingdom's *Life Sciences Vision* prioritizes health innovation and global leadership in therapeutics (UK Government, 2021), while the United States' Executive Order on *Advancing Biotechnology and Biomanufacturing* positions the bioeconomy as critical infrastructure for national security, supply-chain resilience, and economic growth (U.S. Congress, 2025). Collectively, these strategies demonstrate a global shift toward coordinated, state-driven investment in biotechnology, reflecting its expanding role in health, industry, environment, and national sovereignty.

E. Fake News, Ethics, and the Politics of Biotechnology

Biotechnology does not exist in a vacuum; it evolves within a complex ecosystem of public perception, political debate, ethical considerations, and information flows. As biotechnologies become increasingly visible in everyday life through genetic testing services, mRNA vaccines, CRISPR applications, bioengineered foods, and AI-driven biological design, the surrounding information environment becomes a critical factor shaping public understanding, trust, and policy decisions.

A major challenge in this landscape is the proliferation of misinformation and fake news. Misinterpretations of scientific concepts, conspiracy narratives around genetic manipulation, and politically motivated distortions can spread rapidly across digital platforms, often outpacing accurate scientific communication. The recent paper entitled "Misinformation in and about science" (West and Bergstrom 2021) underscores how the challenge of misinformation extends deeply into the scientific enterprise itself - not merely in social media or popular culture. The authors argue that phenomena such as hype, publication bias, predatory publishing, and citation misdirection represent internal scientific vulnerabilities, parallel to the more visible 'fake news' flowing through public discourse. These dynamics were clearly demonstrated during the COVID-19 pandemic, when misinformation about vaccines, viral origins, and biotechnology tools undermined public health efforts and contributed to social polarization (West and Bergstrom 2021). Such episodes reveal how fragile public trust can be when scientific complexity meets simplified or deceptive narratives.

At the same time, biotechnology raises profound ethical questions-from gene editing of embryos to ownership of genetic data, from laboratory automation and AI-designed organisms to synthetic biology with dual-use potential (Wiley et al., 2025). These issues require careful societal deliberation, yet public debate is often distorted by ideological claims or political rhetoric rather than grounded ethical analysis (Wang et al., 2023). Without robust frameworks guiding consent, privacy, biosecurity, and equitable access, societies risk either over-regulating promising innovations or enabling unchecked technological deployment that amplifies inequality.

The political discourse around biotechnology is also becoming increasingly strategic. Governments frame biotechnology as a tool of national sovereignty, economic competitiveness, and security, while political actors may use biotech narratives to mobilize support or opposition. Gene-edited crops, environmental bioengineering, and reproductive technologies often become flashpoints in cultural or partisan debates (Smyth et al., 2017). The resulting politicization can obscure scientific nuance, reduce policy discussions to binary choices, and make it harder for evidence-based governance to prevail.

To navigate this environment, scientific literacy and critical digital literacy are essential components of adult learning. Learners need the ability to evaluate sources, understand the limits of biotechnology, distinguish between credible evidence and misinformation, and engage ethically with new possibilities. Scientific literacy equips individuals to analyze and understand scientific information, make informed decisions, and resist misinformation in an age of information overload (Niels G. Mede, 2023). Equally important is fostering spaces for transparent and inclusive dialogue, where diverse communities can debate the societal implications of biotechnology without sensationalism or misrepresentation.

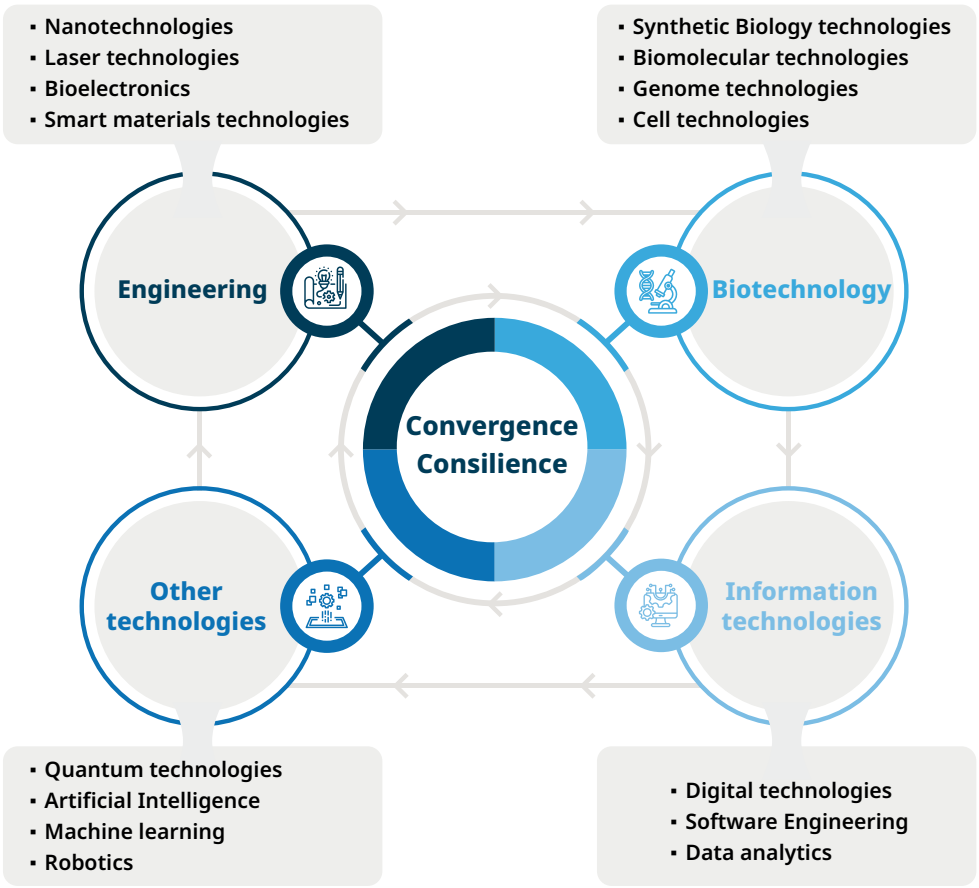
Ultimately, the intersection of fake news, ethics, and political discourse underscores that biotechnology is not only a scientific field but also a social and democratic challenge. Effective governance and meaningful public engagement depend on ensuring that citizens, workers, and policymakers have the knowledge, tools, and trust needed to shape the future of biotechnology responsibly.

PART I. SITUATING BIOTECHNOLOGY IN THE TAXONOMY OF FOUNDATIONAL TECHNOLOGIES

Part I of this research provides an integrated analysis and mapping of the enabling innovations that underpin the contemporary expansion of the biotechnology sector and its diverse products. As illustrated in Figure 5, biotechnology does not emerge as a discrete or isolated industry. Rather, it is the outcome of a multi-layered convergence of scientific, computational, engineering, and data-driven technologies that collectively shape its innovative landscape.

Figure 5.

Bioinnovation. Advanced biological, physical, information, and engineering technologies integrate to form the foundation of bioinnovation, illustrating how convergent disciplines collectively drive new solutions, applications, and technological progress. (Source: adapted from Pretorius et al. 2025).



The biotechnology field is commonly categorized into thematic colors, each representing a distinct application domain. Red biotechnology encompasses medical and clinical applications, including therapeutic development and diagnostic innovations; green biotechnology focuses on agricultural and environmental solutions; white biotechnology refers to industrial and bioprocessing strategies; and blue biotechnology comprises technologies and research related to marine and aquatic (Gomes et al. 2024).

Although broad in scope, Biotechnology sits at the intersection of molecular sciences, data-intensive computation, and advanced biomanufacturing, supported by foundational domains such as genomics and multi-omics analytics, synthetic biology, high-throughput screening, bioprocess engineering, advanced materials, and automation and robotics. These enabling technologies form an integrated architecture, where progress in one domain often accelerates innovation vertically across the entire biotechnology value chain.

Central to this convergence (and focus of this research) is the growing role of AI and Machine Learning (ML) as the primary orchestrators of biological information flows. Like the way AI structures the neurotechnology ecosystem, AI in biotechnology governs the representation, modeling, and prediction of complex biological processes - from protein folding and metabolic engineering to ADMET modeling and phenotype prediction. The unprecedented success of systems such as AlphaFold (Jumper et al., 2021) and the rapidly growing field of AI-enabled biotechnology (Bio-AI), illustrate how computational learning has moved from a supportive analytical tool to a core enabling substrate of biotechnological innovation. For the purposes of the action research, the following taxonomy of emerging technologies (developed in the context of earlier ITCILO research) was used as a starting point.

Emerging technologies in infrastructure domains	
Energy • *Metrics*: energy produced per unit cost, distribution distance per unit cost, energy sustainability measures etc. • *Technology drivers*: renewable energy (Solar, Wind, hydro, incl. space-based solar), energy storage (batteries, supercapacitors), smart grids, hydrogen fuel cells, fusion, carbon capture, circular economy, green algorithms, etc.	**Computer** • *Metrics*: FLOPs-equivalent per unit cost, data storage per unit cost, data retrieval speeds etc. • *Technology drivers*: digital algorithm progress, transistor miniaturization (e.g. via nanotechnologies), retrieval algorithms, superconductors, data infrastructure technologies, neuromorphic computers, DNA data storage, quantum computing hardware etc.
Materials • *Metrics*: number of unique materials/ physical functions we can construct, cost for bespoke construction, ability to intervene in existing physical systems etc. • *Technology drivers*: atomic/molecular science, protein engineering, smart materials, nanotechnology, 3D & 4D additive manufacturing, advanced composites, metamaterials, biomimetic materials, elastocalorics, quantum materials, etc.	**Connectivity** • *Metrics*: reliable GB/second per unit cost/energy, population connectivity coverage ratios, number of items connected to the Internet, latency, etc. • *Technology drivers*: 6G and successor technologies, fiber optic cables, infrastructure build-out, protocols and standards, high altitude platforms, LEO satellite constellations, quantum networking, etc.

Emerging technologies in application domains		
AI & ML • Natural Language Processing • Computer Vision • Predictive Analytics • Robotic Process Automation • Agentic AI • Generative AI / LLMs • AI TRiSM / AI alignment • Explainable AI • Quantum AI/ML algorithms	**XR** • Augmented Reality • Virtual Reality • Mixed Reality • Holography for communication	**Cybersecurity** • Threat Intelligence • Zero Trust Security / ZKPs • Cyber Resilience • Identity & Access Management • Cybersecurity mesh architecture • Disinformation security • Homomorphic encryption • Quantum cryptography
Distributed Ledgers • Blockchain • Cryptocurrencies • Smart Contracts • Decentralized Finance • Supply Chain Management	**Sensors & Internet of Things** • Industrial IoT • Smart Homes • Wearables • Connected Vehicles • Environmental/machine sensors • VLEO satellites • Spatial computing • Quantum metrology	**Biotechnology** • Medical biotechnology • Agricultural biotechnology • Industrial biotechnology • Marine biotechnology • Food biotechnology • Bioinformatics • Environmental biotechnology
Cloud & Edge Computing • Infrastructure as a Service • Platform as a Service • Software as a Service • Serverless Computing • Fog Computing • Edge AI / AI as a service • Real-Time Data Processing • IoT Edge • GitOps / Infrastructure as computing	**Advanced Robotics** • Collaborative Robots • Autonomous Mobile Robots/Vehicles • Drone Technology/Swarm robotics • Robotics Process Automation • Soft robotics • Self-organizing, self-healing robotics • Space manufacturing • Reconfigurable/intelligent surfaces	**Simulation** • Digital twins • Predictive maintenance • Product lifecycle management • Smart Cities and infrastructure • Virtual prototyping • Quantum simulation
Neurotechnology • Neuroimaging and Brain Mapping • Brain-Computer Interfaces (BCI) • Neurostimulation/ Neuromodulation • Neural Prosthetics • Neural Data Analysis • Neuropharmacology/-modulators	**Space & Transport** • Nuclear space propulsion • Hypersonic • Ion propulsion • On-orbit maintenance • Next-gen satellites • Reusable rockets	

The taxonomy proposed by ITCILO, while useful as an initial high-level framework, is too broad to capture the current complexity and specialization of the biotechnology landscape. Categories such as *Medical biotechnology*, *Agricultural biotechnology*, and *Industrial biotechnology* are umbrella concepts that encompass highly diverse scientific domains, techniques, and applications. As a result, important technological areas, particularly those driving innovation in modern biotechnology, remain obscured or insufficiently differentiated.

Many emerging biotechnological techniques, including genome editing, large-scale sequencing, AI-enabled molecular design, and protein structure/function prediction, were originally developed within the medical and biomedical research context. For example, CRISPR–Cas9 gene editing, first advanced as a tool for understanding and treating human genetic diseases, is now applied far beyond clinical settings. The same technology used to correct pathogenic mutations is also employed to improve crop resilience, engineer livestock traits, optimize microbial fermentation, and enhance industrial yeast strains.

As these technologies have matured, their applications have expanded well beyond the health sector. Modern biotechnology is inherently cross-sectoral: the tools that enable advanced therapeutics and precision medicine also underpin progress in agriculture, industrial bioprocessing, environmental monitoring, and food innovation (Demirel et al., 2024; Ranjha et al., 2022). Consequently, the implications for learning and skills development extend far beyond clinical practice. The core learning impact now lies in mastering the underlying techniques, which are increasingly essential across multiple domains. Competencies in genomic data analysis, computational modeling, high-throughput experimentation and AI-driven prediction will become necessary for technicians, researchers, clinicians and industry professionals alike.

For instance, when compared with the taxonomy developed for the Neurotechnology application domain, which focuses on clearly defined subdomains such as Neuroimaging and Brain Mapping, Brain–Computer Interfaces and Neuromodulation, the current ITCILO taxonomy for Biotechnology subdivides the field into very broad application areas (e.g., Medical Biotechnology, Agricultural Biotechnology, Industrial Biotechnology). These categories are so wide that they encompass numerous emerging techniques and trends, many of which are shared across sectors and cannot be meaningfully understood solely through their application domain.

Because the same cutting-edge methodologies are now used across multiple industries, we argue that it is more effective for adult learning strategies to focus on the methods themselves (which are transversal to the many fields of biotechnology). Understanding technological advances, rather than only their application area, enables learners to grasp the cross-sectoral opportunities, innovation pathways and transferable skills that characterize modern biotechnology. This method-driven perspective provides a clearer foundation for anticipating future skills needs and designing relevant learning programmes.

To improve analytical precision and align the classification with contemporary scientific practice, as well as being able to anticipate learning opportunities, we recommend expanding and refining the original ITCILO taxonomy. The updated version distinguishes between clinical and non-clinical medical biotechnology and introduces additional domains that are fundamental to today's biotechnology ecosystem, including genome sequencing, gene editing and gene therapies, structural biology, protein engineering and synthetic biology. These areas form the technological backbone of drug discovery, advanced therapeutics and bio-based innovation. Moreover, we consider marine biotechnology to be a subdomain of environmental

biotechnology, as well as food biotechnology to be already part of industrial and agriculture biotechnology, given their shared methodologies and overlapping objectives.

In the corresponding table below, domains that directly map to the original ITCILO taxonomy are highlighted in green, whereas newly added or expanded categories are marked in blue, reflecting their growing importance in the biotechnology landscape.

<table>
<tr><th colspan="3">Emerging technologies in infrastructure domains</th></tr>
<tr><td colspan="2">Energy
Metrics: energy produced per unit cost, distribution distance per unit cost, energy sustainability measures etc.
Technology drivers: renewable energy (Solar, Wind, hydro, incl. space-based solar), energy storage (batteries, supercapacitors), smart grids, hydrogen fuel cells, fusion, carbon capture, circular economy, green algorithms, etc.</td><td>Compute
Metrics: FLOPs-equivalent per unit cost, data storage per unit cost, data retrieval speeds etc.
Technology drivers: digital algorithm progress, transistor miniaturization (e.g. via nanotechnologies), retrieval algorithms, superconductors, data infrastructure technologies, neuromorphic computers, DNA data storage, quantum computing hardware etc.</td></tr>
<tr><td colspan="2">Materials
Metrics: number of unique materials/ physical functions we can construct, cost for bespoke construction, ability to intervene in existing physical systems etc.
Technology drivers: atomic/molecular science, protein engineering, smart materials, nanotechnology, 3D & 4D additive manufacturing, advanced composites, metamaterials, biomimetic materials, elastocalorics, quantum materials, etc.</td><td>Connectivity
Metrics: reliable GB/second per unit cost/energy, population connectivity coverage ratios, number of items connected to the Internet, latency, etc.
Technology drivers: 6G and successor technologies, fiber optic cables, infrastructure build-out, protocols and standards, high altitude platforms, LEO satellite constellations, quantum networking, etc.</td></tr>
<tr><td colspan="3">Emerging technologies in application domains</td></tr>
<tr><td>AI & ML
Natural Language Processing
Computer Vision
Predictive Analytics
Robotic Process Automation
Agentic AI
Generative AI / LLMs
AI TRiSM / AI alignment
Explainable AI
Quantum AI/ML algorithms</td><td>XR
Augmented Reality
Virtual Reality
Mixed Reality
Holography for communication</td><td>Cybersecurity
Threat Intelligence
Zero Trust Security / ZKPs
Cyber Resilience
Identity & Access Management
Cybersecurity mesh architecture
Disinformation security
Homomorphic encryption
Quantum cryptography</td></tr>
</table>

Emerging technologies in infrastructure domains		
Distributed Ledgers • Blockchain • Cryptocurrencies • Smart Contracts • Decentralized Finance • Supply Chain Management	**Sensors & Internet of Things** • Industrial IoT • Smart Homes • Wearables • Connected Vehicles **Environmental/ machine sensors** • VLEO satellites • Spatial computing • Quantum metrology	**Biotechnology** • Bioinformatics • Genomics and personalized medicine • Gene editing and gene therapy • RNA vaccines • Advanced Diagnostics • Immunotherapy • Genetic testing • Microbiome • Stem cells • Structural Biology • Synthetic Biology • Protein Engineering • Agricultural Biotechnology applications • Environmental Biotechnology applications • Industrial Biotechnology applications
Cloud & Edge Computing • Infrastructure as a Service • Platform as a Service • Software as a Service • Serverless Computing • Fog Computing • Edge AI / AI as a service • Real-Time Data Processing • IoT Edge • GitOps / Infrastructure as computing	**Advanced Robotics** • Collaborative Robots • Autonomous Mobile Robots/Vehicles • Drone Technology/ Swarm robotics • Robotics Process Automation • Soft robotics • Self-organizing, self-healing robotics • Space manufacturing • Reconfigurable/ intelligent surfaces	**Simulation** • Digital twins • Predictive maintenance • Product lifecycle management • Smart Cities and infrastructure • Virtual prototyping • Quantum simulation
Neurotechnology • Neuroimaging and Brain Mapping • Brain-Computer Interfaces (BCI) • Neurostimulation/Neuromodulation • Neural Prosthetics • Neural Data Analysis • Neuropharmacology/-modulators	**Space & Transport** • Nuclear space propulsion • Hypersonic • Ion propulsion • On-orbit maintenance • Next-gen satellites • Reusable rockets	

In the newly proposed taxonomy, it becomes clearer how biotechnology innovations are increasingly woven into the everyday technological environment, shaping consumer products, workplace practices and even general digital literacy. Biotechnology is no longer confined to specialized laboratories: it is progressively embedded in common tools, services and processes encountered in daily life.

As a result, the learning implications are broad and multifaceted. They range from foundational skills, such as interpreting biological data and understanding genetic information, to advanced capabilities in computational biology, laboratory automation, AI-enabled analysis and synthetic design. This refined taxonomy thus provides a more accurate framework for mapping how different biotechnological domains drive evolving skill needs across society.

The biotechnology taxonomy outlined in this report also has clear relevance for agricultural and industrial applications, which are of strategic importance for many ITCILO constituents. Advances in biotechnology are closely linked to food security, climate-resilient agricultural production, sustainable land use, and the development of bio-based industrial processes, including biomanufacturing, bio-materials, and circular-economy solutions. These domains have significant implications for skills development, employment creation, rural livelihoods, and inclusive economic transformation.

While these applications are highly relevant, they were not prioritised in the present analysis. The primary reason for this analytical choice is scope: agricultural and industrial biotechnology encompass a wide and diverse set of technologies, regulatory frameworks, value chains, and skills profiles that would require a dedicated and sector-specific assessment. In contrast, clinical biotechnology and bioinformatics offer a more bounded analytical entry point, with clearer links to learning outcomes, workforce inclusion, and the emerging interface between health, cognition, and labour-market participation.

