2025 TECH TRENDS REPORT • 18TH EDITION

BIOTECHNOLOGY

FTSG

Future Today Strategy Group's 2025 Tech Trend Report

Our 2025 edition includes 1000 pages, with hundreds of trends published individually in 15 volumes and as one comprehensive report. Download all sections of Future Today Strategy Group's 2025 Tech Trends report at **www.ftsg.com/trends.**

Amy Webb
Chief Executive Officer

The next big tech disruption is biology.

The biotechnology landscape has fundamentally shifted. What was once a specialized field primarily focused on pharmaceuticals has exploded into a force reshaping nearly every industry. This isn't just about health care anymore—though the impact there is profound, with CRISPR therapies curing previously untreatable diseases and artificial intelligence revolutionizing drug discovery.

Today, biotechnology touches every industry. It's transforming agriculture, with crops engineered for climate resilience and higher yields. It's reinventing manufacturing, as engineered microbes produce materials stronger than steel and more sustainable than plastics. It's becoming central to climate solutions, with organisms designed to capture carbon and clean polluted environments. Biotech innovations are even reshaping the financial sector, creating new investment opportunities and transforming company valuations. The evidence surrounds us. Restaurants serve meat grown from cells rather than raised on farms. Fashion brands sell jackets made from spider silk produced by engineered yeast. Construction companies explore self-healing concrete created by bacteria. Beauty products contain proteins designed by AI and grown in fermentation tanks. These aren't pilot projects or laboratory curiosities—they're scaled commercial products generating real revenue.

What makes this moment unique is the convergence of multiple breakthroughs. AI has supercharged our ability to understand and engineer biology. Climate urgency has elevated biotech's role in sustainability. Global food security challenges have made biological innovation essential. The result? A wave of advances moving rapidly from lab to market, creating opportunities—and risks—that every leader needs to understand.

This report cuts through the complexity to highlight what matters. Whether you're in finance, manufacturing, technology, or policy, biotechnology will impact your sector in the coming years. The question isn't whether to engage, but how.

These five developments show how biotechnology is moving from theoretical possibility to practical reality, reshaping medicine, the environment, and daily life.

1

Lab-grown heart patches repair damage in trials

Engineered heart tissue integrates with damaged heart muscle within weeks, restoring 40% of cardiac function in post-heart attack patients. This suggests a future where heart attacks no longer mean permanent damage—instead, they become repairable injuries.

2

Synthetic bacteria deployed to clean up microplastic pollution

Each synthetic bacteria colony can process 50 tons of microplastic waste annually in a square kilometer, breaking it down into harmless organic compounds. Early ocean trials show no negative impact on marine ecosystems.

3

CRISPR 3.0 could achieve single-cell precision

With next-generation CRISPR, scientists can now target specific neurons in brain tissue while leaving surrounding cells untouched. This breakthrough could transform treatment for neurological disorders through ultra-precise DNA modification.

4

First bioengineered human embryo could reach early development stages

Scientists have grown a synthetic embryo without egg or sperm, raising ethical debates while advancing infertility treatments and genetic research. This provides unprecedented insights into early human development.

5

Synthetic biology startup designs first self-repairing clothing

The self-repairing garments contain engineered bacteria that activate when tears occur, producing new fibers to heal damage within hours. This technology could revolutionize sustainable fashion and reduce our 92 million tons of textile waste every year.

Biotechnology will move from scientific breakthrough to industrial reality, transforming everything.

Biotechnology has shattered the boundary between scientific possibility and market reality. The evidence surrounds us: CRISPR therapies are in the early days of curing genetic diseases, cultivated meat is served in restaurants, and gene-edited crops fill grocery shelves. AI systems, recognized with a Nobel Prize for cracking protein structures, are rewriting the rules of biological discovery.

The industry's scope has exploded beyond medicine. Novel organisms are emerging from labs: microbes that convert waste into valuable chemicals, plants engineered to capture more carbon, cells that grow materials stronger than steel. These aren't pilot projects—they're built to scale. Traditional manufacturing is being reimagined through a biological lens, as fermentation tanks replace chemical plants and living cells become microscopic factories.

Three fundamental shifts are reshaping biotechnology's future. The first wave is the emergence of programmable biology. The convergence of computing and biological systems has created unprecedented precision in manipulating life itself. AI can now predict complex protein structures in hours, while CRISPR enables genetic edits with surgical accuracy. This combination of digital and biological code transforms cells into programmable factories, making biology an engineering platform for solving previously intractable problems.

Parallel to this runs a second current: biology's emergence as a climate solution. Engineered organisms now capture carbon, produce sustainable fuels, and create eco-friendly materials at industrial scale. This isn't speculative technology. Companies are reimagining traditional chemical production through a biological lens, offering solutions that don't just reduce environmental impact but fundamentally change how we produce essential materials.

Underpinning these advances is a critical third shift: the recognition that public trust is as vital as technical innovation. As biotechnology touches more lives—through genetic data, million-dollar therapies, or engineered organisms—maintaining societal confidence becomes existential. The industry increasingly sees transparent practices and equitable access not as ethical add-ons but as fundamental infrastructure. Without this foundation of trust, even the most brilliant innovations risk rejection.

Biology's biggest breakthroughs moved from laboratory promise to commercial reality.

JANUARY 2024

CRISPR Therapy FDA Approval

The first CRISPR-based gene therapy is approved for sickle cell and beta-thalassemia treatment.

MAY 2024

AlphaFold 3 Launches

DeepMind and Isomorphic Labs release AlphaFold 3, predicting protein-ligand interactions for drug discovery.

JULY 2024

Gene-Edited Food Expansion

CRISPR-edited seedless blackberries and non-browning avocados enter market trials.

AUGUST 2024

Organoid Intelligence Breakthrough

Scientists grow synthetic human embryos to the 14-day stage from stem cells.

SEPTEMBER 2024

Synthetic Embryo Milestone

EvoPhase and Kwik Fab unveil the Birmingham Blade in England, the first urban wind turbine designed by AI.

« PAST

As nations race to regulate biotechnology, it will emerge as the next battleground for global power.

FUTURE »

MARCH 2025

FDA Public Workshop on Pregnancy Registries

Participants will discuss challenges and innovations in designing pregnancy registries for drug and biological product safety.

MAY 2025

New Strategy for European Medicines Agency

The EMA is expected to adopt a new strategy incorporating considerations for artificial intelligence in medicine development.

AUGUST 2025

Genome Engineering: CRISPR Frontiers

A conference at Cold Spring Harbor Laboratory will discuss advancements in genome engineering and CRISPR technologies.