PART II. DEMOCRATIZATION OF BIOTECHNOLOGY: EMERGING BIOTECHNOLOGY DOMAINS WITH HIGH IMPACT ON LEARNING

In Part II, we identify the major biotechnology strands with the greatest potential impact on adult learning, building directly on the analysis developed in Part I. Although medical technologies are often the most visible drivers of innovation, the original subdivision of biotechnology into broad application realms makes it difficult, and sometimes misleading, to focus solely on clinical domains. Instead, this section adopts a method-centric perspective, examining the *genesis, evolution and current state of the art* of the major techniques shaping the field. By assessing how these foundational innovations emerge and diffuse across sectors, we can better understand their implications not only for patients and healthcare professionals but also for consumers, workers and society at large. This approach highlights how cross-cutting biotechnological methods, rather than sectoral applications, are redefining the skills, literacies, and competencies required in the coming decade.

The biotechnology ecosystem is not monolithic. It emerges from the agglomeration of an organic network of enabling technologies, innovation clusters and interdisciplinary research domains. Each innovation strand, whether in gene therapy, enzyme engineering, precision agriculture, diagnostics, or industrial fermentation, is made possible by parallel advances in bioinformatics, AI-driven models, materials engineering, cloud computing and high-throughput biological data generation. Biotechnology must be understood as a convergent technological domain, whose capabilities and challenges are tightly linked to the maturity and interoperability of its enabling layers.

The rapid rise of AI-native biological design, the push for open, standardized experimental datasets, and the development of FAIR data infrastructures exemplify how biotechnology innovation is increasingly shaped by the interaction between wet-lab experimentation, computational modeling, and global data ecosystems. In this sense, biotechnology is best conceptualized not as a single technology, but as an ecosystem of foundational innovations converging toward the design, understanding, and engineering of living systems, an ecosystem where advancements in computation, data governance, biomaterials, and automation are as critical as advances in molecular biology itself (Callahan et al., 2024; Wilkinson et al., 2016).

In this section, we explore the key trends shaping the contemporary biotechnology landscape, examining prominent scientific breakthroughs and assessing how these developments are likely to influence learning and capacity building in the coming decade. We begin with Bioinformatics,

the foundational layer that enables AI-driven biological analysis and supports nearly every modern biotechnological workflow. Building on this, we investigate emerging trends in medical biotechnology through two complementary lenses: the *clinical* and the *non-clinical* domains.

On the clinical front, we highlight key technologies that have a direct impact on the treatment of debilitating diseases, including advances in genomics, gene editing therapies, RNA-based interventions and advanced diagnostics. These innovations redefine the skill sets required of healthcare professionals and increase the demand for interdisciplinary competencies at the interface of biology, data science and clinical practice.

On the non-clinical side, we examine how the widespread availability of genomic technologies is generating new consumer-facing products, such as genetic risk assessments, ancestry testing and microbiome profiling, and how these tools shape public understanding of biology. Together, these perspectives illuminate how emerging biotechnologies will transform professional training, digital literacy and lifelong learning in the years ahead.

Finally, briefly extended the analysis to other major biotechnology sectors as originally proposed by ICTILO, such as Agricultural, Industrial and Environmental biotechnologies. Our goal here is to illustrate how these same foundational methods are driving innovations far beyond the medical domain. By examining advances in molecular biology, gene editing, biomanufacturing, AI-enabled biological design, and the rapidly expanding bioeconomy, this report shows how emerging technologies are reshaping the knowledge, skills, and forms of literacy required of adult learners. Understanding these trajectories is essential for anticipating future skill demands and ensuring that learning systems are equipped to integrate biotechnology in ways that are ethically sound, pedagogically effective and socially inclusive.

2.1 Bioinformatics: Data Standardization, Accessibility, AI Integration, and Adult Learning Needs

Bioinformatics has become the central nervous system of modern biotechnology, the analytical layer that enables researchers to transform raw biological observations into structured knowledge. As biological data grew exponentially over the last four decades, the field evolved to integrate computational science, statistics, molecular biology, and data engineering, forming the indispensable foundation upon which genomics, proteomics, structural biology, drug discovery, synthetic biology, and personalized medicine are built.

Large-scale, high-quality biological databases were created to organize this deluge of information, providing standardized, interoperable, and searchable repositories that have become the backbone of global life sciences research. As examples, GenBank, maintained by the U.S. National Center for Biotechnology Information (NCBI), remains the world's largest public collection of nucleotide sequences, serving as an essential reference for genome annotation, evolutionary biology, metagenomics, and pathogen identification. UniProt functions as the central repository for protein knowledge, offering expertly curated information on protein

sequences, structure, function, post-translational modifications, and disease associations-foundational for proteomics, enzyme engineering, and drug target discovery. The Protein Data Bank (PDB) provides 3D structural data for tens of thousands of macromolecules obtained through X-ray crystallography, cryo-electron microscopy (cryoEM), and nuclear magnetic resonance (NMR); its standardized coordinate files enable structural biology, computational docking, mechanistic interpretation, and AI-driven design of antibodies and small molecules.

Domain-specific resources further enrich this digital ecosystem. CAZy, the Carbohydrate-Active Enzymes database, provides a systematic classification of glycoside hydrolases, transferases, and other polysaccharide-modifying enzymes, and has become central to microbiome research, industrial enzyme engineering, and biomass conversion. KEGG remains one of the most influential integrative platforms, offering comprehensive pathway maps that link genes, proteins, metabolites, and cellular functions. Ensembl and the UCSC Genome Browser consolidate high-quality genomic annotations across diverse species, enabling comparative genomics, transcriptomic analyses, and detailed exploration of regulatory elements. GISAID, initially created for influenza surveillance, has evolved into a cornerstone of real-time global pathogen monitoring-underscoring the essential role of coordinated, open data sharing during public health emergencies. Collectively, these databases provide the foundational architecture upon which nearly all modern biotechnological research, innovation, and capacity-building efforts depend (Bateman et al., 2025; Bittrich et al., 2023; Drula et al., 2022; Hinrichs et al., 2006; Khare et al., 2021; Ogata et al., 1999; Sayers et al., 2025).

They standardize biological knowledge, enable reproducibility, and allow researchers worldwide to interrogate molecular systems at unprecedented scale and resolution. The synergy between high-quality curated databases and increasingly sophisticated analytical tools, ML models, molecular simulations, multi-omics integration, and AI-driven drug discovery platforms, has amplified the power of bioinformatics, turning it into the primary engine driving both scientific discovery and biotechnological application. As biotechnology moves toward increasing data-intensive paradigms such as precision medicine, synthetic biology, and predictive bioengineering, the importance of robust, accessible, and interoperable bioinformatics infrastructures will only grow. Without these databases and computational frameworks, the modern biotechnology landscape-from genome editing to regenerative medicine-would not be possible.

Over the next five to ten years, the transformative potential of bioinformatics will depend not only on the availability of large biological datasets but on the ability to standardize their annotation and perform integrative analysis across multiple domains. Standardization is becoming a strategic priority: without harmonized metadata, consistent ontologies, and interoperable formats, even the most advanced AI systems cannot extract reliable insights. As biological data proliferates, AI-driven tools will be essential for unifying these datasets, identifying hidden patterns, generating predictive models, and supporting decision-making in research, healthcare, and bio-manufacturing.

This evolution has direct implications for adult learning. The future biotechnology workforce will require not only basic data literacy but also the capacity to work with standardized datasets, understand AI-assisted analytical pipelines, and critically interpret integrative multi-omics outputs. Adult learning systems must therefore adopt flexible, modular, and practice-oriented training approaches that expose learners to real datasets, annotation standards, ML workflows, and ethical considerations surrounding data use. Building these competencies will be vital for ensuring an inclusive, capable workforce for the next decade of biotechnology innovation.

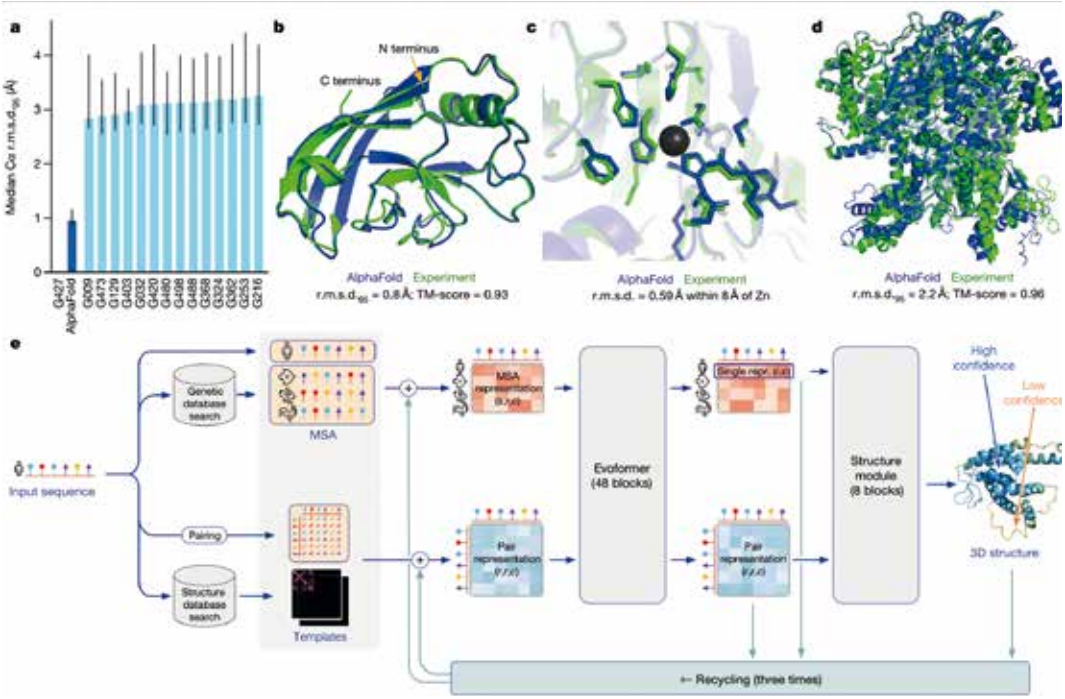
A. Data as the Foundation of Success: Why AlphaFold Worked and What Other Fields Can Learn

The AlphaFold software (Jumper et al., 2021), developed by DeepMind, stands as one of the most extraordinary scientific breakthroughs in computational biology - and arguably one of the most impactful applications of AI to date for mankind, alongside large language models (LLMs) for texts. Its achievement was not solely the result of an advanced neural network architecture, but of a uniquely rich data ecosystem that enabled the model to learn the physical and evolutionary constraints governing protein folding. In recognition of this transformative accomplishment, Demis Hassabis and John Jumper were awarded the 2024 Nobel Prize in Chemistry, underscoring how AI-enabled biological prediction has become a cornerstone of modern science.

Before AlphaFold, accurate protein structure determination relied almost entirely on experimental techniques such as X-ray crystallography, cryo-EM, and NMR. While these methods remain essential for validating molecular mechanisms and capturing dynamic states, they are expensive, time-consuming, labor-intensive, and often technically challenging-sometimes requiring years of optimization for a single structure. AlphaFold radically shifted this paradigm by demonstrating that AI can achieve near-experimental accuracy in silico, dramatically accelerating structural discovery and expanding access to molecular insight across the life sciences, with a current database containing over 200 million predicted structures (https://alphafold.ebi.ac.uk/) (Figure 6).

Figure 6.

The AlphaFold software. A) AlphaFold performance on the CASP14 dataset (87 protein domains), compared with the top 15 groups out of 146 participating teams. B) AlphaFold prediction for CASP14 target T1049 (PDB 6Y4F; blue) overlaid with the experimental structure (green). C) CASP14 target T1056 (PDB 6YJ1), illustrating an accurately predicted zinc-binding site. D) CASP14 target T1044 (PDB 6VR4), a single-chain protein of 2,180 residues, showing correct domain packing. This prediction was generated automatically after CASP using unmodified AlphaFold. E) Schematic of the AlphaFold model architecture. (Source: Jumper et al., 2021).



By making the code, parameters, and model weights freely available, DeepMind catalyzed a rapid wave of innovation, enabling researchers worldwide to adapt, improve, and repurpose the system. This openness sparked an entirely new generation of software tools and predictive models, accelerating progress far beyond what any single laboratory or company could have achieved alone.

The success of AlphaFold relies fundamentally on the existence of the PDB. The PDB provided an unparalleled foundation: a large, standardized, and continuously curated repository containing more than 230,000 experimentally determined structures of proteins and nucleic acids as of 2024 (RCSB PDB, 2024). AlphaFold's deep-learning (DL) models could leverage this homogeneous, richly annotated, and high-confidence dataset to learn the spatial, chemical, and evolutionary regularities that govern protein folding. Decades of rigorous curation-including strict validation procedures, uniform metadata standards, and consistent quality metrics-produced a dataset that was not only vast but also remarkably coherent. In this sense, the breakthrough of AlphaFold was not merely an achievement of algorithmic innovation, but also a testament to the power of open, high-quality scientific data accumulated through global collaboration.

B. Data Fragmentation as a Bottleneck for AI in Other Fields

Unfortunately, the success of AlphaFold has been difficult to reproduce in other scientific domains, largely because no comparable database exists outside structural biology. Most other areas of biology-such as genomics, metabolism, gene regulation, protein–protein and protein-ligand interactions, biomaterials, cell signaling, and phenotypic data-lack comprehensive, clean, and openly accessible datasets of similar scale and quality. Data describing ligand–target binding affinities, ADME/PK (Absorption, Distribution, Metabolism, Excretion and Pharmacokinetics) profiles, or cellular responses remain dispersed across thousands of independent studies and proprietary archives, often recorded under incompatible assay conditions or reported in inconsistent formats, as well as polluted with false-positives results and interpretations. Crucially, many datasets lack contextual metadata-such as temperature, pH, or reagent provenance-which limits the ability to compare, validate, or integrate findings across laboratories.

This scarcity and heterogeneity of high-quality experimental data create significant barriers to AI development. Models trained on fragmented, biased, or noisy information exhibit limited generalization and unpredictable behavior when confronted with new biological entities or disease contexts. In essence, the absence of a "PDB-equivalent" for biochemical interactions, pharmacological profiling, or phenotypic outcomes has constrained the scalability of AlphaFold-like breakthroughs in other domains. The lesson is clear: algorithmic sophistication is not enough; transformative AI in biotechnology requires robust, standardized, FAIR (Findable, Accessible, Interoperable, Reusable) datasets backed by long-term community stewardship.

To address this challenge, a new generation of open-science initiatives are emerging, explicitly focused on constructing structured, validated, and AI-ready datasets for the broader biotechnological ecosystem. For example, OpenADMET harmonizes experimental conditions and metadata in toxicology and pharmacokinetics, enabling more reliable prediction of drug safety and performance (OpenADMET Consortium, 2024). OpenBind consolidates molecular binding and bioactivity data (OpenBind Consortium, 2025), while OpenBioML integrates multi-omics datasets to support predictive modeling of genotype-to-phenotype relationships (OpenBioML, 2023). Together, these platforms aim to bridge the data gap by generating the scale, consistency, and transparency needed for reliable AI training and validation.

The future of AI in Bioinformatics depends on a paradigm shift: from siloed, inconsistent data production to open, standardized, and interoperable knowledge ecosystems. AlphaFold success was not only due neural networks development alone, it succeeded because decades of investment in the PDB provided a trusted, curated, and richly annotated reference framework. Extending these lessons across biomedicine will require global coordination among governments, academic and industry. For learning and workforce development, this transition underscores the need for new digital and data-governance skills, equipping professionals and the public to generate, interpret, and manage complex biological information. By investing in FAIR data infrastructures today, the global community can unlock the next generation of AI-enabled breakthroughs, accelerating discovery, improving health outcomes, and ensuring more equitable participation in the emerging bioeconomy.

C. *Generative AI in Bioinformatic: Learning Biological Complexity Through Integrated Data Ecosystems*

The next decade will mark a decisive transition in bioinformatics: from AI systems that predict isolated biological properties to generative models capable of designing novel biological systems. These new models, spanning generative protein design, RNA engineering, *de novo* metabolic pathways, and synthetic cell behavior, aim to operate not just as analytical tools but as creative engines that propose molecules, interventions, and biological mechanisms never observed in nature.

However, this transition will only succeed if generative AI reflects the true complexity of living systems. Biology is inherently multi-scale and context-dependent: gene expression varies across tissues and time, protein function changes with cellular state, emergent properties arise from networks of interactions, and therapeutic effects depend on human physiology, societal factors, and population diversity. Current databases capture fragments of this complexity, but rarely its integrated structure.

To design functional biological solutions, generative AI models must be trained on interconnected datasets that unify: Genomic information (mutations, epigenetic states, regulatory elements), Proteomic and structural data (folding dynamics, interaction networks), Metabolomic and signaling pathways (fluxes, environmental responsiveness), Cellular and phenotypic outcomes (including spatial and temporal variation), Pharmacological and toxicological responses (validated in humans whenever possible), etc.

Integrating these layers requires harmonized metadata, shared ontologies, and experimental standards that capture the conditions under which biology behaves differently. Without such alignment, even the most advanced neural architectures will be limited to unrealistically simplified models of life. This need becomes urgent as generative AI expands into real-world applications, including the design of next-generation vaccines, programmable cell therapies, and highly specific antimicrobial compounds. Responsible deployment depends on predictive validity: molecules must not only bind to their targets in silico but succeed in the complexity of living organisms, diverse populations, and real clinical contexts.

The coming decade will therefore prioritize:

- Multi-omics data fusion to reveal biological causality
- Human-relevant reference datasets that minimize bias and improve equity
- AI-driven model interpretability to support clinical trust and regulation
- Secure federated infrastructures to protect patient-derived data
- Open, FAIR data ecosystems to enable global participation and oversight

- Generative AI will transform biotechnology only if its outputs are grounded in biological truth, not computational approximations.
- Implications for Learning and Workforce Development

This evolution creates new professional competencies that must be embedded into adult learning systems:

- Ability to work with integrated multi-modal datasets
- Critical understanding of AI-assisted biological design workflows
- Skills in data curation, metadata standards, and quality governance
- Ethical and regulatory literacy for AI-generated therapeutic products

Education must shift toward practice-based, interdisciplinary training, where wet-lab, data-science, and regulatory skills converge. As generative models begin to co-design with human experts, workers must learn not only how AI operates, but how to judge when it is wrong.

The promise of generative bioinformatics is immense: faster cures, sustainable materials, personalized medicines, and radically accelerated discovery. Yet this promise will only materialize if global scientific communities commit to integrated, standardized, and trustworthy data foundations. The strategic challenge of the next 10 years is therefore not merely to build smarter models, but to build the knowledge infrastructure that allows AI and humans together to understand and shape the complexity of living systems.

2.2 Clinical Medical Biotechnology as the Core Engine of Biotechnological Innovation

Medical biotechnology remains the principal engine of biotechnological innovation, driving advances that shape research priorities, investment flows, and global health strategies. The urgency to prevent, diagnose, and treat human disease continually sparks breakthroughs in gene editing, drug discovery, biomanufacturing, and digital bio-analytics. These developments often diffuse beyond medicine into agriculture, industry, and environmental applications, reinforcing the medical domain as the primary source of transformative solutions across the bioeconomy.

Over the past five decades, medical biotechnology has progressed toward increasing precision, programmability, and integration of biological and computational systems. Since the emergence of recombinant DNA technology in the 1970s, each new capability has expanded our ability to read, write, edit, and engineer biological information. Advances in molecular and cellular biology have revealed deeply interconnected networks of regulation and signaling that underpin health and disease. Systems biology, single-cell sequencing, and multi-omics have exposed additional layers of heterogeneity and emergent behavior within tissues, shifting biotechnology from reductionist models toward dynamic and complex interpretations of life.

As technologies mature, they increasingly reach patients and consumers. Genomics, advanced diagnostics, and AI-driven analytics have accelerated the rise of personalized medicine, enabling interventions tailored to an individual's genetic and phenotypic profile. Tools such as non-invasive prenatal testing, carrier screening, and genetic risk reporting are now used in routine healthcare, and in some cases delivered directly to consumers. However, these capabilities introduce ethical and regulatory challenges, including data protection, equitable access, interpretation of probabilistic results, and the governance of genetic information in both clinical and commercial contexts.

The diffusion of personalized technologies reshapes the competencies required for individuals to navigate their own health data and participate responsibly in a rapidly evolving biotechnology landscape. Biotechnology literacy now includes interpreting genomic information, understanding data rights, and recognizing the limitations of predictive analytics. At the same time, scientific progress continues to deepen knowledge about the complexity of biological systems, creating new opportunities to design and engineer living systems with unprecedented precision. Convergence across gene editing, synthetic biology, and AI-enabled design is driving a major transformation in how therapies are developed and delivered.

To analyze these trends systematically, this chapter distinguishes between clinical and non-clinical domains of medical biotechnology, highlighting their respective trajectories, use cases, and implications for skills development and adult learning. This framing enables clearer anticipation of the new demands that AI will place on workforces and education systems-an issue further explored in Part III.

A. AI-Enabled Precision Medicine and Emerging Competencies

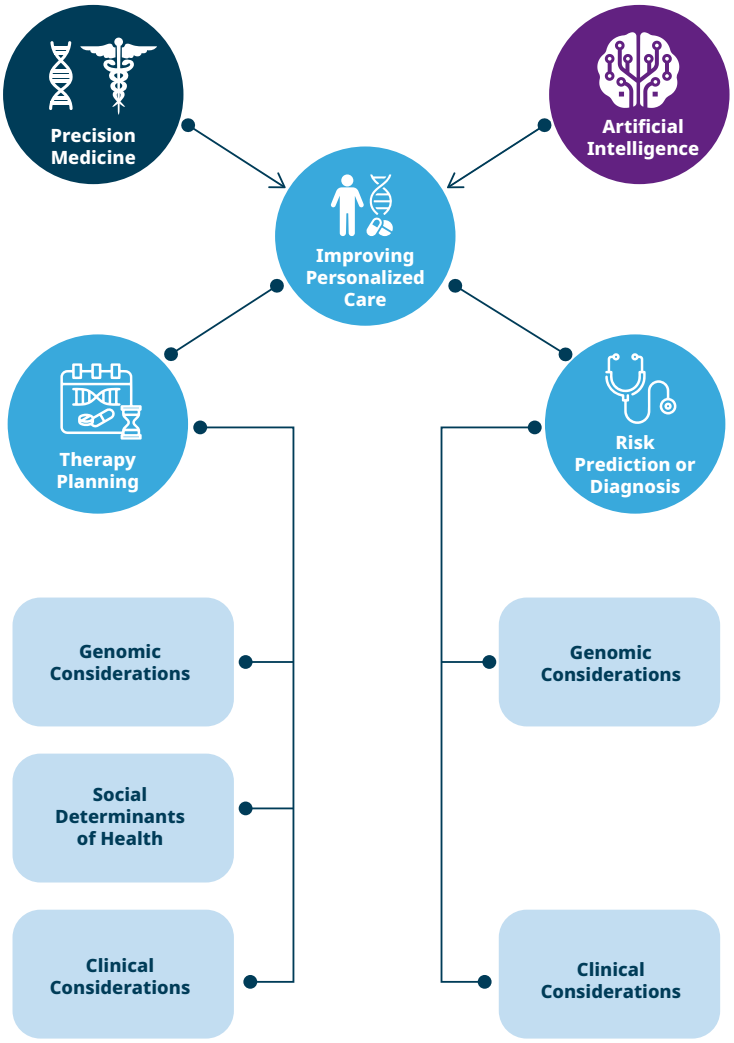
Over the last decade, new techniques, particularly advanced AI methods, have reshaped clinical medical practice. These innovations accelerate drug development, enable interventions against previously "undruggable" molecular targets, revolutionize diagnostics, and open therapeutic pathways for genetic and metabolic diseases that were once considered untreatable.

Advances in sequencing, biomarker discovery, and cell engineering are driving a shift toward precision medicine. Personalized cancer treatments such as CAR-T cell therapy, neoantigen vaccines, and targeted small-molecule inhibitors have demonstrated the power of tailoring interventions to individual patients. Pharmacogenomics enabling medication optimization based on genetic profiles, reducing adverse effects and improving therapeutic outcomes.

In summary, precision medicine increasingly moves beyond just genomic data: it now integrates multi-omics data, medical history, environmental, social, and behavioral factors to define individual health states and disease risk. AI contributes by offering powerful computational and inference tools. Through ML and data-driven methods, AI can combine diverse data (structured and unstructured), reason semantically across modalities, and generate actionable insights to support clinical decision-making (Johnson et al., 2021) (Figure 7).

Figure 7.

Precision medicine and AI intersect across major dimensions that advance personalized care. These include optimizing therapy planning through integration of clinical, genomic, and social–behavioral determinants of health and strengthening risk prediction and diagnostic capabilities by incorporating genomic and additional biological data into clinical decision-making. (Source: Johnson et al., 2021).



The direct impact of these techniques on learning is substantial. As integrative AI analyses become embedded in diagnostics and new clinical techniques emerge, the information that individuals receive about their health will grow significantly more complex. As data collection and computational methods improve, this synergy could enable earlier disease detection, better risk stratification, more precise and effective therapies, and optimized preventative care, thereby increase treatment effectiveness and potentially reducing healthcare costs at a population scale. AI-driven outputs-such as multi-omics diagnostic profiles, genetic predisposition scores, probabilistic risk assessments, and personalized therapeutic recommendations require adults to develop new levels of health and data literacy. Understanding these reports, interpreting predictions about disease susceptibility, and making informed choices about prevention or treatment will increasingly become part of routine healthcare engagement.

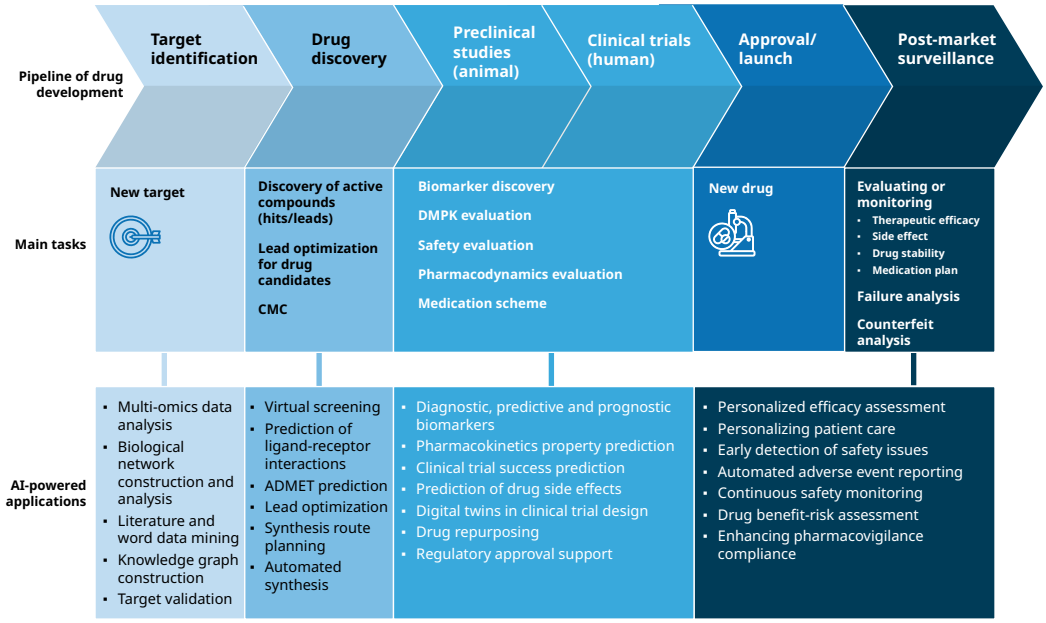
Indirectly, these advances also generate significant regulatory, social, and ethical challenges that shape adult learning needs. As AI becomes embedded in drug discovery, diagnostics, and clinical decision-making, regulators must adapt frameworks for evaluating medicines developed or validated using AI-generated data. This requires legislators, policymakers, and regulatory authorities to understand how AI models work, how training data influence outcomes, and how to ensure transparency, safety, and accountability in AI-enabled medical products. Consequently, adult learning must expand to include not only scientific and data literacy, but also competencies in regulation, governance, and ethical oversight to ensure that society can responsibly manage these emerging capabilities.

B. Direct use of AI and ML in drug discovery pipelines

AI and ML have become transformative pillars of contemporary drug discovery, reshaping nearly every stage of the research and development (R&D) pipeline. Historically, drug development has been lengthy, expensive, and characterized by high attrition rates, with lead identification and optimization often taking many years. AI now disrupts this paradigm by enabling rapid analysis of complex biological datasets, predicting protein structures and ligand interactions with unprecedented accuracy, and designing or optimizing compounds in silico before they ever reach the laboratory. These technologies accelerate hypothesis generation, reduce experimental burden, and allow researchers to prioritize the most promising chemical space early in development. In drug discovery overall, AI also enables more systematic integration of multi-omics data, high-throughput imaging, and real-world clinical data, potentially lowering costs, reducing time to market, and increasing the success rate of new therapeutics (K. Zhang et al., 2025), as synthetized in Figure 8.

Figure 8.

The drug development pipeline. It encompasses several critical stages, including target identification, drug discovery, preclinical studies, clinical trials, regulatory agency review and post-market surveillance. AI technologies have potential applications across nearly all these stages. (Source: K. Zhang et al., 2025).



Despite their immense promise, critical challenges remain. AI models depend heavily on the quality, diversity, and completeness of the datasets used for training; biases or gaps in underlying biological and chemical data can reduce predictive accuracy or lead to erroneous conclusions. Furthermore, ensuring the interpretability and transparency of AI-driven decisions is vital-both for regulatory acceptance and for building trust among scientists and clinicians. Ethical considerations, including data privacy and responsible deployment of AI-generated insights, are increasingly important as computational tools move closer to influencing clinical decision-making. Over the coming decade, advances such as improved data standardization, secure and interoperable computation, and the growth of interdisciplinary expertise will be essential to fully integrate AI into drug discovery pipelines. Nonetheless, the trajectory is clear: AI is poised to continue accelerating the discovery of safer, more effective therapies while reshaping the operational landscape of biotechnology.

C. Modern Genomics and Its Expanding Role in Research, Medicine, and Public Health

Genomics is the field of biology that focuses on the structure, function, evolution, and editing of genomes - the complete set of DNA in an organism. Unlike classical genetics, which often studies single genes in isolation, genomics examines all genes and their interactions simultaneously. This system-level approach enables understanding of how genes work together to influence development, health, disease susceptibility, and biological diversity.

Genomics has undergone a dramatic technological transformation over the last two decades, propelled by breakthroughs that have reshaped both research and clinical practice. New-generation sequencing technologies (NGS) now enable whole genomes, exomes, transcriptomes, and even single cells to be sequenced rapidly and affordably, while metagenomic methods allow comprehensive analysis of microbial communities. Increasingly, genomics operates within a multi-omics framework that incorporates transcriptomics, proteomics, metabolomics, and epigenomics, with AI and ML models integrating these diverse datasets to generate predictive insights into disease, drug response, and phenotype.

Genome sequencing is rapidly becoming more affordable and accessible, accelerating its integration into research, public health, and routine clinical care. The cost of sequencing a human genome has fallen from millions of dollars in the early 2000s to a few hundred dollars today, with new technologies expected to push costs even lower. This dramatic reduction enables large-scale population sequencing programs, broader adoption of whole-genome sequencing in hospitals, and expanded use in fields such as oncology, rare disease diagnostics, prenatal screening, and infectious disease surveillance. As sequencing becomes commoditized, its value will increasingly depend not on generating data, but on the ability to interpret it, highlighting the growing importance of data literacy, bioinformatics skills, and AI-enabled analysis across the healthcare and biotechnology workforce. The democratization of sequencing also raises new questions about data governance, equity, and access, all of which require coordinated policy responses and targeted adult learning initiatives.

Despite enormous progress, genomics continues to face significant scientific, ethical, and societal challenges that shape its future impact. The sheer volume of genomic data, combined with inconsistent metadata, variable annotation quality, and a lack of harmonized formats, undermines cross-study comparability, complicates AI training, limits reproducibility, and slows clinical translation. Interpreting genomic variation remains another major bottleneck, as only a small fraction of detected variants has clear clinical significance; many remain classified as variants of uncertain significance, and limited understanding of gene–gene interactions and phenotype effects further constrains interpretation. Equity and representation pose additional concerns, as most genomic databases disproportionately include individuals of European ancestry, introducing bias into predictive models and reducing diagnostic accuracy for underrepresented populations. Ethical, legal, and social implications are equally pressing, with issues surrounding privacy, data sharing, genetic discrimination, ownership of genetic information, informed consent, and the use of genomic data in AI-driven systems requiring robust governance. Finally, integrating genomics into clinical practice demands substantial workforce training: healthcare professionals and adult learners must be able to understand genomic reports, interpret predisposition scores, communicate probabilistic risks, and apply genomic insights in decision-making-capabilities that remain unevenly distributed across both low- and middle-income countries and high-income settings.

Advances in genome editing, including CRISPR-Cas systems, base editors, and prime editing, have further expanded the field by enabling correction of pathogenic mutations, modification of immune cells for cancer therapy, and engineering of microbial or agricultural strains. In parallel, clinical genomics has moved into mainstream healthcare, supporting the diagnosis of rare disorders, guiding cancer treatment through tumor sequencing, informing pharmacogenomic decisions, and enabling non-invasive prenatal testing. At the population level, large biobanks such as the UK Biobank, All of Us, and Genomics England now link genomic, clinical, and lifestyle data from millions of individuals, providing unprecedented opportunities to understand disease risk and the determinants of health across diverse populations.

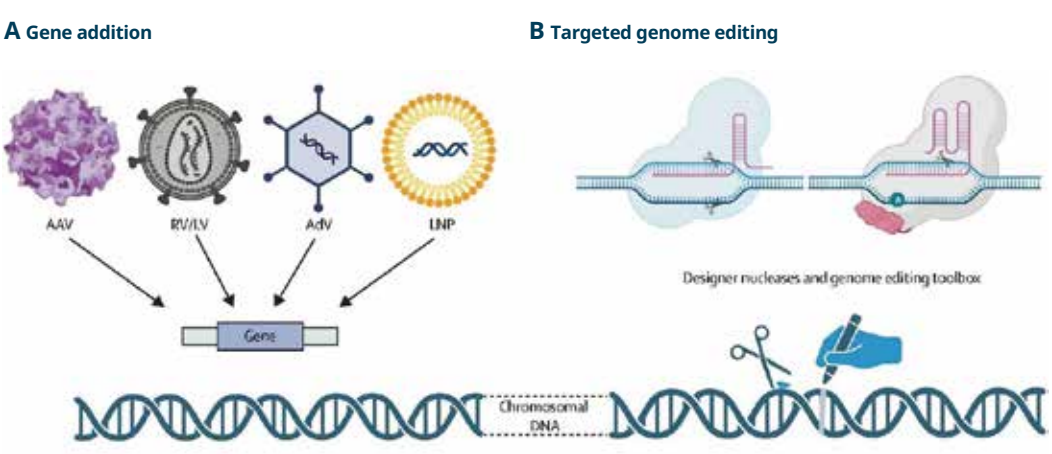
Precision medicine builds directly upon these developments by translating genomic and molecular insights into individualized prevention, diagnosis, and treatment strategies. By integrating multi-omics data, biomarker discovery, advanced imaging, and AI-assisted clinical decision support, precision medicine enables healthcare systems to classify diseases more accurately and select therapies that are specifically tailored to each patient's biological profile. This paradigm is already transforming oncology-through targeted inhibitors, immunotherapies, and liquid biopsies-and is rapidly extending into cardiology, infectious diseases, autoimmune conditions, and rare genetic disorders. As precision medicine becomes more widely adopted, it introduces new demands for data stewardship, bioinformatics literacy, interdisciplinary training, and ethical governance, further highlighting the critical need for continuous adult learning in modern biotechnology.

D. Gene Therapy and Gene Editing: Transforming Medicine at the Molecular Level

Gene therapy and gene editing represent two of the most transformative developments in modern biotechnology, redefining how diseases can be treated at their root molecular causes. Gene therapies traditionally focuses on delivering functional genetic material to compensate for defective or missing genes, using platforms such as adeno-associated viral vectors, lentiviral vectors, and increasingly, non-viral delivery systems like lipid nanoparticles and engineered exosomes (Schambach et al., 2024). In parallel, gene editing technologies-most prominently CRISPR-Cas systems-enable direct modification of DNA sequences within the genome. More advanced modalities such as base editing, prime editing, and CRISPR-associated transposases push this frontier further by enabling highly precise, reversible, or large-scale genomic changes without inducing double-strand breaks (Schambach et al., 2024) (Figure 9).

Figure 9.

Gene therapy and gene editing approaches. (A) In gene-addition methods, delivery vehicles such as adeno-associated viral (AAV) vectors, lentiviral or gammaretroviral (RV/LV) vectors, adenoviral (AdV) vectors, or non-viral systems (e.g., lipid nanoparticles, LNPs) introduce an entire therapeutic gene equipped with regulatory elements (promoters/enhancers and polyadenylation signals). (B) In contrast, gene-editing strategies employ designer nucleases - most commonly CRISPR–Cas9 - to introduce precise nucleotide-level modifications directly within the genome. (Source: Schambach et al., 2024).



Pros	Cons	Pros	Cons
▪ Successful clinical experience ▪ Market authorisations ▪ Functional cure ▪ Effective correction ▪ Optimised delivery route ▪ Assumed to be long lasting	▪ Does not correct underlying genetic defect ▪ Potential safety issues (genotoxicity) ▪ Non-physiological gene expression, fine-tuning is needed ▪ Difficulties with dominant negative mutations ▪ Immunogenicity	▪ Can cure underlying genetic defect, including dominant negative mutations ▪ Easier adaptation for some approaches (CRISPR-Cas9) ▪ Long-lasting correction	▪ Potential ethical dilemmas ▪ Long-term safety to be demonstrated ▪ Monitoring is more challenging ▪ Potential off-target activity and translocations ▪ Delivery needs optimisation ▪ Immunogenicity

Over the past decade, these technologies have moved from academic laboratories into the clinic, producing tangible therapeutic breakthroughs. *Ex vivo* gene editing, in which cells are modified outside the body and reinfused into patients, has shown remarkable success in treating hemoglobinopathies, immunodeficiencies, and certain cancers. CRISPR-edited stem cells and next-generation CAR-T therapies demonstrate how gene editing can improve efficacy, persistence, and safety in cell-based treatments. In vivo editing-altering DNA directly within patient tissues-has also achieved major milestones, such as restoring partial vision in inherited retinal disorders or in the treatment of carbamoyl phosphate synthetase 1 (CPS1) deficiency. In parallel, traditional gene therapy has produced life-changing outcomes for spinal muscular atrophy, congenital blindness, and metabolic diseases through targeted gene replacement.

Despite these advances, significant challenges remain. The primary bottleneck is delivery: ensuring that editing tools reach the correct cells, at the right time, without triggering strong immune responses. Vector tropism, systemic immune barriers, and inefficient delivery to large organs like the brain continue to limit broader application. Safety is another critical concern; unintended genomic modifications, off-target effects, and long-term genotoxic risks require robust monitoring frameworks and improvements in molecular precision. These scientific challenges intersect with profound ethical considerations, including questions surrounding germline modification, equitable access, genetic discrimination, and the obligation to ensure informed consent for complex, permanent interventions. As technologies advance, regulatory systems must adapt to evaluate therapies that blur traditional boundaries between drugs, devices, and living engineered systems.

Looking forward, gene therapy and gene editing are rapidly evolving toward more sophisticated, programmable, and safer interventions. Next-generation tools such as base and prime editors offer the possibility of correcting mutations with minimal collateral damage, while epigenetic editing introduces reversible ways to modulate gene expression without altering the underlying DNA sequence. Improvements in delivery-including engineered viral capsids, non-viral nanoparticles, and targeted exosomes-promise more efficient and tissue-specific in vivo editing. The field is also moving toward integrated therapeutic strategies, combining gene editing with cell therapies, RNA therapeutics, or synthetic biology approaches to create living medicines capable of sensing and responding to disease signals.