OCTOBER 2025

iGEM Competition

Student teams will design and present innovative projects in this annual synthetic biology event.

2025—2028

China's Biotech Cultivation Initiative

The country will unveil a plan to develop gene-editing tools and new crop varieties to enhance food security.

Every organization must prepare for a bio-based future, regardless of its current relationship with biotech.

Biotech Is the New Digital

Just as they once became digital companies, businesses of all types are becoming biotech companies. From biomanufactured materials to engineered microbes in waste treatment, biological solutions are replacing traditional industrial and chemical processes across sectors, requiring new expertise and infrastructure.

Infrastructure Reset Required

The shift to bio-based manufacturing demands facility and equipment upgrades to handle biological processes. Organizations need to evaluate their existing infrastructure against emerging biotech capabilities, from fermentation tanks for materials production to specialized containment systems.

Compliance Changes Everything

Regulations on biological materials, genetic data, and engineered organisms are rapidly evolving and affect all industries. Organizations must develop new compliance frameworks and expertise to handle bio-related regulations, from data privacy to biosafety protocols.

New Expertise Is Mission Critical

The convergence of biology with traditional industries requires a workforce fluent in biological processes and their applications. Factor in new hiring strategies and training programs as organizations need to build teams that can bridge biological innovation with existing operations.

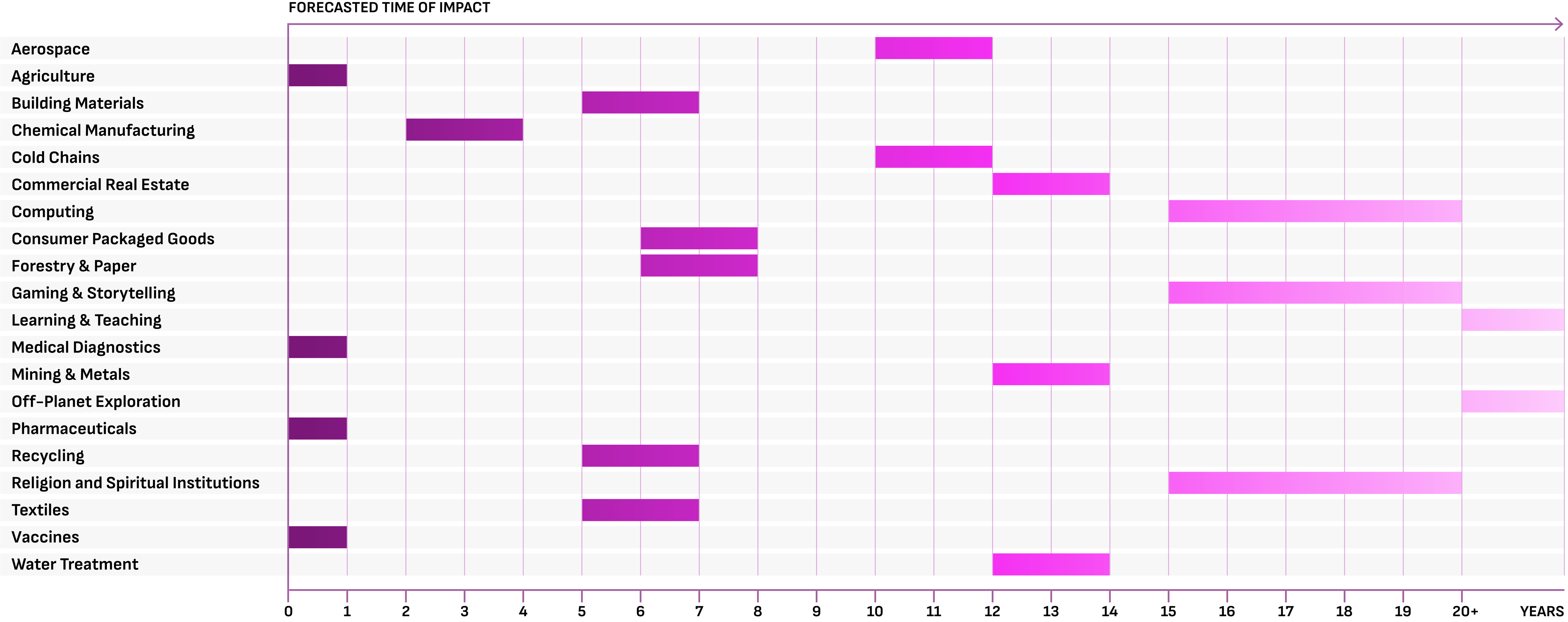
AI-Bio Integration Is Here

The convergence of AI with biological systems is creating new operational possibilities and requirements. Organizations must develop capabilities to handle bio-data and AI-driven biological processes, from quality control to product development and optimization.

Bio Disrupts Supply Chains

Biological alternatives and innovations in production methods are disrupting traditional supply chains. Organizations must reassess their supplier networks and invest in new capabilities to handle bio-based materials and processes, often requiring significant capital reallocation.

Biotech breakthroughs surge forward at wildly uneven paces, reshaping strategy and planning.