As AI and automation become embedded in discovery and manufacturing pipelines, personalized gene-editing strategies for ultra-rare diseases-and eventually even individual patients-are becoming more attainable. These trends point toward a future in which genome-based interventions are not limited to rare or monogenic disorders but extend to more complex conditions, preventive care, and tissue regeneration. Gene therapy and genome editing thus stand at the threshold of a new era-one in which medicine transitions from treating disease to actively engineering health, driven by unprecedented precision in how we can modify, program, and sustain biological systems.

E. RNA-Based Therapeutics

RNA-based therapies have emerged as one of the most dynamic areas of modern biotechnology, offering flexible, programmable platforms for treating a wide range of diseases. Unlike traditional small molecules or protein therapeutics, RNA medicines act at the level of gene expression-either by supplying functional RNA sequences or by modulating the activity of endogenous RNA within cells. Messenger RNA (mRNA) vaccines, widely deployed during the COVID-19 pandemic, demonstrated the speed, scalability, and adaptability of this modality: once the delivery system is optimized, the same platform can be rapidly reprogrammed for new pathogens or therapeutic targets. Beyond vaccines, mRNA therapeutics are being developed for protein replacement (e.g., metabolic disorders), cancer immunotherapy, and regenerative medicine, while small interfering RNA (siRNA) and antisense oligonucleotides (ASOs) are already approved for conditions such as hereditary transthyretin amyloidosis, spinal muscular atrophy, and certain hypercholesterolemias.

The rapid expansion of RNA-based therapeutics brings significant implications for workforce development, regulatory preparedness, and lifelong learning. Because these technologies sit at the intersection of molecular biology, nanotechnology, computational design, and advanced biomanufacturing, they require a workforce capable of integrating skills across multiple domains. During the COVID-19 pandemic, mRNA vaccines became a focal point for false claims, such as the idea that mRNA integrates into human DNA, alters fertility, or permanently changes an individual's genetic makeup-despite overwhelming scientific evidence to the contrary. Similar misinformation now affects other RNA modalities, including claims that siRNA or antisense therapies "rewrite genes" or that lab-grown or RNA-based food products are inherently unsafe. These narratives often spread rapidly through social media, exploiting gaps in scientific literacy and leveraging the novelty of RNA technologies to generate fear. For policymakers, healthcare workers, and educators, this environment underscores the need for targeted science communication, transparent regulatory processes, and adult-learning initiatives that help the public understand what RNA therapies do-and do not-do. Addressing misinformation is therefore not only a public health priority but a critical component of enabling the responsible adoption of modern biotechnologies.

Current challenges in the RNA therapeutics field center on delivery efficiency, molecular stability, and immunogenicity. Achieving targeted delivery remains one of the major bottlenecks: while lipid nanoparticles (LNPs) have enabled first-generation mRNA vaccines, next-generation delivery systems will require enhanced tissue specificity, reduced off-target effects, and improved safety profiles. Stability is another key issue, as RNA molecules are inherently prone to degradation; advances in chemical modification, circular RNA platforms, and optimized purification methods are helping to extend half-life and reduce refrigeration requirements. At the regulatory level, frameworks for RNA therapeutics are still evolving, particularly as the field expands from infectious disease vaccines into areas such as cancer immunotherapy, rare diseases, regenerative medicine, and gene regulation.

From a policy and governance perspective, professionals must be prepared to assess challenges associated with equitable access, genetic data stewardship, global supply chains, and pandemic-readiness manufacturing, issues that the COVID-19 crisis brought sharply into focus. Together, these technical and regulatory demands show that RNA-based medicines are not only a rapidly advancing scientific frontier but also a powerful driver for rethinking training systems, cross-disciplinary competencies, and adult-learning strategies across the biotechnology sector.

F. Advanced Diagnostics

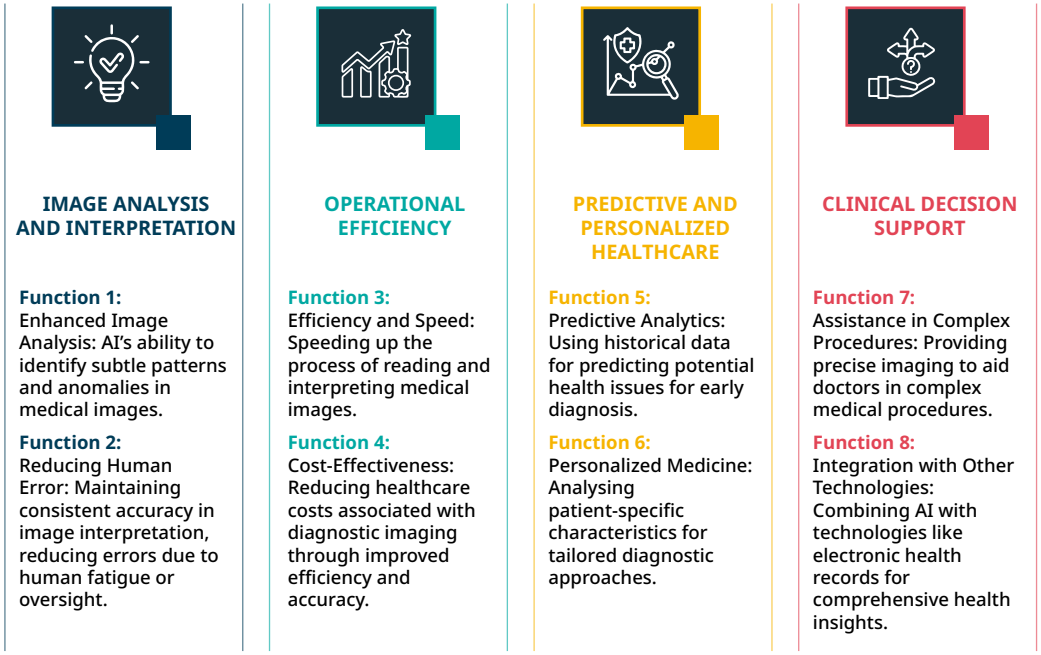
Diagnostic technologies are evolving rapidly, driven by advances in molecular biology, point-of-care platforms, and AI-enabled analytical tools. The paper highlights that, despite these scientific and technological gains, the regulatory landscape for diagnostics remains highly uneven across countries, resulting in fragmented standards, variable product quality, and uneven global access. Unlike pharmaceuticals, which benefit from well-established regulatory pathways, diagnostics encompass a wide and heterogeneous range of risk profiles, from simple lateral-flow tests to complex digital-AI systems, requiring regulatory frameworks that are agile, proportionate, and context-specific.

AI is rapidly reshaping the field of diagnostic imaging, with profound implications for healthcare delivery, workforce training, and regulatory preparedness. A recent review of this field highlights that AI-enabled tools are now integrated across the full imaging workflow, from image acquisition and preprocessing to anomaly detection, segmentation, classification, and clinical decision support. These systems enhance diagnostic accuracy by identifying subtle radiological patterns that may be missed by the human eye, while simultaneously reducing reporting time and operational bottlenecks in clinical environments.

Beyond efficiency gains, AI-driven platforms support a shift toward predictive and personalized healthcare, where imaging data are combined with clinical variables, electronic health records, and population-level datasets to forecast disease progression, stratify risk, and guide targeted interventions. This convergence of imaging, data science, and clinical analytics is transforming radiology from a descriptive specialty into a central component of precision medicine (Figure 10).

Figure 10.

The four domains and eight functional contributions of AI to diagnostic imaging: *Image Analysis and Interpretation, Operational Efficiency, Predictive and Personalised Healthcare,* and *Clinical Decision Support*. Together, these domains illustrate how AI enhances diagnostic precision, accelerates workflows, enables early risk stratification, and supports complex clinical decisions through integrated data-driven insights. (Source: Khalifa and Albadawy 2024).



However, the paper underscores several structural challenges that must be addressed for AI to be safely and equitably deployed. These include biases embedded in training datasets, limited representation of diverse populations, algorithmic opacity, and gaps in data-governance frameworks. Moreover, AI adoption requires robust infrastructure, secure data pipelines, interoperable information systems, and continuous quality assurance mechanisms, which remain unevenly distributed across countries, especially in low- and middle-income settings.

From a policy and adult-learning perspective, the integration of AI into diagnostic imaging calls for new competencies across the health workforce. Radiologists, technicians, and clinicians will need training in digital literacy, algorithmic interpretation, model validation, and ethical considerations surrounding data use. Equally important are regulatory and governance skills: as AI-enabled diagnostics enter clinical workflows, professionals must navigate evolving approval pathways, post-market surveillance requirements, and standards for transparency and accountability.

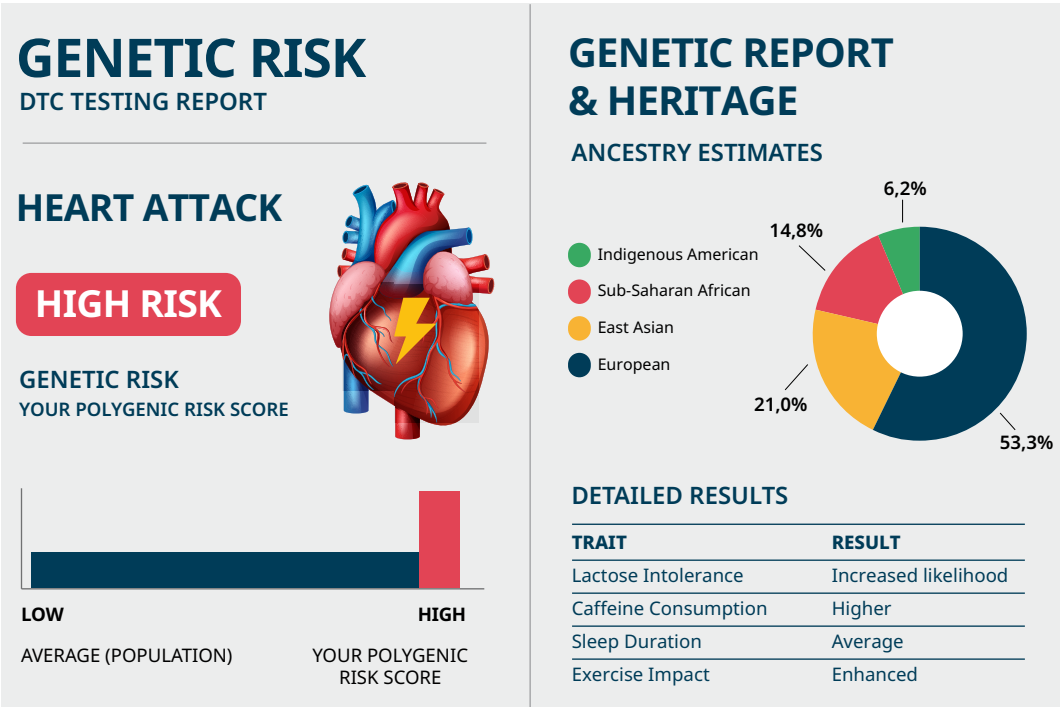
2.3 Non-clinical Medical Biotechnology and the Rise of Accessible Bio-Products

A. Personalized Biology for Consumers: Opportunities, Risks, and Learning Needs

Over the past decade, consumer-facing biotechnology products have expanded rapidly, enabling individuals to engage directly with their own biological information outside traditional clinical settings. Genetic risk testing, ancestry analysis, and microbiome profiling are now widely available as direct-to-consumer (DTC) services, reflecting a broader shift toward participatory and data-driven models of health and identity.

Genomic consumer testing uses genotyping or whole-genome sequencing to provide insights into potential disease predispositions, pharmacogenomic sensitivities, and inherited traits. While often marketed for lifestyle or ancestry exploration, these tests can surface medically relevant variants and prompt clinical follow-up. Evidence shows their diagnostic value: in a large real-world cohort of patients with suspected hereditary cardiac conditions, pathogenic variants were identified in 24% of cases, directly informing care pathways (Kosiborod et al., 2025). Ancestry testing, though positioned as recreational, often intersects with medical genetics through carrier detection and ancestry-specific disease risks. In Figure 11, we illustrate a mock genetic and heritage report based on companies standard formats.

Figure 11.
Mock genetic risk and heritage report, generated for illustrative purposes.



In parallel, microbiome profiling has emerged as another rapidly growing consumer product. Sequencing-based kits allow users to examine the composition of their gut, skin, or oral microbiota and receive personalized wellness recommendations. These offerings tap into rising awareness of the microbiome's influence on metabolism, immunity, and neurological function. However, scientific validity varies widely: many platforms rely on limited reference datasets, non-standardized pipelines, and unproven correlations, which can lead to over-interpretation or inappropriate health behaviors.

Together, these technologies raise complex ethical, regulatory, and equity concerns. Genetic and microbiome data are inherently personal, and commercial handling of such information-whether through data sharing, profiling, or research partnerships-heightens risks related to privacy, discrimination, and long-term governance. Scientific limitations also persist genetic risk predictions are probabilistic and less reliable for underrepresented populations, while microbiome-based interventions remain early in clinical validation. In fact, some countries in Europe like Germany and France have restrictive rules about DTC genetic tests, where in others health-related tests must involve a doctor and/or genetic counselling (Kalokairinou et al., 2017).

These trends can have profound implications for adult learning and workforce development. Individuals exposed to biological data outside clinical environments must be equipped to interpret risk probabilities, ancestry uncertainty, variant classifications, and the scientific maturity of microbiome insights. Without appropriate literacy, consumers may misinterpret probabilistic information, experience unnecessary anxiety, or adopt unsupported interventions.

As datasets expand and analytical pipelines mature, consumer platforms may evolve from offering generic wellness advice to providing more actionable, evidence-based insights that interface with clinical care, nutrition planning, and preventive health strategies. This evolution has significant implications for adult learning. As individuals engage more directly with their own biological data, there will be growing demand for accessible education on microbiome science, data literacy, and the interpretation of probabilistic health information.

At the professional level, clinicians, nutritionists, health coaches, and regulatory professionals will require new competencies to evaluate microbiome reports, counsel consumers, and navigate rapidly changing standards for data accuracy, privacy, and ethical use. More broadly, consumer-facing microbiome technologies highlight a wider societal shift toward personalized, data-centric health management, underscoring the need for continuous learning systems that equip adults with the knowledge to critically interpret biological data, make informed health decisions, and participate meaningfully in emerging models of preventive and participatory healthcare.

Consumer-facing biotechnology exemplifies a broader transformation in health engagement: biological data is no longer confined to laboratories and hospitals. Preparing citizens and professionals to navigate this landscape responsibly will be essential for ensuring equitable access, informed decision-making, and trust in emerging models of personalized and participatory healthcare

2.4 Brief overview of original application domains proposed by ITCILO

Although we understand that these definitions function as broad umbrella concepts, we will briefly outline the original application domains proposed by ITCILO. This overview serves to contextualize the scope of biotechnology within the Centre's existing taxonomy of emerging technologies and to clarify how each domain intersects with learning, capacity building, and future skills development.

For this exercise, we have prioritized medical biotechnology, providing an overview of its main trends, methods, and applications. However, it is important to note that these same methods, such as genomics, gene editing, molecular diagnostics, bioinformatics, and AI-enabled analytics, are routinely incorporated across agricultural, environmental, and food biotechnology domains as well. These fields offer significant opportunities for learning and capacity building, driven by urgent global challenges such as climate change, emerging agricultural pests and diseases, sustainable crop improvement, biosurveillance, and food safety. Topics like GMO labelling, precision agriculture, bioengineered crops, microbiome-based soil restoration, and lab-generated meat and alternative proteins require new competencies that blend biology, digital technologies, regulatory literacy, and ethical considerations.

Yet, given the limited timeframe available for this specific exercise, a comprehensive treatment of all biotechnology application domains is not feasible. Instead, we have focused on the most relevant areas to the mandate of this Action Research, while acknowledging the broader landscape and the importance of these adjacent sectors for future learning agendas.

A. Agricultural biotechnology

Agricultural biotechnology encompasses a range of technological approaches applied to plants, livestock, and agricultural production systems. Advances in this field, particularly those aimed at improving crops, provide innovative solutions to long-standing global challenges, including food security, sustainability, and climate resilience. Over the past century, rapid technological progress, especially in molecular tools and breeding strategies, has significantly accelerated crop genetic improvement, enabling the development of varieties with enhanced yield, nutritional value, and tolerance to biotic and abiotic stresses (Li et al., 2025).

Discovery technologies, including omics approaches such as genomics, transcriptomics, proteomics, and metabolomics, have generated extensive datasets and provided deeper insights into plant biology, with genomics playing a particularly central role (Li et al., 2025). Currently, emerging AI-enabled technologies are reshaping biological research, with clear applications in crop improvement. For example, AlphaFold can generate high-quality protein structure predictions, expanding access to structural data for numerous plant proteins. Likewise, recent advances in protein engineering, including both the optimization of endogenous proteins and the *de novo* design of novel proteins (Kortemme, 2024), have progressed to a level at which they can be directly integrated into crop improvement pipelines through the engineering of genes encoding these designed proteins. Furthermore, recent advances have highlighted the unprecedented capabilities of AI in deciphering complex biological relationships (Abramson et al., 2024) and performing combinatorial optimization (Silver et al., 2016), offering powerful tools for accelerating breeding by identifying optimal genomic combinations. Additionally, high-throughput phenotyping technologies enable the systematic evaluation of genetic variation and engineered genomic configurations, thereby strengthening genotype-to-phenotype associations and providing critical insights to guide crop improvement strategies.

Biotechnology companies are increasingly integrating AI and ML tools into autonomous robotic platforms capable of performing essential agricultural activities, such as crop harvesting, at significantly higher speed and efficiency than manual labor. Computer vision systems combined with DL algorithms are used to process and analyze high-resolution imagery collected by drones, enabling real-time monitoring of crop status, soil conditions, and potential stress factors. Furthermore, ML-based predictive models support decision-making by tracking and forecasting environmental variables - including weather patterns - that directly influence crop performance and yield outcomes (Holzinger et al., 2023).

B. Food biotechnology

Food biotechnology, closely related to agricultural biotechnology, involves applying biological sciences and technological innovations to improve food production, processing, quality, safety, nutritional value, and environmental sustainability (Lee, 2015). It encompasses the use of microorganisms, enzymes, and molecular or genetic techniques to develop or modify foods, increase beneficial traits, reduce undesirable components, extend shelf life, and support efficient and safe food systems (Boukid et al., 2023).Technological advances have largely taken place in areas such as genetics, metabolic engineering, precision fermentation, and enzyme- or cell-based bioprocesses, ultimately aiming to improve food ingredients and final products, as well as to enable novel and more sustainable alternatives (Nielsen et al., 2024).

AI has become an important tool in the food sector, supporting activities such as process modeling, quality prediction and control, sensory evaluation, drying optimization, and addressing complex food processing challenges. In addition to technical applications, AI can also strengthen business decision-making by predicting sales trends, improving supply-chain efficiency, and increasing production yield. Owing to its accuracy, scalability, and cost-effectiveness, AI is now widely regarded as a strategic asset in modern food systems (Bidyalakshmi et al., 2024).

The adoption of AI-assisted sensing platforms, often referred to as intelligent or smart systems, is rapidly expanding across the industry, with the potential to transform food manufacturing by enhancing process efficiency, optimizing production parameters, and maintaining high standards of safety, freshness, and nutritional quality. In food science and technology, AI is commonly applied for tasks such as process modeling, classification, optimization, and prediction (e.g., forecasting critical processing temperatures). Among the most widely used AI methodologies are Artificial Neural Networks (ANN), Fuzzy Logic (FL), and Genetic Algorithms (GA) (Bidyalakshmi et al., 2024).

AI also holds significant promise for biotechnology-driven innovation in the food sector. For example, enzyme development can be accelerated through AI by enabling the design and modeling of complex biochemical reactions, thereby facilitating the creation of novel or improved food ingredients and processing solutions. Moreover, precision fermentation, where specific microorganisms such as yeasts or fungi are used to produce high-value compounds, may benefit from AI-enhanced structural and functional analysis of microbial systems, as well as from advanced computational tools that support strain optimization and genome editing (Gomes et al., 2024).