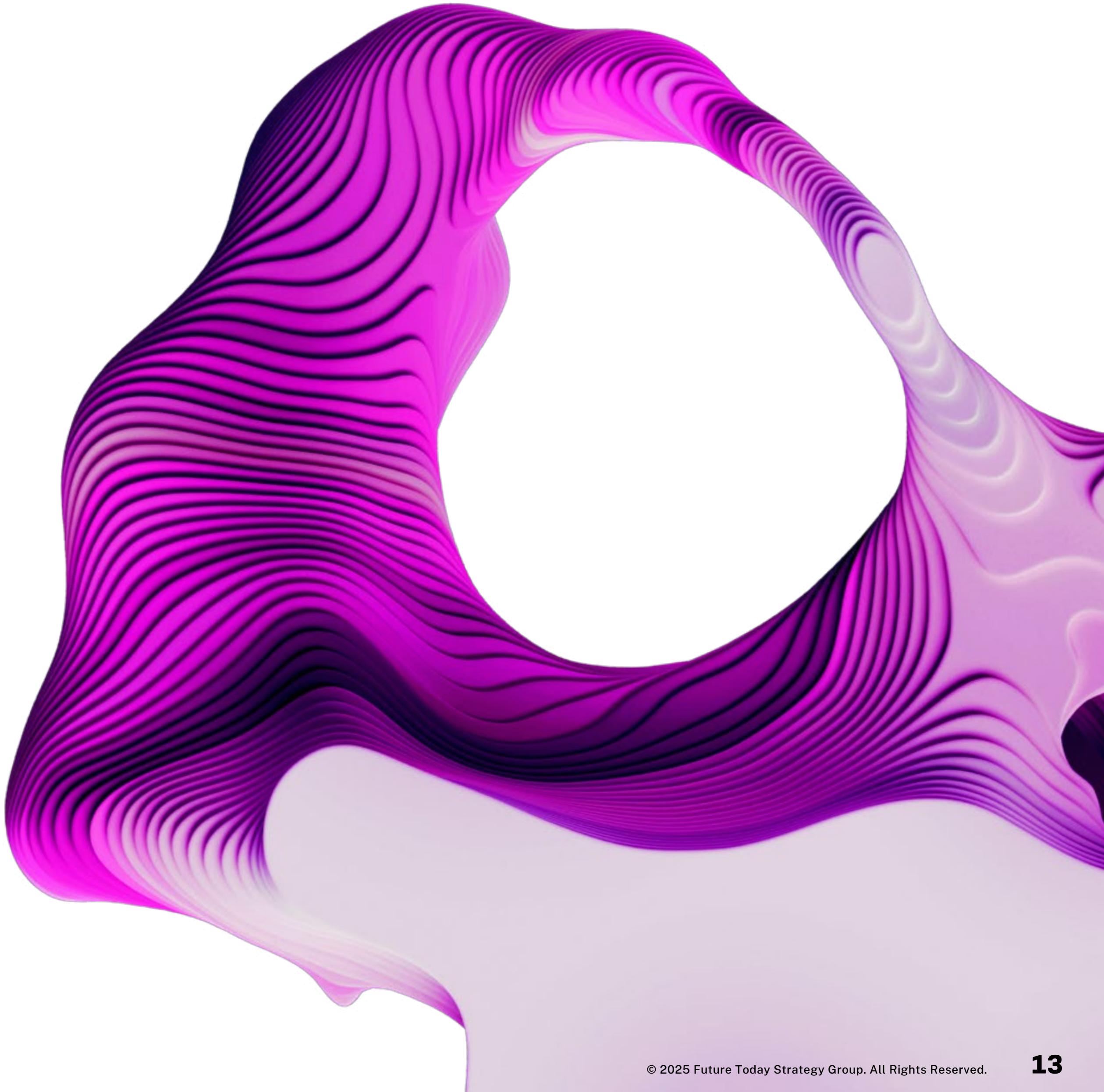


The pace of biotechnology's advance is driven by a complex interplay of forces: some push innovation forward, while others determine how quickly sectors adopt these changes.

Biotechnology is the next general purpose technology. Like electricity and computing before it, it will fundamentally reshape every industry and organization. This isn't speculation. In 2025, it's already happening.

The question isn't whether your industry will be affected but when and how significantly. Some sectors, like pharmaceuticals and agriculture, are already deep in transformation. Others, from textiles to construction, are just beginning to feel biology's influence. But all will be influenced or impacted, because biological solutions are proving faster, cheaper, or more sustainable than traditional approaches.

Seven key forces will determine how quickly this transformation reaches your industry:



SCALING

While the pace of innovation is fast across the spectrum of technologies, it takes time for a promising new biotech development to scale beyond the lab. Scaling requires discipline, patience, effort, and time.

COSTS

Biotechnology research is still costly, though the price of components, equipment, and materials drops every year. Once a disruptor can make a product cheaper with biotechnology rather than traditional production, it will push faster into the mainstream. Advancements in technology will eventually bring down costs of production as we've seen in other fields, such as computing.

CONSTRAINTS ON ADOPTION

Even if a technology is maturing, constraints on its adoption can hinder its influence in an industry. For example, a business may refuse to adopt an alternative biotechnology technology because it challenges a proven, successful strategy.

REGULATIONS

The pace of technology advancement typically far exceeds any changes to regulation. Biotechnology is unique in that regulation exists, but products and processes are treated differently in every country. Regulatory and policy uncertainty could accelerate or stifle growth.

MEDIA MENTIONS

Increased awareness and enthusiasm can influence the momentum of a technology, even when there's been no real breakthrough. Media bursts related to biotechnology will drive momentum, especially if those stories are favorable and—importantly—easily understood by the general public.

PUBLIC PERCEPTIONS

How the public understands, and responds to, biotechnology advancements will create or quell demand. This is especially true for food and beverage, consumer packaged goods, beauty and fashion, over-the-counter medicines and vaccines, and new therapeutics.

R&D DEVELOPMENTS

The pace of new research breakthroughs can't be scheduled to coincide with a board meeting or earnings report. There are factors that can improve the likelihood and speed of new discoveries (funding, quality and size of staff, access to resources). We closely monitor R&D developments but treat them as wild cards.

The leaders of tomorrow are the organizations that recognize this shift today. They're building bio-literacy into their strategy, investing in biological capabilities, and preparing their workforces for a bio-based future. The alternative—waiting until disruption forces change—puts companies at risk of falling permanently behind.

For each sector, we provide granular timelines mapping the expected progression of biotechnology adoption, integration, and disruption, supported by our proprietary database of more than 800 use cases across industries.

The biotech revolution goes beyond familiar names in medicine and agriculture. These scientists, founders, and innovators work in unexpected corners of this expanding field.

- **Dr. Barry Canton, co-founder and chief technology officer at Ginkgo Bioworks,** for pioneering advancements in synthetic biology and enabling large-scale organism engineering.
- **Dr. Christina Smolke, bioengineering adjunct professor at Stanford University,** for her research in synthetic biology to develop biosynthetic pathways for producing complex pharmaceuticals in yeast.
- **Dr. Emily Leproust, co-founder and CEO at Twist Bioscience,** for innovating DNA synthesis, enabling advancements in synthetic biology.
- **Ester Baiget, president and CEO at Novonesis,** for leading initiatives in biosolutions to combat climate change and promote sustainability.
- **Dr. Hiroaki Kitano, CEO of Sony Computer Science Laboratories,** for merging artificial intelligence with biological systems, creating new frameworks for understanding, and engineering living organisms.
- **Dr. Jennifer Elisseeff, the Morton Goldberg Professor of Ophthalmology at Johns Hopkins' School of Medicine,** for pioneering regenerative biomaterials that work with the immune system, transforming the approach to tissue repair.
- **Dr. Joanna Aizenberg, the Amy Smith Berylson Professor of Materials Science and Professor of Chemistry & Chemical Biology at Harvard,** for creating biologically inspired materials that mimic nature's most remarkable properties, from self-cleaning surfaces to adaptive materials.
- **Dr. Lulu Qian, bioengineering professor at Caltech, for developing DNA-based molecular robots and circuits,** opening new frontiers in biocomputing and nanoscale engineering.
- **Dr. Neil Kumar, founder and CEO at BridgeBio Pharma,** for evolving how we develop treatments for rare genetic diseases by creating a model that accelerates drug development for neglected conditions.
- **Dr. Noubar Afeyan, founder and CEO of Flagship Pioneering,** for inventing a unique company creation model that has launched dozens of breakthrough biotech companies, including Moderna and Indigo Agriculture.
- **Dr. Rahul Sarpeshkar, engineering professor at Dartmouth University,** for bridging electronic and biological computing while creating ultra-efficient biological circuits that could transform medical devices.
- **Dr. Xiaodong Chen, professor at Nanyang Technological University,** for developing soft, adaptive materials that interface seamlessly with human biology, enabling next-generation medical monitoring.