C. Industrial biotechnology

Industrial biotechnology refers to the application of biological systems, organisms, or derivatives in industrial processes to produce goods, materials, and energy. Its scope ranges from the development of biofuels, biochemicals, enzymes, and other high-value biomolecules to large-scale fermentation processes and applications within the food and biomanufacturing industries (Heux et al., 2015). It largely relies on cultivating and engineering different microorganisms, including bacteria, yeast, and filamentous fungi. Controlled microbial fermentations have been used by humans since ancient times for producing fermented foods and beverages. In the early 20th century, industrial-scale fermentation emerged for manufacturing chemicals such as acetone, butanol, and citric acid. A breakthrough occurred in 1919 with the aerobic production of citric acid using *Aspergillus niger*, which required innovative technologies to supply large volumes of sterile air. This achievement enabled subsequent aerobic, large-scale fermentation

processes, most notably the production of penicillin during World War II. In the postwar period, several new processes were established for manufacturing a variety of antibiotics. By the 1960s and 1970s, microbial fermentation had expanded to include the production of amino acids for food and animal feed, as well as industrial enzymes with broad commercial applications (J. Nielsen et al., 2022).

The faster development of new biotechnological processes for chemical production has been driven by major advances in industrial biotechnology, metabolic engineering, and synthetic biology. These innovations can be grouped into five main areas: (i) new synthetic biology tools that have accelerated strain construction; (ii) rapid synthesis of genes and even entire genomes, leading to the emergence of companies such as Twist Bioscience and Codex DNA that supply synthetic DNA to the biotechnology sector; (iii) advanced data generation and integration (e.g., multi-omics), enabling more comprehensive phenotypic characterization of engineered strains; (iv) improved quantitative modeling of metabolism, providing more accurate predictions for strain design strategies; and (v) the use of robotics and automation to enable multiplexed, high-throughput strain construction, screening, and characterization.

The rapid and precise engineering and characterization of microbial cell factories, together with advances in data acquisition, analysis, and integration, are positioning biotechnology closer to traditional engineering disciplines with increasingly rational and predictable design. This transition aligns with the broader context of the Fourth Industrial Revolution, which is driven by the integration of advanced digital technologies into industrial operations and the emergence of highly connected and intelligent "smart factories" emphasizing efficiency, cost reduction, sustainability, productivity, and ethical practices through AI-enabled control, optimization, and automation. Although metabolic models provide a strong framework for integrating diverse biological datasets, they still face inherent limitations, and ML and AI are becoming essential to advance computational biotechnology. Looking ahead, progress in biological engineering will rely on high-quality data and metadata, coupled with ML- and AI-driven analytics, and achieving a comprehensive predictive understanding of genotype/phenotype relationships may ultimately require next-generation computational approaches, including quantum computing (Gomes et al., 2024; J. Nielsen et al., 2022).

D Marine biotechnology

Blue biotechnology, also referred to as marine or aquatic biotechnology, has been an emerging field since the 1940s. It focuses on developing processes that utilize aquatic organisms such as algae, microalgae, bacteria, and fungi, as well as other marine resources, to produce a wide range of high-value products with diverse industrial, environmental, nutritional, and biomedical applications (Gomes et al., 2024). The application of this technology spans a wide range of sectors, from biofuel production, such as bioethanol obtained through the fermentation of macro- and microalgae, to the extraction of enzymes used in paper, textiles, detergent, and laboratory industries. A notable example is Pfu DNA polymerase, derived from the extremophilic archaeon *Pyrococcus furiosus*, which is widely employed in PCR due to its high replication fidelity (Leary et al., 2009). Marine organisms also provide a diverse set of bioactive compounds with pharmaceutical, cosmetic, and nutritional potential, including minerals, fibers, lipids, and carotenoids extracted from algae and cyanobacteria for use as supplements or nutraceuticals, as well as omega-3 fatty acids sourced mainly from fish, known for their cardioprotective and antioxidant properties (Suleria et al., 2015). In cosmetics, marine-derived molecules are increasingly used as active ingredients due to their antioxidant, moisturizing, anti-inflammatory, and photoprotective properties (Corinaldesi et al., 2017).

Despite its vast potential, the marine environment remains largely unexplored, with more than 90% of its biodiversity still unknown. Scientific progress is limited by the difficulty of accessing deep-sea habitats, challenges in taxonomic classification, and the inability to reproduce isolation and characterization of bioactive compounds. Emerging technologies, including remotely operated vehicles, automated data collection, advanced analytical methods, and modern high-throughput screening, are helping overcome these barriers by enabling efficient sampling, rapid compound testing, and more targeted drug discovery. Integrating these approaches with bioinformatics, IT-driven predictive methods, and multi-omics strategies has further accelerated the identification of novel molecules and uncovered a hidden reservoir of bioactive substances, including those from non-cultivable microorganisms. Metagenomic screening, supported by synthetic biology innovations, has already yielded new antibiotic compounds, demonstrating the significant untapped pharmaceutical potential of marine resources (Daniotti & Re, 2021).

Although AI applications in marine biotechnology are still emerging, literature highlights several promising opportunities. AI could enhance aquaculture efficiency and sustainability by monitoring and controlling water quality, reducing chemical use, detecting early signs of disease through behavioral analysis, and predicting outbreaks. Additionally, AI-based predictive models may support better stock management by estimating species size and gender, ultimately improving productivity and culture health (Ashraf Rather et al., 2024; Mustapha et al., 2021).

E. Environmental biotechnology

Environmental biotechnology focuses on the use of engineered microbial systems to deliver essential ecosystem services, with biological wastewater treatment representing the most widespread application for removing organic and inorganic pollutants and protecting water bodies from eutrophication and contamination (Jones et al., 2021; Sampara et al., 2024). More broadly, this field leverages biological processes such as microbial degradation, enzymatic transformation, and biofiltration to mitigate pollution, manage waste, and restore ecosystems. The exploration and understanding of life in natural and engineered environments are increasingly driven by high-throughput meta-approaches based on shotgun sequencing, multi-omics technologies, and advanced bioinformatics, which together enable the reconstruction and characterization of complex biological systems (Armengaud, 2016). As environmental challenges grow in scale and complexity, AI is emerging as a transformative tool to strengthen these biotechnological strategies through predictive modeling of pollutant degradation, optimization of bioprocess parameters, modeling of microbial community dynamics, and real-time environmental monitoring and control (Alavian et al., 2025).

Recent advances in AI have greatly accelerated microbial bioremediation by enabling the rapid discovery of pollutant-degrading microorganisms and the design of more efficient enzymes. ML and DL models support enzyme prediction, metabolic pathway optimization, and early pollutant detection by leveraging large genomic and proteomic datasets (Meng et al., 2023). A prominent example is the AI-assisted engineering of PET-degrading enzymes, where computational tools guided the development of enhanced PETase variants such as FAST-PETase, capable of degrading post-consumer plastic under mild conditions, alongside additional optimized mutants with improved stability and catalytic performance (Lu et al., 2022).

AI has also expanded capabilities for detecting and monitoring environmental contaminants through non-invasive, real-time analytical approaches. Machine vision, hyperspectral imaging, and Raman spectroscopy enhanced with AI improve the identification and classification of microplastics in soil and water, while predictive models are used to estimate heavy-metal contamination and ecological risk (Agrawal & Solanki, 2025; Sarker et al., 2024). Additionally, hybrid AI frameworks combining genetic algorithms and support vector machines have been applied to assess mercury toxicity in fish using image-based analysis, strengthening environmental and food safety monitoring (Maurya et al., 2023). Despite progress, key barriers still limit real-world application of AI-based bioremediation, including data reliability, model transparency, biosafety of engineered organisms, and enzyme scalability. Additionally, unclear regulatory standards for using AI-guided microbial systems in natural environments create ecological and public trust concerns (Alavian et al., 2025).

PART III. IN-DEPTH ANALYSIS OF PRIORITIZED BIOTECHNOLOGY TRENDS WITH POTENTIAL IMPACT ON ADULT LEARNING

In Part II, we mapped the broad landscape of biotechnology and identified medical biotechnology and bioinformatics as the primary drivers of innovation with the most direct relevance to ITCILO's mandate for capacity development. Within these domains, several fast-moving trends were highlighted, including genomic medicine, RNA-based therapeutics, AI-enabled diagnostics and consumer biotechnology services, as particularly impactful for future workforce skills and adult-learning needs.

Biotechnology advancements are reshaping human health, cognition, and workforce participation. For ITCILO, these developments define priority areas for capacity building that ensure equitable access to innovation and support lifelong learning. This section analyzes four key domains: I. neurological interventions, II. mental-health innovation, III. AI-enabled care and IV. citizen-driven biotechnology, followed by actionable learning opportunities for the next decade.

In this section, we will provide a deeper assessment of these priority biotechnology trends through the lens of ITCILO's mission, considering their learning potential, ethical and governance implications and relevance for future skills development. The aim is to identify actionable opportunities that ITCILO may pursue toward 2030 and beyond, equipping workers, institutions, and policymakers with the competencies required to navigate a world in which biotechnology is increasingly embedded across healthcare systems, markets, and society at large.

For the purposes of this report, we will not address diagnostic interactions with LLM chat systems (e.g., ChatGPT). Although the literature in this field is rapidly expanding and model performance continues to improve, these advances are largely driven by computational and data-science innovation rather than biotechnology and therefore fall outside the primary scope of this analysis.

3.1. Biotechnology Advancing Cognitive Health and Learning Capacity

As discussed previously, biotechnology innovations are transforming our ability to prevent, diagnose, and treat a wide range of conditions. However, because biological systems are extraordinarily complex and interconnected, it is not possible to analyze these advances in isolation or strictly within a single category. For example, an AI tool developed to predict protein structure can influence drug discovery, vaccine design, industrial enzyme engineering, and even agricultural biotechnology.

In biotech, techniques are transversal and generate impact across multiple domains simultaneously. For ITCILO, recognizing this dynamic and multidimensional landscape will be essential for shaping future-ready adult learning strategies, ensuring professionals are prepared not only to use individual technologies but to navigate the growing intersections between them.

In this section, we examine how selected breakthroughs can restore cognitive function, support lifelong learning, and expand opportunities for social and workforce participation. Importantly, these innovations do not map neatly to one technique in our taxonomy but emerge from the convergence of complementary technologies such as gene therapy, precision delivery systems, and AI-enabled design tools.

A. Restoring Cognition: Gene and Cell-Based Innovations for Neurodevelopment and Neurodegeneration

Recent breakthroughs in biotechnology, particularly gene therapy, precision genome editing, RNA-based therapeutics and cell-based interventions, are opening new possibilities for treating disorders that impair cognitive development or lead to neurodegeneration. These technologies move beyond symptom management toward directly addressing underlying molecular causes, offering the potential to improve learning capacity, memory, and overall cognitive health. Importantly, these innovations are emerging alongside more accessible digital learning tools, making inclusive education more achievable.

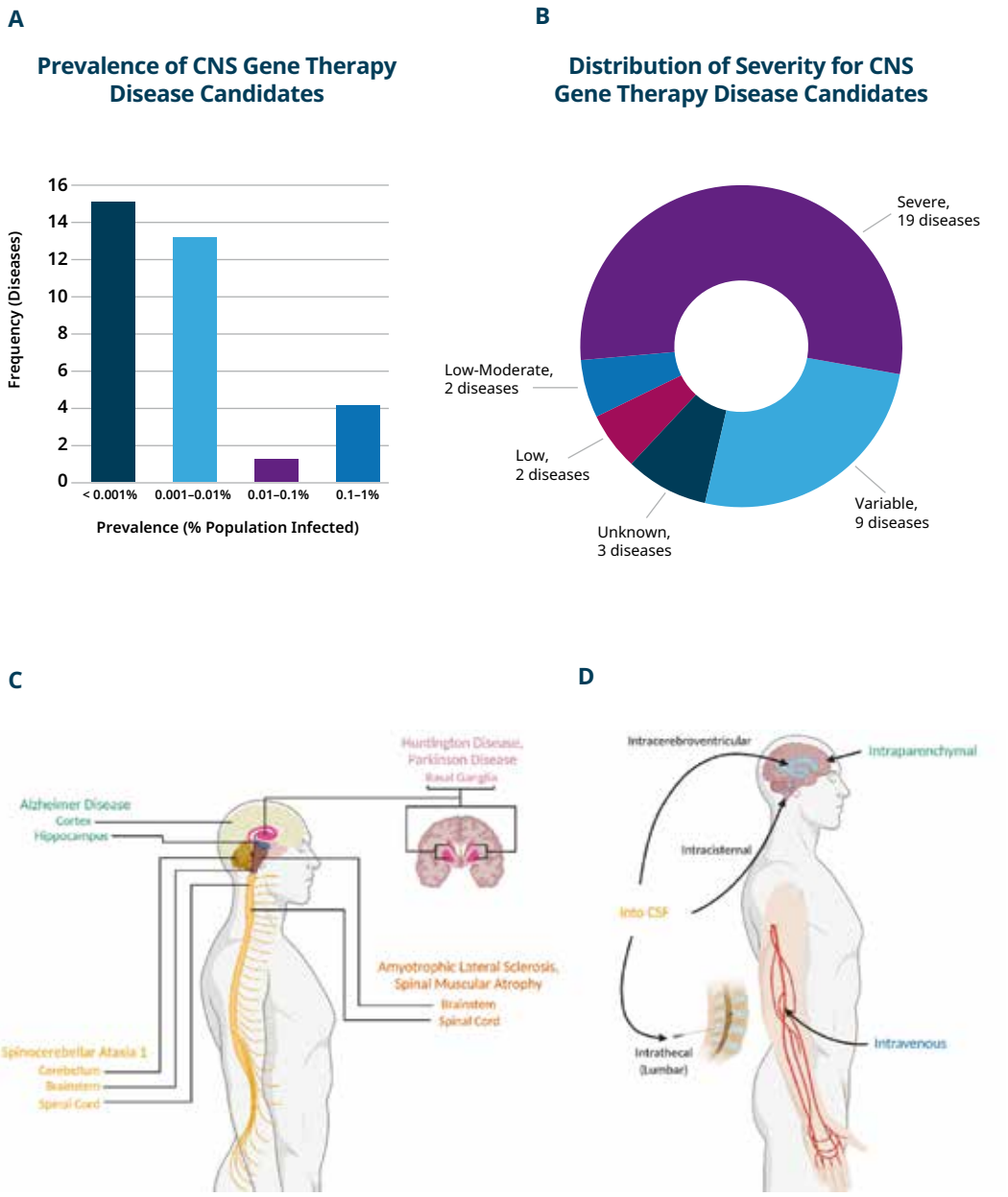
Neurodevelopmental genetic disorders, such as *Down Syndrome*, have historically been viewed as irreversible because they arise from chromosomal abnormalities affecting brain development. Advances in gene regulation, targeted transcript modulation and neuronal plasticity enhancement are beginning to challenge this paradigm. Experimental approaches, including silencing, modulating overexpressed genes on chromosome 21 and restoring synaptic function, aim to improve learning ability, communication, and quality of life for individuals with the condition (Huang et al., 2024).

In Alzheimer's disease and other dementias, biotechnology is rapidly reshaping treatment strategies. Gene therapies targeting *APOE* risk variants, monoclonal antibodies that remove toxic amyloid aggregates and RNA-based treatments modulating tau protein expression are showing promise in slowing or modifying disease progression (Sugandhi et al., 2025). These advances have implications for lifelong learning: stabilizing or preserving memory function allows older adults to remain active in education, work, and community participation for longer, a key priority given aging global workforces.

Gene therapy is emerging as one of the most promising approaches for treating severe central nervous system (CNS) disorders that currently lack curative options. By delivering corrective DNA or RNA payloads that directly target disease-causing mutations, gene therapy can achieve long-lasting or even disease-modifying effects that conventional pharmaceuticals cannot. The review by Leong and colleagues (2023) highlights rapid growth in clinical research for monogenic and neurodegenerative CNS conditions, including AADC deficiency, SMA, Parkinson's disease, ALS, and Alzheimer's disease, while emphasizing the unique anatomical and physiological barriers that complicate drug delivery into the brain and spinal cord. Novel AAV capsids (e.g., AAV9, AAV-PHP variants) capable of crossing the blood–brain barrier are enabling less invasive administration routes and expanding therapeutic reach across CNS tissue. Despite the advances, achieving widespread, safe, and durable CNS transduction remains an ongoing challenge, and advances in the delivery system are urgently needed (Leong et al., 2023) (Figure 12).

Figure 12.

Overview of the landscape of central nervous system (CNS) disorders currently considered amenable to gene therapy approaches. Panel (a) illustrates the relative prevalence of 33 target diseases within the general population, highlighting that although many are individually rare, their collective burden is substantial. Panel (b) classifies these disorders by lethality, showing wide variation in mortality risk depending on disease phenotype and progression, with several conditions falling into the moderate-to-severe range. Panel (c) maps the primary anatomical regions of degeneration across these disorders, reflecting diverse neurological pathways and cell types implicated in disease mechanisms. Finally, panel (d) illustrates the clinical administration routes employed in current trials-including intraparenchymal, cerebrospinal fluid–based (intrathecal, intracerebroventricular, intracisternal), and systemic intravenous delivery-each offering distinct advantages and limitations for achieving therapeutic distribution within the CNS. (Source: Leong et al., 2023).



Biotechnological advances have begun to reshape the treatment of CNS diseases, with several gene and RNA-based therapies now approved for clinical use. These therapies target the underlying genetic causes of severe neurological conditions, marking a shift from symptomatic care toward disease-modifying interventions. Notable examples include voretigene neparvovec for Leber congenital amaurosis, onasemnogene abeparvovec and nusinersen for spinal muscular atrophy, and targeted antisense therapies for Batten disease and hereditary transthyretin-mediated amyloidosis. These approvals demonstrate that altering or supplementing defective gene expression can restore essential protein function, halt degeneration, and in some cases recover motor or sensory capabilities (Shahryari et al., 2019).

The clinical pipeline continues to expand rapidly, with dozens of ongoing trials investigating new therapies (Table 1). Through these studies, treatment goals include improving cognitive performance, slowing neurodegeneration, enhancing movement control and extending overall life expectancy. Importantly, many investigation approaches are tailoring interventions to specific patient populations and genetic subtypes, supporting the rise of precision medicine for CNS disorders. Overall, the field is transitioning from early isolated successes in rare pediatric diseases toward broader conditions with significant global burden.

Table 1. Current clinical trials using AAV-mediated gene therapy to treat CNS diseases.

Disease	Method	Gene Target	Clinical Trial ID	Phase
Alzheimer's disease	IPa	BDNF	NCT05040217	I
	ICis	APOE2	NCT03634007	I
	I.V., I.T.	TERT	NCT04133454	I
AADC deficiency	IPa (SNc, VTA)	DDC	NCT02852213	I
	IPa (Put)	DDC	NCT01395641	I–II
	IPa (Put)	DDC	NCT02926066	II
	IPa (Put)	DDC	NCT04903288	II
Canavan disease	I.C.V.	ASPA	NCT04833907	I–II
	I.V.	ASPA	NCT04998396	I–II
Frontotemporal dementia	ICis	GRN	NCT04747431	I–II
	ICis	GRN	NCT04408625	I–II
GM1 gangliosidosis	I.V.	GLB1	NCT03952637	I–II
	ICis	GLB1	NCT04273269	I–II
GM2 gangliosidosis	IPa / ICis / I.T.	HEXA / HEXB	NCT04669535	I
	I.T.	HEXA / HEXB	NCT04798235	I–II
Giant axonal neuropathy (GAN)	I.T.	GAN	NCT02362438	I
Huntington's disease	IPa (Str)	HTT*	NCT04120493	I–II

Disease	Method	Gene Target	Clinical Trial ID	Phase
Mucopolysaccharidoses (MPS)	I.V.	F9, IDS, IDUA†	NCT04628871	NA
	ICis	IDS	NCT03566043	I–II
	ICis / I.C.V.	IDS	NCT04571970	I–II
	ICis / I.C.V.	IDS	NCT04597385	NA
	ICis	IDUA	NCT03580083	I–II
	I.V.	NAGLU	NCT03315182	I–II
	I.V.	NAGLU	NCT04655911	NA
	I.V.	SGSH	NCT02716246	I–II
	I.V.	SGSH	NCT04088734	I–II
	I.V.	SGSH	NCT04360265	NA
	IPa	SGSH	NCT03612869	II–III
Multiple system atrophy (MSA)	IPa (Putamen)	GDNF	NCT04680065	I
Neuronal ceroid lipofuscinoses (NCL)	I.T.	MFSD8	NCT04737460	I
	I.T.	CLN3	NCT03770572	I–II
	I.T.	CLN6	NCT04273243	NA
Parkinson's disease	IPa (Putamen)	GDNF	NCT04167540	I
	IPa (Putamen)	DDC	NCT03562494	II
	IPa (Putamen)	DDC	NCT03733496	NA
	ICis	GBA1	NCT04127578	I–II
Spinal muscular atrophy (SMA)	I.T.	IGHMBP2	NCT05152823	I–II
	I.V., I.T.	SMN	NCT04042025	IV
	I.V.	SMN	NCT03421977	NA

Adapted from (Leong et al., 2023).