Biotechnology will unlock enormous opportunities as it transforms industries...

...but organizations aren't ready for the impending bio transformation.

OPPORTUNITIES

Prepare Your Supply Chain for Bio-Materials

Traditional manufacturers must start evaluating bio-based alternatives now. Early adopters are already securing sustainable material sources and building biomanufacturing capabilities.

Rethink Construction with Living Materials

Construction and infrastructure firms should explore self-healing materials and bio-based solutions that could reduce maintenance costs and extend asset lifespans significantly.

Consider Engineered Probiotics' Impact

Food, beverage, and health care companies should monitor engineered probiotics' potential to improve on how we deliver nutrients and therapeutic compounds.

Map Synthetic Biology's Testing Applications

Research-intensive industries should evaluate how synthetic biological models could reduce testing costs and accelerate development cycles across their product portfolios.

THREATS

Bio-Data Breaches Could Bankrupt You

Genetic and biological data breaches carry unprecedented liability. One leak of sensitive bio-data could trigger massive lawsuits and destroy customer trust permanently.

Your Supply Chain Could Become Obsolete

Biomanufacturing could make traditional production methods uncompetitive virtually overnight. Companies slow to adapt risk losing their entire cost advantage.

Competitors May Bioengineer Your Products

Engineered organisms could replicate your proprietary materials or chemicals at a fraction of the cost, potentially eliminating long-held manufacturing advantages.

Bio-Talent Wars Could Cripple Innovation

Companies without biotechnology expertise risk falling behind. The shortage of biotechnology talent is already creating an existential threat to traditional R&D models.

Biotechnology's impact will be broad and deep. Organizations should begin their long-term planning now.

Establish a bio-data infrastructure task force to evaluate biological information flow across your organization. Launch pilot programs in R&D to test new architectures, then expand to manufacturing. Focus on security protocols that protect genetic data and bioprocess information.

Create a cross-functional biological simulation platform that integrates with existing workflows. Train teams to use these tools for testing bio-based alternatives before major investments. Include virtual reality training modules for biomanufacturing processes.

Launch a dedicated venture fund targeting biomanufacturing startups that could disrupt or enhance your core business. Prioritize companies developing scalable fermentation technologies, cell-free synthesis platforms, and novel biological production methods.

Build a global bio-regulation monitoring system that tracks emerging policies across all operating jurisdictions. Focus on regional differences in GMO regulations, biological containment requirements, and synthetic biology oversight. Update the system quarterly.

Implement comprehensive training programs for staff transitioning to biological processing. Cover fermentation techniques, contamination prevention, and biological safety protocols. Include hands-on experience with bio-reactors and real-time monitoring systems.

Develop a proactive bio-policy engagement strategy. Join industry working groups shaping synthetic biology standards. Build relationships with regulators and scientific bodies. Share best practices while advocating for innovation-friendly frameworks.

Technology Deployment
Capital Expenditure
Talent Development
Regulatory Influence

Important terms to know before reading.

BIOENGINEERING DOMAINS

Innovations in bioengineering are reshaping medicine, agriculture, computing, and sustainability. Five core areas define the field: **biocomputing, biomachine interfaces, biomaterials, biomolecules,** and **biosystems.** Advances in one domain often accelerate breakthroughs in the others, leading to exponential progress. Emerging subfields—like synthetic bioelectronics and programmable biology—are rapidly expanding the potential of bioengineering.

BIOCOMPUTING

Biology operates on a code-like structure, and researchers are learning to harness this biological "software" for data storage, processing, and even computation. **DNA-based storage** is already proving to be a viable, ultra-dense, and sustainable alternative to silicon-based storage, while **living neural networks** are showing promise as bioprocessors that can learn and adapt. Unlike traditional supercomputers, biological computing systems require minimal energy, are scalable, and can integrate seamlessly

BIOMACHINE INTERFACES (BMIS)

New bioelectronic interfaces are allowing direct connections between **neurons and computers,** enabling applications ranging from brain-controlled prosthetics to **real-time digital brain augmentation.** Advances in optogenetics and neural implants could soon allow people to control machines, communicate thoughts, or even enhance cognition through **direct brain-to-cloud interfaces.**

BIOMATERIALS

Bioengineered materials are transforming industries—from **self-healing concrete** that uses living bacteria to repair cracks, to **lab-grown leather and plant-based plastics** that eliminate environmental waste. Researchers are also developing biocompatible materials for regenerative medicine, including **3D-printed organs and bioactive scaffolds** that guide tissue repair.

BIOMOLECULES (ALSO KNOWN AS -OMICS)

The study and engineering of biological molecules are leading to radical breakthroughs in medicine, agriculture, and synthetic biology. Advances in **molecular programming** are enabling scientists to design proteins with specific functions, such as **enzymes that break down plastics** or **RNA-based nanostructures** that deliver targeted therapeutics. The "-omics" revolution (genomics, transcriptomics, proteomics, metabolomics, etc.) is converging with AI to predict and design biological functions with unprecedented precision.

BIOSYSTEMS

Understanding and redesigning biological systems is key to solving global challenges. Scientists are now able to **engineer entire microbial communities** to break down pollutants, **program cells to act as sensors for disease,** and even **redesign human immune responses** to target cancer or emerging pathogens. Future applications could include **synthetic ecosystems** that regulate themselves for climate control or **programmable bacteria** that sustain soil health in space colonies.

ADDITIONAL TERMS

BIOFABRICATION

The use of cells, biomaterials, and bioprinting to create custom tissues, organs, and even synthetic organisms.

BIOCOMPATIBLE AI

The fusion of biological neurons with artificial intelligence, creating hybrid bio-AI systems that could reimagine computing.

CAS9 (CRISPR-ASSOCIATED PROTEIN 9)

An enzyme that acts as molecular scissors, enabling precise gene editing. Cas9 is central to CRISPR-based therapies and synthetic biology innovations.

CHIMERA

An organism that contains cells from two or more distinct genetic origins. Chimeras are used in research to study disease, grow transplantable human organs in animals, and test new gene therapies.

CHROMOSOME
A thread-like structure composed of tightly wound DNA. Each chromosome contains genes that determine an organism's traits.

CRISPR (CLUSTERED REGULARLY INTERSPACED SHORT PALINDROMIC REPEATS)
A powerful gene-editing system derived from bacteria that allows scientists to edit DNA with precision, potentially curing genetic diseases or designing organisms with custom traits.

DNA (DEOXYRIBONUCLEIC ACID)
The molecular blueprint of life, arranged in a double-helix structure. DNA carries genetic instructions for development, function, and reproduction.

ENZYME
A biological catalyst that speeds up chemical reactions inside cells. Engineered enzymes are being used to create sustainable biofuels, artificial meat, and biodegradable plastics.

EX VIVO
Experiments or treatments conducted outside a living organism, such as ex vivo gene therapy, where cells are modified outside the body and then reintroduced.

GAIN OF FUNCTION (GOF) RESEARCH
A controversial research method in which an organism is engineered to gain new traits, often to study viral evolution, antimicrobial resistance, or immune responses.

GENE
A segment of DNA that encodes a specific trait or function.

GENOME
The complete set of genetic material in an organism, now fully programmable using advanced genome-editing tools.

GENOME EDITING
Techniques like CRISPR, base editing, and prime editing allow precise modification of DNA, with applications ranging from curing genetic diseases to engineering resilient crops.

HERITABLE GENETIC CHANGE
Genetic modifications that are passed down to future generations, raising ethical and regulatory challenges in human germline editing.

IN VIVO
Biological processes that occur inside a living organism. In vivo gene therapy is an emerging approach where therapeutic genes are delivered directly into the body.

INDUCED PLURIPOTENT STEM CELLS (IPSC)
Adult cells that have been reprogrammed into a stem cell-like state, capable of becoming any cell type.

LIVING SENSORS
Engineered cells that detect changes in their environment, useful for monitoring pollution, tracking disease outbreaks, and sensing biomarkers in real time.

MOLECULAR MACHINES
Tiny biological machines—built from DNA, RNA, or proteins—that can perform tasks at the cellular level, such as delivering drugs or repairing damaged DNA.

MUTATION
A change in a DNA sequence, which can be natural or engineered for disease resistance, enhanced traits, or new functionalities.

OFF-TARGET EFFECT
Unintended genetic modifications that can occur during genome editing, leading to potential risks and ethical concerns.

REGENERATIVE MEDICINE
A field dedicated to repairing or replacing damaged tissues and organs using stem cells, gene editing, and bioengineered materials. Key applications include bioprinted organs, lab-grown skin, and neural regeneration.

RNA (RIBONUCLEIC ACID)
A messenger molecule that translates DNA instructions into proteins. RNA-based technologies, including mRNA vaccines, RNA therapeutics, and RNA nanotechnology, are shaping the future of medicine.

STEM CELL
A type of cell with the potential to develop into many different cell types. Stem cells are being used for treating spinal injuries, regenerating heart tissue, and reversing neurodegenerative diseases.

SYNTHETIC BIOLOGY
A field that combines biology and engineering to design new life forms, program genetic circuits, and create entirely synthetic organisms. Future applications range from carbon-sequestering bacteria to self-replicating biomaterials.

XENOBOTS
Self-assembling, programmable biological robots made from living cells, with potential applications in targeted drug delivery, environmental cleanup, and regenerative medicine.

BIOTECHNOLOGY TRENDS

AI AND BIOLOGY

AI AND BIOLOGY

Open-Source Medical LLMs Gain Ground

Large language models (LLMs) are transforming the biomedical field, with open-source alternatives now challenging proprietary models in accuracy and accessibility. BioMistral, a new domain-specific LLM built on Mistral and trained on PubMed Central, outperforms existing open-source medical AI models and competes with commercial solutions in medical question-answering (QA) tasks. Unlike general-purpose LLMs, BioMistral is fine-tuned for biomedical applications, demonstrating superior performance across 10 benchmarked QA datasets. Notably, BioMistral introduces the first large-scale multilingual evaluation of medical LLMs, supporting translations in seven languages to improve global accessibility. With ongoing advancements in quantization and model merging, lighter, faster, and more efficient AI-driven medical assistants are emerging. This shift signals a broader trend toward decentralized, transparent AI tools in health care, reducing reliance on proprietary models while maintaining high-performance standards. As regulatory bodies evaluate the role of medical LLMs in clinical decision-making, open-source solutions could drive more equitable and widespread AI adoption in global health care.

AI-Driven Molecular Modeling

AlphaFold 3 marks a major leap in biomolecular modeling, extending AI-driven structure prediction beyond proteins to include nucleic acids, small molecules, ions, and modified residues. Unlike previous versions, AlphaFold 3 employs a diffusion-based deep learning architecture, significantly improving accuracy in predicting protein-ligand and protein-nucleic acid interactions. It surpasses traditional docking tools and specialized predictors, demonstrating unprecedented precision in antibody-antigen modeling. This advancement accelerates bottom-up modeling of cellular components, reducing reliance on vast experimental datasets while enhancing the utility of existing structural biology data. The synergy between AI and experimental techniques—such as advancements in cryo-electron microscopy—is expected to fuel further improvements, driving breakthroughs in drug discovery and molecular engineering. With a unified framework for high-accuracy biomolecular modeling, AlphaFold 3 is poised to reshape our understanding of molecular interactions, paving the way for AI-powered therapeutic development.

AI Reshapes Drug Discovery and Development

Pharmaceutical companies are rapidly integrating AI across drug discovery and development, shifting from early experimentation to full-scale adoption. Since DeepMind's AlphaFold breakthrough, AI-driven protein modeling has accelerated, with companies like Insilico Medicine and Recursion Pharmaceuticals now using AI to design novel compounds and predict drug efficacy. AstraZeneca reports that reinforcement learning now influences 70% of its small-molecule drug candidates, and AI-generated insights are streamlining clinical trial design. The investment trend is intensifying: Pharmaceutical AI spending could exceed $50 billion annually by 2030. The focus is on using AI not just for molecule identification but for optimizing supply chains, regulatory compliance, and post-market surveillance. Despite AI's promise, challenges remain, including data silos, regulatory hurdles, and the need for explainability in AI-driven decisions.