As these examples highlight, the treatment landscape for neurological and neurogenetic conditions is rapidly evolving, offering increasingly promising avenues for intervention. Continued advances in gene therapy, precision medicine and innovative delivery modalities are expected to improve quality of life, preserve cognitive and motor function and reduce long-term disability for affected individuals. Earlier and more accurate diagnoses, supported by genomics, advanced imaging, and AI-enabled decision tools, will be essential to ensure timely access to emerging therapies and maximize therapeutic benefit. Collectively, these developments suggest a future in which debilitating CNS diseases can be managed more effectively, enabling greater participation in education, employment, and community life throughout the lifespan.

This progress also creates new opportunities for ITCILO and other capacity-building institutions to design tools, training programs and initiative-taking methodologies that anticipate evolving skills needs in healthcare systems and the wider labor market. By systematically monitoring breakthroughs in biotechnology and integrating them into adult-learning strategies, ITCILO can help ensure that professionals, patients, and caregivers are well prepared to understand

and benefit from innovation. Furthermore, the convergence of biomedical advances with neurotechnology, such as brain–computer interfaces, AI-driven cognitive rehabilitation and personalized neurostimulation, will increasingly connect therapeutic interventions with adaptive learning technologies that respond to individual neurological profiles. In summary, the next 5–10 years will redefine what is possible in maintaining cognitive function, enabling inclusion, and supporting lifelong learning for individuals affected by CNS disorders.

B. Innovation Supports Advancements in Mental-Health and Neurodevelopmental Therapies: Toward Inclusive Learning and Work Participation

Neurodevelopmental and mental-health disorders, including attention-deficit/hyperactivity disorder (ADHD), major depressive disorder, anxiety disorders, work-related stress and burnout, impose a substantial and growing global burden. According to the World Health Organization (WHO), in 2021 approximately 1.1 billion people worldwide lived with a mental disorder (World Health Organization, 2025). Mental disorders remain among the top ten leading causes of global health loss, accounting for a significant share of years lived with disability (YLDs) (GBD 2019 Mental Disorders Collaborators, 2022). Their impact extends beyond health: depression and anxiety alone cost the global economy an estimated US$ 1 trillion per year in lost productivity, largely through absenteeism, reduced performance, and early exit from the labor force (World Health Organization & International Labour Organization, 2022; World Health Organization, 2016). These pressures on individuals, workplaces, and economies underscore the urgent need for more effective, scalable, and accessible interventions.

In response, biotechnology and digital-health innovation are reshaping how these conditions can be managed by offering new pathways for lifelong learning, rehabilitation, and social inclusion. For ADHD, care models are shifting toward multimodal, personalized support that combines pharmacotherapy, digital therapeutics (DTx), cognitive training and behavioral interventions to enhance attention, executive function and educational outcomes. In depressive disorders and anxiety, emerging treatments, including prescription-grade digital therapeutics, non-invasive neurostimulation and novel pharmacologic mechanisms, are expanding beyond conventional antidepressants and psychotherapy. For work-related burnout, scalable and workplace-integrated digital mental-health tools, resilience training and preventive care programmes offer promising alternatives to traditional, often overstressed mental-health systems.

These advances carry significant implications for learning, social participation and workforce inclusion. Improved mental-health management can safeguard cognitive capacity, motivation and functional resilience enabling individuals to pursue education, vocational training and lifelong learning even in the presence of chronic conditions. Scalable and widely accessible digital-health solutions can bridge gaps in service delivery, particularly in low- and middle-income countries where mental-health infrastructure is limited. For institutions such as ITCILO, this evolving landscape presents strategic opportunities to integrate mental-health literacy, digital-health skills and inclusive learning methodologies into capacity-building programs,

ensuring that professionals, educators, employers and communities are prepared to leverage innovations responsibly and effectively.

Accelerated progress in drug discovery, driven by improved understanding of disease mechanisms, high-throughput screening and precision pharmacology, is enabling a new generation of treatments that are more effective, more precise, longer-lasting and more tolerable than many traditional therapies. For example, in major depressive disorder (MDD), the approval of esketamine nasal spray represents a breakthrough in treatment-resistant cases, offering rapid-acting relief through modulation of glutamatergic neurotransmission rather than the classic monoamine mechanism of traditional antidepressants (Daly et al., 2019; Kumari et al., 2024; Oraee et al., 2024; Wang et al., 2025). Clinical evidence supports its use in treatment-resistant depression and in patients with acute suicidal ideation, highlighting how mechanistically novel drugs can address unmet needs in mental-health care (Kumari et al., 2024).

In neurodegenerative and motor disorders such as Parkinson's disease (PD), improved drug-delivery and optimized pharmacokinetics have enhanced long-term management. The use of continuous infusion therapy via levodopa–carbidopa intestinal gel (LCIG), for example, smooths dopamine availability, reduces motor fluctuations and improves both motor and non-motor symptoms, relative to traditional oral levodopa regimens. This more stable dopaminergic stimulation can translate into better quality of life and functional capacity for patients with advanced PD (Antonini et al., 2017; Chung et al., 2022; Fernandez et al., 2015; Juhász et al., 2017; Slevin et al., 2015; Zhang et al., 2020).

For neurodevelopmental and attention disorders, advances in pharmacology are yielding longer acting and more stable formulations. Extended-release stimulant prodrugs, such as newer methylphenidate-based compounds, offer smoother symptom control throughout the day, reduce rebound effects and lower misuse potential, contributing to better adherence and consistent function in schooling or work contexts (see example of serdexmethylphenidate/dexmethylphenidate; clinical data indicate prolonged efficacy over traditional formulations) (Vasiliu, 2023).

Beyond improvements in efficacy and pharmacodynamics, modern drug-discovery is increasingly guided by mechanistic insights, biomarker stratification and personalized medicine. This allows for therapies tailored to patient subtypes, reducing trial-and-error prescribing and minimizing side effects. For instance, glutamatergic modulators like esketamine target specific neurochemical pathways rather than broadly affecting monoamines, offering faster onset, alternative action mechanisms and potentially avoiding limitations of classical antidepressants (Kumari et al., 2024). Similarly, drug delivery strategies such as LCIG address limitations of pharmacokinetics, reducing fluctuations and improving long-term tolerability and functional outcomes in chronic neurological disease (L. Wang et al., 2018).

Collectively, these innovations illustrate a transition from broad, symptom-based treatment toward precision and mechanism-based therapeutics. Such treatments are better aligned with

individual biology, disease pathology and real-life functioning, thereby supporting cognitive well-being, occupational participation and lifelong learning. As drug pipelines diversify and integrate with diagnostics, digital monitoring and real-world data, the potential for transformative impact on global mental health and neurodevelopment becomes increasingly tangible (Table 2).

Table 2. Examples of mental-Health–Related Conditions and Emerging Interventions with Implications for Learning, Work, and Inclusion

Condition / Use Case	Emerging Intervention / Approach	Potential Benefits for Learning, Work & Inclusion
ADHD	Digital therapeutics (DTx) + cognitive training + behavioural support	Improved attention, executive function, reduced dropout - better educational and work outcomes
Depression / Anxiety / Common Mental Disorders	Prescription-grade digital therapeutics; non-invasive neurostimulation (e.g., tDCS); novel pharmacology targeting neuroplasticity/neuro-immune pathways	Stabilized mood, improved cognitive/ emotional resilience, reduced absenteeism, sustained work capacity
Burnout & Work-related Stress	Workplace-integrated digital mental-health platforms; resilience training; tele-counseling	Prevention or mitigation of burnout; maintained productivity; inclusion of vulnerable workers; reduced workforce turnover
Chronic or Recurrent Mental Health Conditions	Long-term care models combining digital tools, behavioural support, social integration, workplace accommodations	Support for lifelong learning, reskilling, social participation, reduced social exclusion

C. Smart Drugs for Cognitive Enhancement - Evidence, Uses, and Risks

Nootropics and cognitive enhancers, often refereed as “smart drugs” are substances taken with the intention of improving cognitive functions such as attention, memory, alertness and executive functioning. While many of these compounds were originally developed for medical conditions (e.g., ADHD, narcolepsy), their use has expanded in healthy individuals seeking better academic, professional, or mental-performance outcomes (Battleday & Brem, 2015; Farah et al., 2004; Malík & Tlustoš, 2022; Repantis et al., 2010; Smith & Farah, 2011).

Among the most studied are prescription stimulants such as Methylphenidate (e.g., Ritalin), Amphetamine-based drugs, and Modafinil, as well as common substances like caffeine. Research shows that these drugs can enhance certain cognitive processes: for example, stimulants can improve attention, reaction time, working memory and executive function, including healthy adults (Battleday & Brem, 2015; Einöther & Giesbrecht, 2013; Ilieva et al., 2015; Repantis et al., 2010; Smith & Farah, 2011).

However, the magnitude of cognitive enhancement in healthy, well-rested individuals is often modest. Meta-analyses and reviews suggest that improvements tend to be small and

sometimes limited to specific domains such as sustained attention or memory recall, rather than broad or dramatic "intelligence boosting". For example, in controlled trials methylphenidate showed moderate gains in recall and sustained attention, while modafinil delivered only small, statistically significant effects in some studies (Roberts et al., 2020).

Moreover, the benefits come with non-trivial risks. Regular use or misuse of stimulants and other nootropics has been linked to potential side effects, including sleep disruption, mood instability, increased cardiovascular strain, dependency or addiction, and possible negative effects on long-term brain plasticity. Studies note that in healthy high-performing individuals, cognitive gains may be limited or even offset by adverse effects; the risk–benefit ratio is therefore more uncertain in this population (Schifano et al., 2025; Silczuk et al., 2025).

Beyond physiological concerns, the use of smart drugs raises social and ethical questions. Widespread nonmedical use among students and professionals may contribute to unequal access to "performance enhancement pressure" to use drugs in competitive environments, and questions about fairness and long-term societal consequences.

In sum, while smart drugs can offer modest enhancements in specific cognitive domains, especially under conditions such as sleep deprivation or attentional deficit, they should not be regarded as a reliable path to significantly increased intelligence or cognitive "super-performance". Their use involves trade-offs in safety, ethics, and long-term brain health.

From a learning and workforce-development perspective, cognitive-enhancing smart drugs have the potential to influence adult learning outcomes, particularly in contexts requiring sustained attention, complex reasoning, and rapid skill acquisition. In the short term, their use could lead to improved concentration, reduced fatigue, and better performance under stress, especially for learners with attentional difficulties or demanding schedules. However, the uneven access, variable efficacy, and risks of dependency introduce equity and safety concerns in educational settings. The emergence of biotechnology-driven "smarter smart drugs", with improved precision and reduced side effects, could further normalize enhancement practices, creating new expectations for productivity and competitiveness in training programs.

For ITCILO, this trend underscores the need to anticipate ethical guidelines, promote health-first learning environments, and develop policies that balance potential benefits with fairness and wellbeing. Preparing adult learners and institutions for this reality will require not only scientific literacy but also strong governance frameworks that ensure enhancements are used responsibly, voluntarily, and inclusively.

3.2. Engaging with Biological Data: A New Vector for Adult Learning

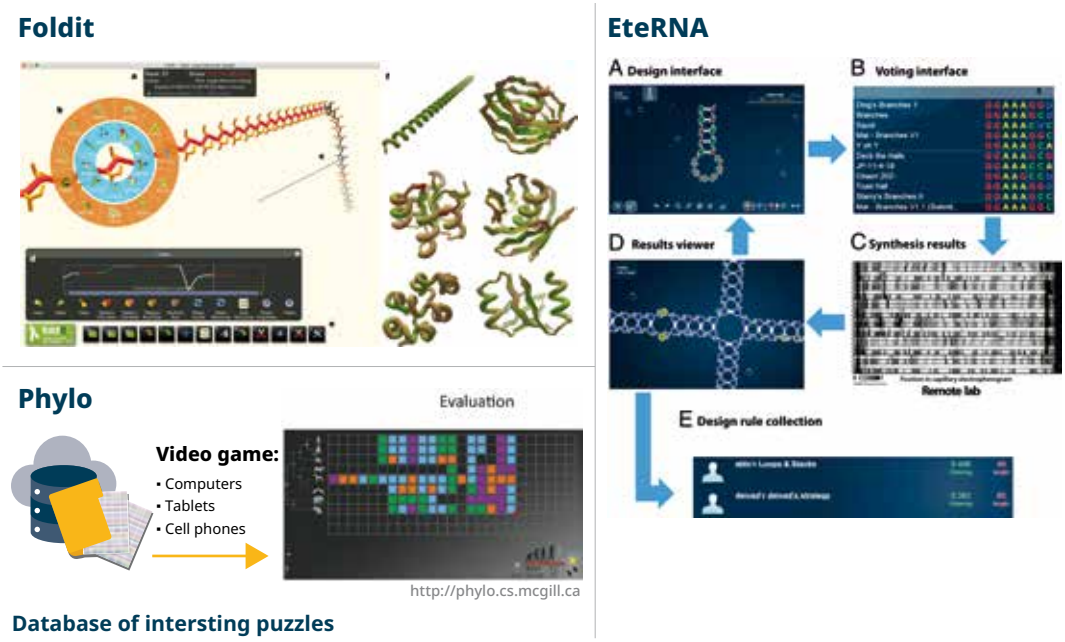
A. Gamified and Citizen-Science Platforms for Learning Complex Biotechnology Concepts

Biotechnology concepts are inherently complex, often requiring specialized knowledge of molecular structures, genomic data, and biochemical pathways. Even widely used bioinformatics resources such as the PDB or GenBank can be challenging for non-experts to navigate due to their technical interfaces, assumptions of domain expertise, and reliance on abstract scientific representations. These barriers can limit public understanding and reduce opportunities for learners without formal training to engage meaningfully with science shaping modern health and society.

Gamified environments and citizen-science platforms are emerging as powerful tools to bridge this gap. By transforming complex biotechnology tasks into interactive and engaging challenges, these platforms enable users to explore protein folding, genome annotation, or gene regulation through experiential learning. Notably, many of these initiatives allow participants to contribute directly to real scientific discoveries, fostering both motivation and a sense of purpose (Figure 13). In doing so, they establish a dynamic intersection between public engagement, workforce skill development, and open innovation, a combination highly relevant in rapidly evolving fields such as AI-enabled genomics and precision medicine.

Figure 13.

Foldit, EteRNA and Phylo. Examples of gamified environments for citizen-scientists. Figures adapted from (Kawrykow et al., 2012; Koepnick et al., 2019; J. Lee et al., 2014)



These tools demonstrate how challenge-based learning and active participation can increase understanding of biological systems, strengthen collaboration, and cultivate computational reasoning and data literacy. They also lower barriers to entering domains like structural biology and bioinformatics, providing inclusive and accessible starting points for adults who may encounter genetic risk scores, AI-driven diagnostics or personalized therapies in their personal or professional lives. As biotechnology becomes increasingly embedded in everyday healthcare, work, and policy, such platforms can democratize scientific knowledge and support more informed decision-making across society.

Several successful platforms illustrate the potential of gamified and participatory biotechnology learning (Table 3). Foldit allows users to manipulate protein structures to discover low-energy conformations, and players have contributed to peer-reviewed breakthroughs, including the design of novel enzymes. EteRNA engages participants in RNA folding challenges, with top community-designed molecules synthesized and tested in real laboratories, reinforcing iterative learning between digital play and experimental validation. Phylo transforms multiple sequence alignment challenges into intuitive puzzles, enabling non-experts to help improve the accuracy of comparative genomics data (Kawrykow et al., 2012; Koepnick et al., 2019; J. Lee et al., 2014).

New immersive VR/AR molecular biology labs extend experiential learning further, enabling realistic simulations of PCR setup, CRISPR genome editing, phylogenetics workflows, and next-generation sequencing pipelines. Together, these platforms demonstrate how complex biotechnology concepts can be made accessible, engaging, and scientifically productive for diverse adult learners.

Table 3. Examples of Gamified and Immersive Tools for Biotechnology and Bioinformatics Learning.

Platform / Tool	What It Does	Key Learning Competencies
Foldit	Protein-folding puzzle game where players manipulate 3D structures to find optimal conformations. Player solutions have contributed to real enzyme designs and structure predictions.	Protein structure and energetics, molecular visualization, structural bioinformatics, spatial reasoning, scientific problem-solving
EteRNA	RNA-folding game where users design molecules that may be synthesized in real laboratories, providing experimental validation of player designs.	RNA structure prediction, base-pairing thermodynamics, iterative design logic, hypothesis testing
Phylo	Visual DNA alignment puzzle that improves multiple-sequence alignments used in phylogenetic and disease-gene studies.	Sequence alignment principles, conservation and mutation mapping, evolutionary genomics
VR/AR Molecular Biology Labs (PCR, CRISPR, phylogenetics, sequencing workflows)	Immersive virtual labs that simulate experiments, from DNA extraction to gene editing and evolutionary analysis.	Laboratory procedural awareness, protocol logic, genotype-to-phenotype reasoning, analysis of experimental outputs

Why These Tools Matter

These platforms demonstrate how experiential and challenge-based learning can:

- Increase understanding of complex biological systems through hands-on exploration;
- Build foundational data literacy and computational reasoning, needed for AI-enabled biotech;
- Lower barriers to engaging with genomics, structural biology, and bioinformatics;
- Create inclusive entry points to real scientific research for non-experts and upskilling professionals;
- Strengthening collaboration and motivation, since participation often contributes to authentic discoveries.

Importantly, this model of learning aligns with societal shifts where adults encounter genetic risk scores, AI-driven diagnostics or personalized treatment choices. As biotechnology becomes embedded in everyday healthcare and work, such tools can democratize understanding and support informed decision-making.

Implications for ITCILO and Workforce Development

For future capacity-building programs, these platforms provide:

- Scalable learning experiences that can be adapted to diverse audiences and contexts;
- Mechanisms to practice real skills - from molecular modeling to coding and data interpretation;
- Opportunities to integrate globally distributed learning communities, supporting peer-based development;
- A pathway to introduce ethical considerations and public engagement in biotechnology.

By incorporating gamification and citizen-science strategies into adult education, ITCILO can help develop a workforce that is not only more competent in emerging biotechnologies but also more confident and empowered to navigate them as they reshape labour markets and healthcare systems.

B. Engaging with Personal Biological Data: A New Vector for Adult Learning

As biotechnology becomes increasingly accessible through new sequencing technologies, DTC testing, smartphone-enabled diagnostics, and digital health platforms, and other techniques, individuals today have unprecedented access to personal biological data. Rapid advances in AI-driven prediction models, machine-learning analytics, and interoperable biomedical databases are further lowering barriers to interpretation, making complex genomic and health information more understandable for non-specialists. This shift represents not only a transformation in healthcare delivery but also a profound new opportunity for adult learning.

Personal biological data can serve as a powerful catalyst for motivation. Rather than passively receiving a genetic risk score or ancestry report, individuals can actively engage with the underlying science, developing foundational literacy in genetics, molecular biology, data analytics, and preventive health. Evidence in learning sciences demonstrates that personal relevance maximizes engagement and deepens knowledge retention (Priniski et al., 2018). When the content pertains directly to one's own genome, ancestry, or health traits, motivation to understand and explore could be significantly higher than for generic information. This can create a gateway to sustain learning about disease risk, lifestyle implications, and biomedical research more broadly.

We suggest that ITCILO explore and pilot learning models that connect personal data access with guided educational experiences, potentially integrating gamified platforms, citizen-science engagement, and workplace health initiatives. By doing so, the Centre can foster a workforce that is informed, empowered, and prepared to participate in the increasingly data-driven future of health and biotechnology.

Connecting personal genomic data, gamified learning, and inclusion by combining personal data access (e.g., from genetic tests or microbiome profiles) with interactive learning platforms, individuals can move from passive consumers of health information to active learners and informed participants. For instance:

- A consumer who obtains a genomic risk report might then use a platform like Foldit or a bioinformatics simulator to explore how proteins coded by their genome fold and function, deepening understanding of disease risk, gene function, and molecular biology.
- An adult using a digital therapeutic or mental-health app may gain insights into behavioral responses, stress triggers, or lifestyle factors linked to their genomic or biometric data, reinforcing health literacy and self-management.
- Educational or workforce-training programmes can integrate these tools to support lifelong learning, neurodiversity inclusion, and health-conscious career development, especially in biotech, health, or data-science sectors.