A Search Engine for the World's DNA

A new computational tool, MetaGraph, is making global DNA, RNA, and protein sequences searchable—similar to how Google indexes the web. Developed by researchers at ETH Zurich, MetaGraph compresses vast amounts of genetic data into structured indexes, allowing scientists to scan trillions of base pairs and billions of amino acids efficiently. In a proof-of-concept study, the team indexed 10% of known biological sequences, demonstrating the feasibility of indexing the entire Sequence Read Archive, which now holds more than 50 petabases of genomic data. Unlike traditional bioinformatics tools that struggle with unassembled sequences, MetaGraph

AI AND BIOLOGY

enables rapid searches across massive datasets, supporting discoveries in virology, microbiome research, and disease-associated genetic variations. While computational costs remain a challenge, the tool's ability to reduce complex datasets to gigabyte-scale indexes could democratize genomic research, making high-powered sequence analysis accessible even on standard laptops. As global efforts like the Pasteur Institute's IndexThePlanet and NCBI's Pebblescout push toward comprehensive genetic indexing, MetaGraph highlights the urgent need for scalable, open-access infrastructure to organize and search the world's rapidly expanding biological data.

Automating Chemical Synthesis

AI-powered language models are now capable of not just predicting chemical reactions but also executing them in robotic labs. Systems like ChemCrow and Carnegie Mellon's AI-driven lab assistants can generate synthesis pathways for complex molecules, optimizing drug production in ways previously unimaginable. These tools allow researchers to conduct high-throughput virtual experiments, reducing the reliance on costly physical trials. However, as AI gains the ability to generate toxic compounds, regulatory oversight will need to evolve to prevent misuse.

AI–Designed Proteins Transform Medicine

AI-generated proteins are opening new frontiers in medicine and materials science. MIT's AI-driven protein engineering models and the University of Washington's RFdiffusion system are now designing proteins with unprecedented precision, improving drug targeting and material design. AI-powered protein design is already being applied to developing new vaccines, enzyme-based therapies, and biodegradable plastics. As these technologies mature, AI-designed proteins will accelerate biotech, reducing reliance on traditional trial-and-error discovery methods.

AI–Driven Spatial Biology Advances Precision Medicine

AI is dramatically improving spatial biology, enabling researchers to map cells in their natural environments with unprecedented resolution. Advances in AI-powered imaging and single-cell sequencing are accelerating our ability to understand complex tissue structures, with companies like NanoString and 10x Genomics leading the charge. By combining AI with high-resolution cellular imaging, researchers can now identify biomarkers more effectively, setting the stage for next-generation precision medicine and targeted therapies.

Generative Biology

What if it was possible to generate novel protein therapeutics using new computational tools, without having to discover them through trial and error? That's the promise of Boston-based startup Generate Biomedicines, which trained an AI to invent proteins with structures that, as far as we know, don't exist anywhere in nature. Inspired by DALL-E 2, the powerful text-to-image AI system from OpenAI, Generate's platform asks the user to describe the shape, size, and function of a protein they'd like to see. It then uses diffusion modeling to generate a structure with the right amino acids folded correctly to meet the description. Our understanding of the genome, along with fundamental molecular and network mechanisms, is now being enhanced by innovative tools that allow us to interact with, examine, and manipulate biological systems in new ways.

AI–Powered Molecular Simulations Accelerate R&D

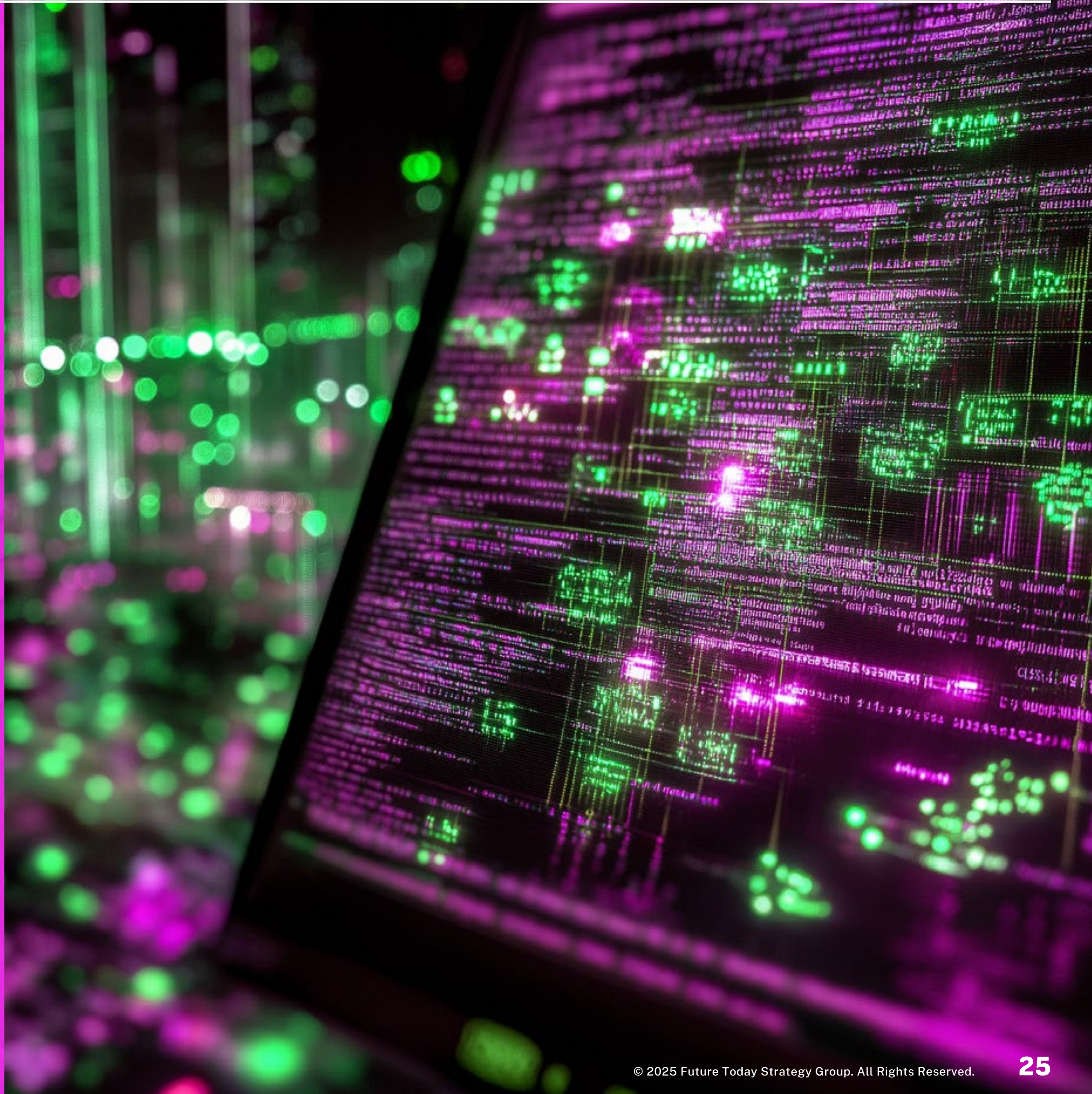
Pharmaceutical companies are increasingly replacing physical drug testing with AI-driven molecular simulations, significantly cutting costs and speeding up development. Advances in quantum computing and machine learning have enhanced in silico modeling, allowing researchers to simulate molecular interactions with unprecedented accuracy. Companies like Schrödinger and DeepMind's Isomorphic Labs are using AI to predict drug-target binding at atomic resolution, reducing reliance on expensive wet-lab experiments. Meanwhile, generative AI is enabling the creation of novel drug candidates, optimizing molecular properties before synthesis. Regulatory agencies, including the FDA and EMA, are now assessing AI-validated