This integrative approach can help democratize biotechnology knowledge, bridge gaps between specialized and public understanding, and foster ecosystems where citizens are not just recipients of biotech innovations but informed collaborators.

C. Challenges to Address: Data Privacy, Interpretation, Equity

In its 2021 guidance, WHO identifies six foundational principles for the responsible use of AI in health: protecting human autonomy, safeguarding privacy and data security, ensuring safety and transparency, promoting inclusiveness and fairness, and fostering responsiveness and accountability (WHO, 2021). These principles emphasize that AI should augment (but not replace) human care relationships and clinical judgment. AI systems must be explainable, auditable, and subject to public oversight to prevent opaque decision-making, clinical errors, and erosion of patient trust.

Complementing WHO's ethical framework, the OECD stresses that collective action is essential to scaling responsible AI in health systems worldwide (Anderson & Sutherland, 2024). Its recommendations call for strengthening regulatory standards and international cooperation; investing in digital infrastructure and workforce training; advancing interoperability and shared evaluation frameworks; and promoting cross-sector collaboration among governments, industry, healthcare providers, and civil society. These priorities align directly with ITCILO's mission to build future-oriented learning systems that equip adults with the skills needed to comprehend biotechnology. Achieving trustworthy, equitable adoption will require comprehensive adult-learning strategies, strong regulatory stewardship, and long-term investment in health-system resilience.

This creates a strategic opportunity for ITCILO. By integrating personal data-enabled learning modules and digital literacy training into its programs, the Centre can strengthen understanding of both biotechnology tools and their implications for privacy, fairness, and ethics. Such initiatives would empower individuals to engage with AI-powered health services responsibly enhancing public trust, supporting equitable implementation, and ensuring that the future of AI in health remains firmly anchored in human dignity and social inclusion.

While these innovations are promising, they also raise important challenges:

- Data privacy and consent: engagement with personal genomic or health data requires robust frameworks for privacy, informed consent and long-term data stewardship.
- Quality of interpretation: without guidance, individuals may misinterpret probabilistic risk, overestimate meaning, or misapply insights, highlighting the need for educational scaffolding and transparent communication.
- Equity in access: gamified tools and digital therapeutics often require reliable internet, computing resources, or language access, risking exclusion of marginalized or low-resource populations.

- Regulation and validation: For citizen-science platforms to contribute meaningfully to research or public health, data quality, reproducibility, and linkage with verified labs or databases must be ensured.
- Addressing these challenges will require coordinated efforts from policymakers, educators, regulators and developers, but the potential benefits for health literacy, inclusion and lifelong learning are significant.

3.3. Sandbox Experiment Prototype: "MyData BioLab" – Learning with Personal Genomic & Gamified Tools

A prototype sandbox experiment in which adult learners combine personal or avatar-based genomic data with gamified bioinformatics tools (Foldit, Phylo, virtual labs, etc.) to build data literacy, health literacy, and regulatory and ethical awareness. The aim is to move citizens from passive recipients of genomic risk reports to active interpreters and co-creators of knowledge.

The proposed sandbox experiment can be interpreted as a response to the growing societal exposure to biological data, which until recently was largely confined to medical institutions and scientific research laboratories. Recent advances in biotechnology, combined with AI-driven natural-language processing tools, are enabling individuals to access, interpret, and act upon biodata directly. At the same time, employers, insurers, digital platforms, and public authorities may increasingly gain access to large-scale biological datasets.

The rationale of the experiment is therefore to prepare constituents to operate in labour markets where biodata becomes more visible, more portable, and more commercially valuable. As part of capacity-building efforts, workers will need to develop an understanding of how their biological data can be generated and used, how informed consent operates in practice, and how to protect themselves from potential misuse or discrimination.

In parallel, regulatory and institutional capacity-building must anticipate how third parties - particularly employers, platforms, insurers, and public authorities - may seek to use biodata in contexts such as recruitment, performance monitoring, insurance underwriting, eligibility assessments, or surveillance. Addressing these challenges through a controlled sandbox environment can help inform policy design, governance frameworks, and learning strategies that support fair, ethical, and inclusive use of biodata in the future of work.

Objective: To test whether combining *personal* genomic/microbiome data with gamified bioinformatics platforms (e.g. Foldit, EteRNA, Phylo, virtual labs, Rosalind-style exercises) can improve adults' health/data literacy, engagement, and sense of inclusion in biotechnology. Below, we suggest a set of prototype interventions and evaluation measures that can be piloted within ITCILO learning programs.

1. Target Participants

- Primary group:
  - Adults (20–60) with basic digital literacy, mixed backgrounds (healthcare, education, policy, non-specialists).
- Optional sub-groups:
  - Health professionals in training (nurses, technicians).
  - Policy/regulatory staff (for "AI in health" literacy).

Participants may or may not already possess commercial genetic test results (e.g., ancestry profiles or disease-predisposition reports). Because regulations governing direct-to-consumer testing across Europe are fragmented - with some countries restricting or effectively prohibiting health-related genetic tests - not all learners will be able to obtain personal data legally or easily. To ensure inclusivity and regulatory compliance, programs can incorporate simulated datasets, privacy-preserving synthetic results, or fictional case profiles that mirror the structure and interpretation challenges of real reports. This approach allows all participants to engage meaningfully with genomic literacy, ethical decision-making, and data-interpretation skills, regardless of their country's legal framework or personal access to testing.

2. Data & Tools

Personal / mock datasets

- Real personal data where available and consented:
  - Consumer genetic tests (raw genotype file or summary of disease predisposition, ancestry, pharmacogenomics markers).
  - Microbiome reports (basic taxonomic abundances).
- For those without tests: synthetic but realistic "avatars" – not ideal
  - Simulated genomic profiles, ancestry breakdowns, disease-risk scores.
  - Synthetic datasets wont be as effective for learning as personal data. However, would be interesting to compare the level of engagement of participants using personal vs synthetic data

Gamified / interactive platforms

- Foldit / Foldit-like protein puzzle: Manipulate a protein related to a trait or disease in the (real or synthetic) report.
- EteRNA-style RNA design game: Design RNA hairpins/aptamers related to known disease genes.
- Phylo-style sequence alignment puzzle: Align short sequences from variants associated with a selected trait.
- Virtual lab / VR module (optional): Simulate PCR, sequencing, or CRISPR design targeting a mutation in the dataset.

3. Experimental Design (4–6 Week Sandbox)

Phase 1 – Onboarding & Baseline (Week 0–1)

- Pre-questionnaire:
  - Health literacy, data literacy, trust in genomics/AI, perceived inclusion in science.
- Short intro session:
  - What is a genome? What is a variant? What is a risk score? What is a "game" like Foldit actually doing?
- Data onboarding:
  - Participants upload or select their "data avatar" with clear consent and privacy explanation.
  - Simple visualization of their dataset (no heavy interpretation yet).

Phase 2 – Guided Gamified Activities (Week 1–3)

Each week combines one personal-data reflection + one gamified activity:

📅 Example Week 1: "From SNP to Protein"

- Examine a trait/risk variant in the report (e.g., drug metabolism gene).
- In Foldit, explore a protein related to that gene (or a close example):
  - "What does it mean that this protein folds stably?"
  - "How might a mutation change shape/function?"
- Short guided discussion: how sequence → structure → function relates to disease predisposition.

📅 Example Week 2: "Signals and Risk"

- Look at a polygenic risk score or simple genetic predisposition result.
- Use a Phylo-like game to align sequences from different individuals or species and talk about conservation, variation, and uncertainty.
- Debrief on why risk is probabilistic, not deterministic.

📅 Example Week 3: "Decoding and Reporting"

- Use a Rosalind-style or notebook exercise:
  - Filter mock variants; count microbiome taxa; generate a simple visualization.
- Compare the "raw" data to the polished consumer report; discuss what's hidden in the simplification.

Throughout, highlight data limitations, bias, uncertainty, and ethical issues.

Phase 3 – Reflection, Inclusion & Governance (Week 3–4)

- Small-group sessions, questions focusing learning
  - "How did using your own (or avatar) data change your understanding?"
  - "What made you feel more or less included?"
  - "How should regulators and companies explain AI-based genomic tools to citizens?"
  - "Your data shows high predisposition to heart diseases. Would you share that data with your family? Your doctor, nutritionist, personal trainer? With your employer? With your insurance company?"
- Optional track for policymakers/regulators:
  - Scenario: approval of an AI-driven diagnostic that uses genomic data.
  - Participants use what they've learned to raise questions about bias, consent, and explainability.

Phase 4 – Evaluation & Feedback (Week 4–6)

- Post-questionnaire:
  - Knowledge and confidence in interpreting genomic and AI-based health information.
  - Changes in perceived agency ("I feel able to ask questions / challenge a report").
- Qualitative feedback:
  - Which game/activity felt most engaging or inclusive?
  - What barriers remained (language, numeracy, time, emotional load)?

4. Learning Outcomes to Measure

- Cognitive:
  - Basic understanding of genome, variants, disease predisposition, and uncertainty.
  - Ability to read simple genomic/microbiome outputs and ask critical questions.
- Affective/inclusion:
  - Increased sense of belonging in conversations about biotech and AI.
  - Reduced "intimidation" by technical language or platforms.
- Practical:
  - Hands-on familiarity with at least one gamified or citizen-science bioinformatics tool.
  - Improved comfort handling data (filtering, plotting, comparing outputs).

5. Inclusion, Ethics, and Safeguards

- Use opt-in only for real personal data; avatars by default.
- Provide de-identified datasets for group tasks.
- Prepare support materials to avoid anxiety (especially around disease risk).
- Build accessible design:
  - Multiple formats (visual, text, audio).
  - Short missions instead of long lectures.
  - Clear “pause/opt-out” options for sensitive topics (e.g., severe disease risks).

COMPARATIVE SOCIETAL AND LEARNING IMPACTS OF KEY BIOTECHNOLOGY STRANDS (2025–2030)

The table 4 below provides a comparative assessment of the three major biotechnology strands analyzed in this report, examining their implications for learning systems, workforce readiness, ethical governance, and broader societal impact. It synthesizes insights from Parts II and III to evaluate how each strand, ranging from data-driven bioinformatics to clinical medical biotechnology and consumer-facing biological tools, differs in its maturity, accessibility, risks, and opportunities through 2030. By mapping ease of integration, scalability, collaboration potential, ethical and environmental considerations, and equity implications, the table offers a strategic framework to guide ITCILO in identifying priority areas for capacity-building, policy development, and socially inclusive adult-learning interventions.

Table 4. Comparative Assessment of Biotechnology Strands Across Learning, Cost, and Integration Criteria (2025–2030)

Criteria	Bioinformatics, Data Ecosystems & AI-for-Biology	Clinical Medical Biotechnology	Non-Clinical & Consumer Biotechnology
Ease of Integration into existing learning/work environments	High. Tools are cloud-based, scalable, and require only computational access. Fits easily into universities, training centres and remote learning.	Medium–Low. Clinical workflows require regulated environments, lab infrastructure, specialized expertise. Integration depends on health-system capacity.	Medium. Consumer-facing, app-based tools are simple to incorporate into adult-learning programs; however countries regulation can be impeditive.
Cost and scalability (2025–2030)	Very high scalability. Costs fall rapidly as clouds compute and open datasets expand. The main cost is skilled workforce.	High cost. Gene therapies, sequencing-integrated diagnostics, and advanced trials remain expensive; scalability constrained by regulatory pathways and biomanufacturing	Low costs. DTC sequencing costs continue to decrease; microbiome and wearable diagnostics becoming more affordable
Content creation & customization flexibility	Very high. AI-native tools allow simulation, annotation tasks, custom datasets, synthetic examples for restricted countries, and virtual labs	Low–Medium. Highly regulated content; clinical accuracy required; limited flexibility; ethical/legal constraints.	High. Educational content can be heavily customized (simulated genomic reports, microbiome dashboards, ancestry exploration)

Criteria	Bioinformatics, Data Ecosystems & AI-for-Biology	Clinical Medical Biotechnology	Non-Clinical & Consumer Biotechnology
Collaboration potential	Very high. International datasets, federated analyses, open-science platforms, suitable for global cooperation	Low. Collaboration limited by data-privacy laws, ethics committees, and clinical governance	Medium-low. Collaboration limited by data-privacy laws, ethics committees, and clinical governance and countries' legislation.
Impact on experiential & practical learning	Very high. Enables hands-on data analysis, AI tool use, virtual experiments, integrative multi-omics exploration. Ideal for capacity-building.	Medium. Hands-on learning is impactful but requires specialized instructors. Harder to scale.	High. Participants can use their own (or simulated) reports to engage directly with biological concepts; strong experiential component.
Projected maturity by 2030 (e.g. using maturity roadmaps and R&D dynamics / np of research papers and patents as source of reference	Very high. Fastest-growing strand, driven by exponential data production, AI advancements, strong publication and patent growth. Predicted to be fully mainstream by 2030.	Medium–High. Rapid clinical translation, but constrained by regulation, delivery technologies, and cost. Gene editing, mRNA platforms, and cell therapies will mature but not fully democratize by 2030.	Medium. Product ecosystems mature rapidly, but regulation of consumer genomics, health apps, and microbiome tests will determine growth.
Ethical concerns (privacy rights, digital identity, social skills development etc.)	Very high. Genetic data governance, AI bias, data standardization, misuse of models, cross-border data flows. Requires strict ethical-AI frameworks.	Very high. Informed consent, genetic discrimination, therapeutic risk, reproductive ethics, long-term monitoring, equity in access to advanced therapies	Very high. Interpretation errors, anxiety from uncertain results, misuse by employers/insurers, privacy of personal data, cultural sensitivities.
Environmental impacts (both negative and positive)	Low direct impact; positive through reduction of physical lab use (virtualization). Computer-related carbon footprint must be managed.	Medium. Biomanufacturing footprints vary; specialized vectors and reagents have non-negligible environmental impacts; but precision therapies reduce long-term healthcare footprint.	Low. Minimal direct environmental footprint; positive impact via public engagement in sustainability and health-aware behaviors.
Access and equity (e.g. digital inclusion, global accessibility, inclusivity for special needs, gender-specific concerns))	High potential if infrastructure exists. AI-driven explanations, disability-adapted interfaces, multilingual tools expand access. Digital divide remains key barrier.	Medium–Low. Access depends on national health budgets, clinical capacity, insurance systems, and regulatory frameworks. High inequity risk.	High. DTC tools and simulated datasets allow participation even in restrictive countries. Requires strong literacy support to avoid misinterpretation.
Impact on society overall and risks	Very high. Democratizes access to biological knowledge; reduces dependency on physical labs; enables open, global scientific collaboration; accelerates innovation cycles; strengthens national sovereignty through data infrastructures; and increases public exposure to biological concepts. Risk: acceleration of misinformation, digital inequality, and algorithmic biases	Extreme. Major improvements in diagnosis, treatment, and quality of life; potential cures for previously untreatable diseases; reduces burden of chronic diseases. Strong societal debates around ethics, genetic privacy, equity in access, and long-term healthcare sustainability. Benefits remain concentrated in well-resourced health systems unless governance and equity frameworks expand.	Medium. Shifts public engagement with health, ancestry, identity, and lifestyle. Normalizes interaction with biological data and introduces biotechnology into everyday life. Risks include misunderstanding probabilistic results, commercial exploitation of genetic data, and widening inequality between those who can interpret personal reports and those who cannot

CONCLUSION. TOWARDS A NEW PARADIGM OF PARTICIPATORY LEARNING AND BIOTECH LITERACY

Biotechnology is transitioning from a specialized scientific domain to a pervasive driver of societal transformation. Across clinical medicine, industrial and environmental applications, consumer genomics, and AI-enabled bioinformatics, the field is rapidly reshaping how societies understand health, produce knowledge, organize labor, and manage biological information. This report demonstrates that the convergence of genomics, data infrastructures, AI, and biomanufacturing does not only accelerate innovation - but it also expands the cognitive, ethical, and digital competencies required for all individuals to meaningfully participate in a bio-driven world.

For ITCILO, the implications are profound. Emerging biotechnologies will not simply create new technical roles; they will redefine foundational literacies. Adults will increasingly need the ability to interpret probabilistic risk scores, navigate personal biological data, understand the capabilities and limits of AI-generated insights, and recognize the ethical implications of gene editing, data sharing, and synthetic biology. Without inclusive learning ecosystems, these transformations risk deepening existing inequalities, amplifying misinformation, and marginalizing populations with limited digital or scientific access.

At the same time, biotechnology offers powerful opportunities to expand learning and promote social justice. Cloud-based bioinformatics platforms, virtual laboratories, and accessible consumer tools can democratize scientific engagement, while advances in cognitive health, neurodevelopmental therapies, and precision medicine can help restore learning capacities and support lifelong participation for people with disabilities or chronic conditions. The refinement of the ITCILO taxonomy presented here makes these cross-cutting dynamics visible, shifting the focus from siloed application areas to the transversal techniques and data infrastructures that truly shape the future of work.

Looking toward 2030, the central challenge is not technological scarcity but governance, pedagogy, and equitable access. Building capacity in bioethics, data stewardship, interdisciplinary problem-solving, and critical digital literacy will be essential for ensuring that biotechnology strengthens democratic participation, worker agency, and global inclusion. ITCILO is uniquely positioned to lead this transformation, helping Member States build learning systems that are agile, evidence-based, ethically grounded, and capable of empowering all people to engage with the biological dimensions of modern life.

In essence, the future bioeconomy will be shaped not only by breakthroughs in laboratories but by the readiness of societies to learn, adapt, and govern responsibly. By investing today in inclusive, forward-looking adult learning strategies, ITCILO can help ensure that the benefits of biotechnology are shared widely, sustainably, and justly across the world.

REFERENCES

Abramson, J., Adler, J., Dunger, J., Evans, R., Green, T., Pritzel, A., Ronneberger, O., Willmore, L., Ballard, A. J., Bambrick, J., Bodenstein, S. W., Evans, D. A., Hung, C. C., O'Neill, M., Reiman, D., Tunyasuvunakool, K., Wu, Z., Žemgulytė, A., Arvaniti, E., … Jumper, J. M. (2024). Accurate structure prediction of biomolecular interactions with AlphaFold 3. *Nature, 630*(8016), 493–500.

Agrawal, A., & Solanki, S. (2025). Raman spectroscopy enhanced by machine learning for effective microplastic detection in aquatic systems. *International Journal of Environmental Sciences, 11*(7S), 1000–1010.

Alavian, F., & Khodabakhshi, F. (2025). Integrating artificial intelligence with microbial biotechnology for sustainable environmental remediation. *Environmental Monitoring and Assessment, 197*(11), 1183.

Amer, B., & Baidoo, E. E. K. (2021). Omics-driven biotechnology for industrial applications. *Frontiers in Bioengineering and Biotechnology, 9*, 613307.

Anderson, B., & Sutherland, E. (2024). Collective action for responsible AI in health. *OECD Artificial Intelligence Papers, 10*.

Armengaud, J. (2016). Next-generation proteomics faces new challenges in environmental biotechnology. *Current Opinion in Biotechnology, 38*, 174–182.

Ashraf Rather, M., Ahmad, I., Shah, A., Hajam, Y. A., Amin, A., Khursheed, S. & Rasool, S. (2024). Exploring opportunities of artificial intelligence in aquaculture to meet increasing food demand. *Food Chemistry: X, 22*, 101309.

Bateman, A., Martin, M. J., Orchard, S., Magrane, M., Adesina, A., Ahmad, S., Bowler-Barnett, E. H., Bye-A-Jee, H., Carpentier, D., Denny, P., Fan, J., Garmiri, P., da Costa Gonzales, L. J., Hussein, A., Ignatchenko, A., Insana, G., Ishtiaq, R., Joshi, V., Jyothi, D., Zhang, J. (2025). UniProt: The Universal Protein Knowledgebase in 2025. *Nucleic Acids Research, 53*(D1), D609–D617.

Battleday, R. M., & Brem, A. K. (2015). Modafinil for cognitive neuroenhancement in healthy non-sleep-deprived subjects: A systematic review. *European Neuropsychopharmacology, 25*(11), 1865–1881.

Bidyalakshmi, T., Jyoti, B., Mansuri, S. M., Srivastava, A., Mohapatra, D., Kalnar, Y. B., Narsaiah, K., & Indore, N. (2024). Application of artificial intelligence in food processing: Current status and future prospects. *Food Engineering Reviews, 17*(1), 27–54.

Bittrich, S., Bhikadiya, C., Bi, C., Chao, H., Duarte, J. M., Dutta, S., Fayazi, M., Henry, J., Khokhriakov, I., Lowe, R., Piehl, D. W., Segura, J., Vallat, B., Voigt, M., Westbrook, J. D., Burley, S. K., & Rose, Y. (2023). RCSB Protein Data Bank: Efficient searching and simultaneous access to one million computed structure models alongside the PDB structures enabled by architectural advances. *Journal of Molecular Biology, 435*(14), 167994.

Boukid, F., Ganeshan, S., Wang, Y., Tülbek, M. Ç., & Nickerson, M. T. (2023). Bioengineered enzymes and precision fermentation in the food industry. *International Journal of Molecular Sciences, 24*(12), 10156.

Buchman, L., & Kovak, E. (2025). A call for congressional action: Revisiting the U.S. coordinated framework for the regulation of biotechnology. *Frontiers in Bioengineering and Biotechnology, 13*, 1702481.

Callahan, T. J., Tripodi, I. J., Stefanski, A. L., Cappelletti, L., Taneja, S. B., Wyrwa, J. M., Casiraghi, E., Matentzoglu, N. A., Reese, J., Silverstein, J. C., Hoyt, C. T., Boyce, R. D., Malec, S. A., Unni, D. R., Joachimiak, M. P., Robinson, P. N., Mungall, C. J., Cavalleri, E., Fontana, T., … Hunter, L. E. (2024). An open source knowledge graph ecosystem for the life sciences. *Scientific Data, 11*(1).

Corinaldesi, C., Barone, G., Marcellini, F., Dell'Anno, A., & Danovaro, R. (2017). Marine microbial-derived molecules and their potential use in cosmeceutical and cosmetic products. *Marine Drugs, 15*(4).

Daniotti, S., & Re, I. (2021). Marine biotechnology: Challenges and development market trends for the enhancement of biotic resources in industrial pharmaceutical and food applications—A statistical analysis of scientific literature and business models. *Marine Drugs, 19*(2), 61.

Demirel, Ö., Güneş, H., & Can, C. (2024). Sustainable and modern bio-based technologies: New approaches to food safety and security. *Environment, Development and Sustainability, 27*(10), 24899–24926.

Drula, E., Garron, M. L., Dogan, S., Lombard, V., Henrissat, B., & Terrapon, N. (2022). The carbohydrate-active enzyme database: Functions and literature. *Nucleic Acids Research, 50*(D1), D571–D577.

Einöther, S. J. L., & Giesbrecht, T. (2013). Caffeine as an attention enhancer: Reviewing existing assumptions. *Psychopharmacology, 225*(2), 251–274.

Farah, M. J., Illes, J., Cook-Deegan, R., Gardner, H., Kandel, E., King, P., Parens, E., Sahakian, B., & Wolpe, P. R. (2004). Neurocognitive enhancement: What can we do and what should we do? *Nature Reviews Neuroscience, 5*(5), 421–425.

Gardossi, L., Philp, J., Fava, F., Winickoff, D., D'Aprile, L., Dell'Anno, B., Marvik, O. J., & Lenzi, A. (2023). Bioeconomy national strategies in the G20 and OECD countries: Sharing experiences and comparing existing policies. *EFB Bioeconomy Journal, 3*, 100053.

Goh, W. W. B., & Sze, C. C. (2019). AI paradigms for teaching biotechnology. *Trends in Biotechnology, 37*(1), 1–5.

Gomes, A., Gonçalves, B., Inglês, B., Silvério, S., Pinto, C. A., & Saraiva, J. A. (2024). Potential impacts of artificial intelligence (AI) in biotechnology. *Applied Sciences, 14*(24), 11801.

Grand View Research. (2023). *Biotechnology market size, share & trends analysis report by technology (nanobiotechnology, DNA sequencing, cell-based assays), by application (health, bioinformatics), by region, and segment forecasts, 2023–2030*.

Heux, S., Meynial-Salles, I., O'Donohue, M. J., & Dumon, C. (2015). White biotechnology: State of the art strategies for the development of biocatalysts for biorefining. *Biotechnology Advances, 33*(8), 1653–1670.

Hinrichs, A. S., Karolchik, D., Baertsch, R., Barber, G. P., Bejerano, G., Clawson, H., Diekhans, M., Furey, T. S., Harte, R. A., Hsu, F., Hillman-Jackson, J., Kuhn, R. M., Pedersen, J. S., Pohl, A., Raney, B. J., Rosenbloom, K. R., Siepel, A., Smith, K. E., Sugnet, C. W., Kent, W. J. (2006). The UCSC Genome Browser Database: Update 2006. *Nucleic Acids Research, 34*, D590–D598.

Holzinger, A., Keiblinger, K., Holub, P., Zatloukal, K., & Müller, H. (2023). AI for life: Trends in artificial intelligence for biotechnology. *New Biotechnology, 74*, 16–24.

Ilieva, I. P., Hook, C. J., & Farah, M. J. (2015). Prescription stimulants' effects on healthy inhibitory control, working memory, and episodic memory: A meta-analysis. *Journal of Cognitive Neuroscience, 27*(6), 1069–1089.

Johnson, K. B., Wei, W. Q., Weeraratne, D., Frisse, M. E., Misulis, K., Rhee, K., Zhao, J., & Snowdon, J. L. (2021). Precision medicine, AI, and the future of personalized health care. *Clinical and Translational Science, 14*(1), 86–93.

Jones, E. R., Van Vliet, M. T. H., Qadir, M., & Bierkens, M. F. P. (2021). Country-level and gridded estimates of wastewater production, collection, treatment and reuse. *Earth System Science Data, 13*(2), 237–254.

Jumper, J., Evans, R., Pritzel, A., Green, T., Figurnov, M., Ronneberger, O., Tunyasuvunakool, K., Bates, R., Žídek, A., Potapenko, A., Bridgland, A., Meyer, C., Kohl, S. A. A., Ballard, A. J., Cowie, A., Romera-Paredes, B., Nikolov, S., Jain, R., Adler, J., … Hassabis, D. (2021). Highly accurate protein structure prediction with AlphaFold. *Nature, 596*(7873), 583–589.

Kalokairinou, L., Howard, H. C., Slokenberga, S., Fisher, E., Flatscher-Thöni, M., Hartlev, M., van Hellemondt, R., Juškevičius, J., Kapelenska-Pregowska, J., Kováč, P., Lovrečić, L., Nys, H., de Paor, A., Phillips, A., Prudil, L., Rial-Sebbag, E., Romeo Casabona, C. M., Sándor, J., Schuster, A., … Borry, P. (2017). Legislation of direct-to-consumer genetic testing in Europe: A fragmented regulatory landscape. *Journal of Community Genetics, 9*(2), 117–132.

Kawrykow, A., Roumanis, G., Kam, A., Kwak, D., Leung, C., Wu, C., Zarour, E., Sarmenta, L., Blanchette, M., & Waldispühl, J. (2012). Phylo: A citizen science approach for improving multiple sequence alignment. *PLOS ONE, 7*(3), e31362.

Khare, S., Gurry, C., Freitas, L., Schultz, M. B., Bach, G., Diallo, A., Akite, N., Ho, J., Lee, R. T. C., Yeo, W., Team, G. C. C., & Maurer-Stroh, S. (2021). GISAID's role in pandemic response. *China CDC Weekly, 3*(49), 1049–1051.

Koepnick, B., Flatten, J., Husain, T., Ford, A., Silva, D. A., Bick, M. J., Bauer, A., Liu, G., Ishida, Y., Boykov, A., Estep, R. D., Kleinfelter, S., Nørgård-Solano, T., Wei, L., Players, F., Montelione, G. T., DiMaio, F., Popović, Z., Khatib, F., … Baker, D. (2019). *De novo* protein design by citizen scientists. *Nature, 570*(7761), 390–394.

Kortemme, T. (2024). De novo protein design—From new structures to programmable functions. *Cell, 187*(3), 526–544.

Kosiborod, M. N., Cherney, D. Z. I., Desai, A. S., Testani, J. M., Verma, S., Chinnakondepalli, K., Dolling, D., Patel, S., Dahl, M., Eudicone, J. M., Friberg, L., Ouwens, M., Antunes, M. O., Connelly, K. A., Madrini, V., Kuthi, L., Lala, A., Lorenzo, M., Guimarães, P. O., … Petrie, M. C. (2025). Sodium zirconium cyclosilicate for management of hyperkalemia during spironolactone optimization in patients with heart failure. *Journal of the American College of Cardiology, 85*(10), 971–984.

Leary, D., Vierros, M., Hamon, G., Arico, S., & Monagle, C. (2009). Marine genetic resources: A review of scientific and commercial interest. *Marine Policy, 33*(2), 183–194.

Lee, B. H. (2015). *Fundamentals of food biotechnology* (2nd ed.).

Lee, J., Kladwang, W., Lee, M., Cantu, D., Azizyan, M., Kim, H., Limpaecher, A., Yoon, S., Treuille, A., & Das, R. (2014). RNA design rules from a massive open laboratory. *Proceedings of the National Academy of Sciences of the United States of America, 111*(6), 2122–2127.

Li, G., An, L., Yang, W., Yang, L., Wei, T., Shi, J., Wang, J., Doonan, J. H., Xie, K., Fernie, A. R., Lagudah, E. S., Wing, R. A., & Gao, C. (2025). Integrated biotechnological and AI innovations for crop improvement. *Nature, 643*(8073), 925–937.

Lu, H., Diaz, D. J., Czarnecki, N. J., Zhu, C., Kim, W., Shroff, R., Acosta, D. J., Alexander, B. R., Cole, H. O., Zhang, Y., Lynd, N. A., Ellington, A. D., & Alper, H. S. (2022). Machine learning-aided engineering of hydrolases for PET depolymerization. *Nature, 604*(7907), 662–667.

Malík, M., & Tlustoš, P. (2022). Nootropics as cognitive enhancers: Types, dosage and side effects of smart drugs. *Nutrients, 14*(16), 3367.

Maurya, R., Srivastava, A., Srivastava, A., Pathak, V. K., & Dutta, M. K. (2023). Computer-aided detection of mercury heavy metal intoxicated fish: An application of machine vision and artificial intelligence technique. *Multimedia Tools and Applications, 82*(13), 20517–20536.

Meng, S., Li, Z., Zhang, P., Contreras, F., Ji, Y., & Schwaneberg, U. (2023). Deep learning guided enzyme engineering of *Thermobifida fusca* cutinase for increased PET depolymerization. *Chinese Journal of Catalysis, 50*, 229–238.

Mustapha, U. F., Alhassan, A. W., Jiang, D. N., & Li, G. L. (2021). Sustainable aquaculture development: A review on the roles of cloud computing, internet of things and artificial intelligence. *Reviews in Aquaculture, 13*(4), 2076–2091.

Mede, N. G. (2023). Rethink science communication for the post-pandemic era. *UNESCO Inclusive Policy Lab*.

Nielsen, J., Tillegreen, C. B., & Petranovic, D. (2022). Innovation trends in industrial biotechnology. *Trends in Biotechnology, 40*(10), 1160–1172.

Nielsen, M. B., Meyer, A. S., & Arnau, J. (2024). The next food revolution is here: Recombinant microbial production of milk and egg proteins by precision fermentation. *Annual Review of Food Science and Technology, 15*(1), 173–187.

Ogata, H., Goto, S., Sato, K., Fujibuchi, W., Bono, H., & Kanehisa, M. (1999). KEGG: Kyoto encyclopedia of genes and genomes. *Nucleic Acids Research, 27*(1), 29–34.

OpenADMET Consortium. (2024). *OpenADMET – Next generation ADMET modeling: Democratizing AI models and data for therapeutic development*.

OpenBind Consortium. (2025). *OpenBind – Foundational structural biology data for AI-driven drug discovery*.

OpenBioML. (2023). *OpenBioML – Open collaborative research laboratory at the intersection of machine learning and biology*.

Papadopoulou, C. I., Loizou, E., & Chatzitheodoridis, F. (2022). Priorities in bioeconomy strategies: A systematic literature review. *Energies, 15*(19), 7258.

Priniski, S. J., Hecht, C. A., & Harackiewicz, J. M. (2018). Making learning personally meaningful: A new framework for relevance research. *Journal of Experimental Education, 86*(1), 11–29.

Proestou, M., Goritz, N., & Feindt, P. H. (2025). Resilience orientation in bioeconomy policies: A global comparative analysis. *Circular Economy and Sustainability*, 1–25.

Ranjha, M. M. A. N., Shafique, B., Khalid, W., Nadeem, H. R., Mueen-ud-Din, G., & Khalid, M. Z. (2022). Applications of biotechnology in food and agriculture: A mini-review. *Proceedings of the National Academy of Sciences, India, Section B, 92*(1), 11–15.

Repantis, D., Schlattmann, P., Laisney, O., & Heuser, I. (2010). Modafinil and methylphenidate for neuroenhancement in healthy individuals: A systematic review. *Pharmacological Research, 62*(3), 187–206.

Roberts, C. A., Jones, A., Sumnall, H., Gage, S. H., & Montgomery, C. (2020). How effective are pharmaceuticals for cognitive enhancement in healthy adults? A series of meta-analyses of cognitive performance during acute administration of modafinil, methylphenidate and D-amphetamine. *European Neuropsychopharmacology, 38*, 40–62.

Sampara, P., Lawson, C. E., Scarborough, M. J., & Ziels, R. M. (2024). Advancing environmental biotechnology with microbial community modeling rooted in functional 'omics. *Current Opinion in Biotechnology, 88*, 103165.

Sarker, M. A. B., Imtiaz, M. H., Holsen, T. M., & Baki, A. B. M. (2024). Real-time detection of microplastics using an AI camera. *Sensors, 24*(13), 4394.

Sayers, E. W., Cavanaugh, M., Frisse, L., Pruitt, K. D., Schneider, V. A., Underwood, B. A., Yankie, L., & Karsch-Mizrachi, I. (2025). GenBank 2025 update. *Nucleic Acids Research, 53*(D1), D56–D61.

Schambach, A., Buchholz, C. J., Torres-Ruiz, R., Cichutek, K., Morgan, M., Trapani, I., & Büning, H. (2024). A new age of precision gene therapy. *The Lancet, 403*(10426), 568–582.

Schifano, F., Bonaccorso, S., Arillotta, D., Corkery, J. M., Floresta, G., Papanti Pelletier, G. D., & Guirguis, A. (2025). Focus on cognitive enhancement: A narrative overview of nootropics and "smart drug" use and misuse. *Biology, 14*(9), 1244.

Shahryari, A., Jazi, M. S., Mohammadi, S., Nikoo, H. R., Nazari, Z., Hosseini, E. S., Burtscher, I., Mowla, S. J., & Lickert, H. (2019). Development and clinical translation of approved gene therapy products for genetic disorders. *Frontiers in Genetics, 10*, 450496.

Silczuk, A., Lewandowska, A., Filip, M., Atroszko, P. A., Podolec, J., Gałecka, M., Madejek, R., & Czyżewski, Ł. (2025). Current insights into the safety and adverse effects of methylphenidate in children, adolescents, and adults: Narrative review. *Pharmacological Reports, 77*(5), 1247.

Silver, D., Huang, A., Maddison, C. J., Guez, A., Sifre, L., Van Den Driessche, G., Schrittwieser, J., Antonoglou, I., Panneershelvam, V., Lanctot, M., Dieleman, S., Grewe, D., Nham, J., Kalchbrenner, N., Sutskever, I., Lillicrap, T., Leach, M., Kavukcuoglu, K., Graepel, T., & Hassabis,

D. (2016). Mastering the game of Go with deep neural networks and tree search. *Nature, 529*(7587), 484–489.

Smith, M. E., & Farah, M. J. (2011). Are prescription stimulants "smart pills"? The epidemiology and cognitive neuroscience of prescription stimulant use by normal healthy individuals. *Psychological Bulletin, 137*(5), 717–741.

Smyth, S. J., Phillips, P. W. B., & Castle, D. (2017). (Mis)information and the politicization of food security. *Animal Frontiers, 7*(2), 33–38.

Suleria, H. A. R., Osborne, S., Masci, P., & Gobe, G. (2015). Marine-based nutraceuticals: An innovative trend in the food and supplement industries. *Marine Drugs, 13*(10), 6336–6351.

Trixa, J., & Kaspar, K. (2024). Information literacy in the digital age: Information sources, evaluation strategies, and perceived teaching competences of pre-service teachers. *Frontiers in Psychology, 15*, 1336436.

UK Government. (2021). *Life sciences vision*. Office for Life Sciences, Department for Science, Innovation and Technology; Department for Business, Energy & Industrial Strategy.

U.S. Congress. (2025). *White House initiative to advance the bioeconomy, E.O. 14081: In brief*.

Wang, G., Kong, Q., Wang, D., & Asmi, F. (2023). Ethical and social insights into synthetic biology: Predicting research fronts in the post-COVID-19 era. *Frontiers in Bioengineering and Biotechnology, 11*, 1085797.

World Health Organization. (2021). *Ethics and governance of artificial intelligence for health: WHO guidance*.

Wiley, L., Cheek, M., LaFar, E., Ma, X., Sekowski, J., Tanguturi, N., & Iltis, A. (2025). The ethics of human embryo editing via CRISPR-Cas9 technology: A systematic review of ethical arguments, reasons, and concerns. *HEC Forum, 37*(2), 267–303.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J. W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., … Mons, B. (2016). The FAIR guiding principles for scientific data management and stewardship. *Scientific Data, 3*, 160018.

Zhang, K., Yang, X., Wang, Y., Yu, Y., Huang, N., Li, G., Li, X., Wu, J. C., & Yang, S. (2025). Artificial intelligence in drug development. *Nature Medicine, 31*(1), 45–59.

Zhang, X., Zhao, C., Shao, M.-W., Chen, Y.-L., Liu, P., & Chen, G.-Q. (2022). The roadmap of bioeconomy in China. *Engineering Biology, 6*(4), 71–81.

APPENDIX 1

Examples of Government Strategies and Roadmaps

Canada

Canada's Bioeconomy Strategy: Leveraging our Strengths for a Sustainable Future. (2019) Bioindustrial Innovation Canada in partnership with Agriculture & Agri-Food Canada. https://www.biotech.ca/wp-content/uploads/2022/01/National_Bioeconomy_Strategy_EN-compressed.pdf

China

14th Five-Year Plan for Bioeconomy Development (2021-2025) and vision to 2035. (2022) National Development and Reform Commission, People's Republic of China. https://en.ndrc.gov.cn/netcoo/achievements/202205/t20220520_1326683.html

France

A Bioeconomy Strategy for France – 2018-2020 Action Plan. (2018) Ministère de l'Agriculture et de l'Alimentation. https://agriculture.gouv.fr/bioeconomy-strategy-france-2018-2020-action-plan?utm_source=chatgpt.com

Germany

National Bioeconomy Strategy (2020). (2020) Federal Ministry of Education and Research & Federal Ministry of Food and Agriculture, Germany. https://biooekonomie.de/sites/default/files/files/2020-08/bmbf_national-bioeconomy-strategy_en.pdf

Italy

Italian Bioeconomy Strategy (BIT II). (2019) Agenzia per la Coesione Territoriale, Italy. https://cnbbsv.palazzochigi.it/media/1903/bit_ii_en_2019_final.pdf

Japan

Bioeconomy Strategy. (Updated 2024) Cabinet Office of Japan, Council for Science, Technology and Innovation. https://www8.cao.go.jp/cstp/english/bio/bio_economy_en.pdf

United Kingdom

Life Sciences Vision. (2021) Office for Life Sciences / UK Government. https://assets.publishing.service.gov.uk/media/612763b4e90e0705437230c3/life-sciences-vision-2021.pdf

United States

Executive Order: "Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy". (2022) White House (87 Federal Register 56849). https://bidenwhitehouse.archives.gov/briefing-room/presidential-actions/2022/09/12/executive-order-on-advancing-biotechnology-and-biomanufacturing-innovation-for-a-sustainable-safe-and-secure-american-bioeconomy/

INFO

FOR FURTHER INFORMATION
PLEASE CONTACT

International Training Centre of the ILO
Viale Maestri del Lavoro, 10
10127 Turin - Italy