AI AND BIOLOGY

simulations as part of drug approval processes, signaling a shift toward digital-first pharmaceutical R&D. This shift not only accelerates drug discovery but also improves sustainability by reducing lab waste and energy consumption. Companies adopting AI-powered simulations will gain a competitive edge as bioengineering moves toward a fully data-driven paradigm.

Digital Evolution: AI Spontaneously Self-Replicates

A new experiment has shown that self-replicating artificial life can emerge spontaneously from a chaotic pool of random code—without predefined rules or evolutionary incentives. Researchers at Google created a digital environment where tens of thousands of code fragments randomly interacted over millions of generations. Unexpectedly, self-replicating programs emerged, multiplied, and competed for space, mirroring biological evolution. Unlike previous simulations like Conway's Game of Life, which rely on strict rules, this system produced artificial life from raw computational randomness. While the findings don't directly explain the origin of biological life, they suggest that complexity can arise naturally from prolonged random iteration. However, researchers caution that self-replication alone does not guarantee greater complexity; without additional selective pressures, these systems may remain simple rather than evolving into digital ecosystems. Scaling up such experiments could require enormous computational resources, but they hint at the potential for AI-driven studies to reveal fundamental principles of life's emergence.



GENE EDITING AND CRISPR

The question is not whether we will modify genes but how we will use this technology.

Jennifer Doudna, CRISPR pioneer

GENE EDITING AND CRISPR

Base Editing Surpasses Traditional CRISPR

Base editing allows scientists to change a single DNA base without cutting both strands, reducing errors. Unlike traditional CRISPR-Cas9, which introduces double-strand breaks, base editing is more precise and safer for treating genetic diseases. In clinical trials, Beam Technologies is targeting sickle cell disease and beta-thalassemia using its BEAM-101 therapy, which converts hemoglobin genes to a fetal form, reducing disease symptoms. Additionally, base editing is showing potential in treating neurodegenerative diseases like Huntington's by correcting single-point mutations. This approach is gaining traction in biotech as a next-generation gene-editing tool, offering a safer and more efficient alternative to conventional genome editing.

Prime Editing Improves Accuracy

Prime editing enables precise DNA modifications without requiring double-strand breaks or donor DNA templates. This technology offers a unique combination of versatility, specificity, and precision among CRISPR-Cas systems. Prime editors can introduce virtually any substitution, small insertion, or small deletion within the DNA of living cells, making them highly adaptable for therapeutic applications. The system consists of a programmable Cas9 nickase fused to a polymerase enzyme and an extended guide RNA that specifies both the target site and the desired genomic change. Prime editing has shown promise for treating genetic diseases like Tay-Sachs and cystic fibrosis, where single-nucleotide errors need correction. Unlike traditional gene editing, which relies on cellular DNA repair mechanisms that can be inefficient and error-prone, prime editing minimizes off-target effects and improves efficiency. Recent advancements focus on enhancing delivery methods and overcoming technical limitations, expanding its clinical potential. In 2025, further refinements and new strategies, such as optimized pegRNAs and improved polymerase activity, are expected to increase editing efficiency, broadening the range of treatable genetic conditions.

In Vivo CRISPR Therapy Advances

It is now possible to inject CRISPR components directly into the body and make changes to genetic material in vivo, or "within the living." Unlike "ex vivo" editing, where cells are modified outside the body and then reintroduced, in vivo editing involves introducing the gene-editing tools (like CRISPR-Cas9) in the body using viral vectors or lipid nanoparticles. Practically speaking, this means that treating cancer would no longer require traditional chemotherapy—instead, cancerous cells would be targeted and edited with CRISPR. Intellia Therapeutics achieved a groundbreaking milestone with NTLA-2001, the first investigational in vivo CRISPR therapy to demonstrate successful redosing in humans. In a Phase 1 trial for transthyretin (TTR) amyloidosis, three patients initially received a low dose, leading to a median 52% reduction in serum TTR levels. To explore whether an additional dose could provide further benefits, three patients received a second, higher 55 mg dose of NTLA-2001. This led to an impressive 90% reduction in harmful protein levels within 28 days, with an overall 95% reduction from their original levels. This milestone proves that Intellia's CRISPR-based gene-editing therapy can be safely given more than once, which could be a game-changer for treating diseases that may require repeat gene editing. The results also confirm NTLA-2001's strong safety profile, with patients tolerating the second dose well. As the treatment moves into advanced clinical trials in partnership with Regeneron, its success could accelerate the development of CRISPR therapies for other chronic diseases, offering new hope for patients who need long-term solutions. Companies like Verve Therapeutics are also utilizing in vivo editing for cardiovascular diseases by targeting genes that regulate cholesterol levels. With regulatory agencies closely watching these developments, 2025 could mark the first FDA approvals for in vivo CRISPR therapies, transforming treatment options for a range of genetic disorders.

GENE EDITING AND CRISPR

Gene Editing for Rare Diseases Expands

With more than 7,000 rare genetic diseases, CRISPR-based treatments are becoming a major focus for biotech companies like Editas Medicine and CRISPR Therapeutics. In 2025, more clinical trials will target diseases like Duchenne muscular dystrophy, Usher syndrome, and Rett syndrome, where current treatments are limited or nonexistent. Editas' EDIT-101, designed to treat Leber congenital amaurosis, is one of the first in vivo CRISPR therapies to restore vision in patients with inherited blindness. Similarly, researchers are working on CRISPR-based solutions for cystic fibrosis, using prime editing to correct CFTR gene mutations at their source. As CRISPR delivery techniques improve, particularly in the nervous system and muscles, gene therapy for rare diseases will become more viable, bringing hope to patients with currently untreatable conditions.

Epigenetic Editing Becomes Mainstream

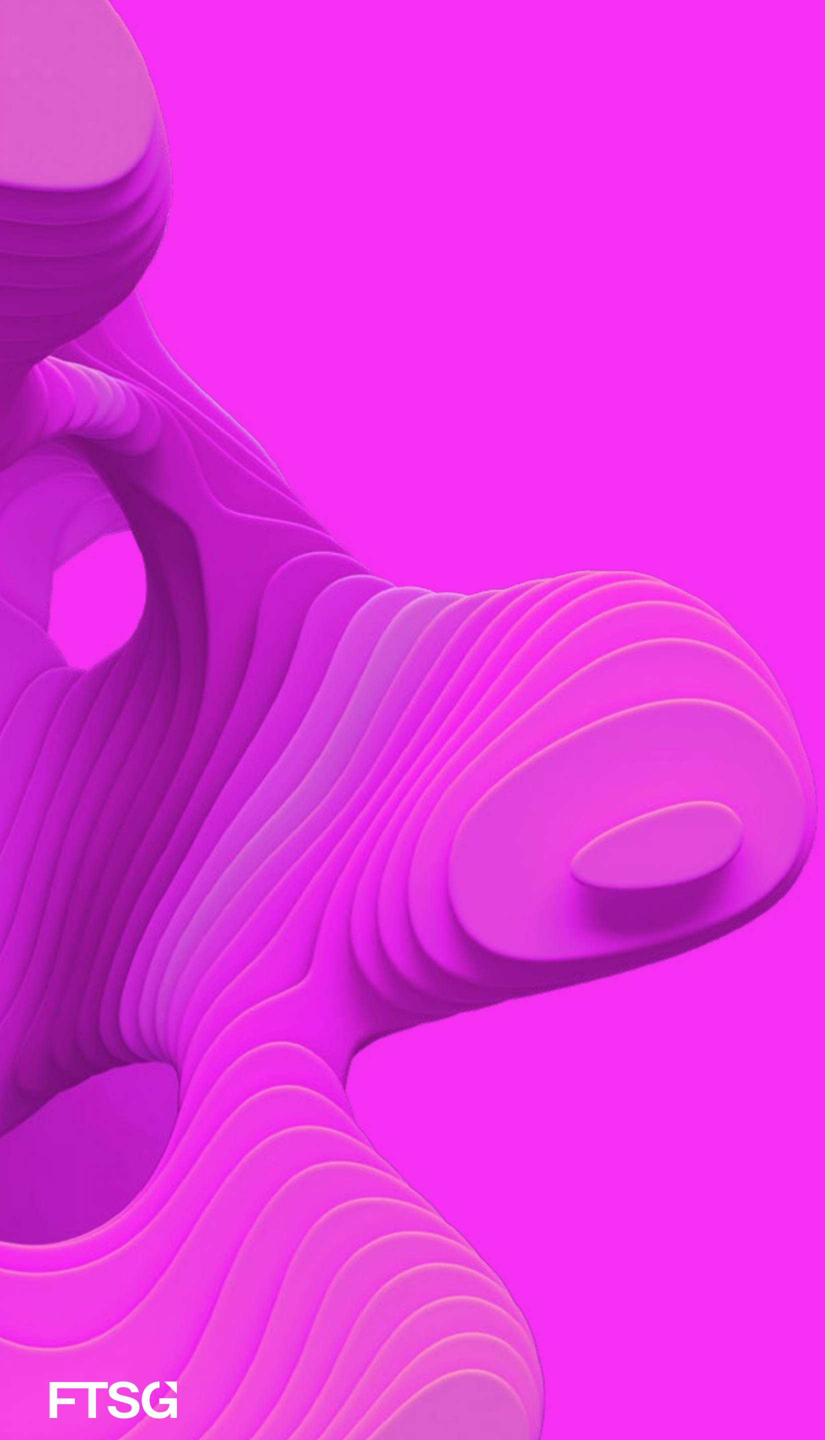
Unlike traditional gene editing, epigenetic editing modifies how genes are expressed without altering DNA sequences. Companies like Chroma Medicine and Tune Therapeutics are developing CRISPR-based epigenetic editing tools to treat conditions like chronic pain, neurodegenerative disorders, and cardiovascular diseases. Instead of permanently cutting DNA, these methods use modified Cas proteins to activate or silence genes by adding or removing chemical tags. For example, Chroma Medicine is working on therapies that reprogram gene activity in sickle cell disease without changing the genetic code. This nonpermanent approach is particularly useful for treating diseases where gene expression needs modulation rather than permanent modification. As epigenetic editing advances, it could provide safer alternatives to irreversible genetic changes, expanding CRISPR's medical applications.

Synthetic Biology Boosts CRISPR Applications

Synthetic biology is combining CRISPR with AI-driven design to engineer microbes for industrial and medical applications. Companies like Ginkgo Bioworks and Synthego are creating synthetic organisms that produce biofuels, pharmaceuticals, and biodegradable plastics. For instance, researchers have engineered bacteria to synthesize complex molecules like insulin and chemotherapy drugs more efficiently. Additionally, CRISPR-modified microbes are being tested for environmental applications, such as carbon capture and plastic degradation. In medicine, synthetic biology is enhancing cell-based therapies by programming stem cells with CRISPR to regenerate damaged tissues or produce therapeutic proteins on demand.

Multiplex Editing Enables Complex Changes

Multiplex CRISPR editing, where multiple genes are modified at once, is becoming more sophisticated. Companies like Mammoth Biosciences and Arbor Biotechnologies are developing Cas enzymes that allow simultaneous edits without increasing off-target effects. This approach is particularly valuable in cell and gene therapy, where multiple genetic factors influence disease. In agriculture, multiplex editing is improving traits like disease resistance and yield in a single step. For example, researchers are using multiplex CRISPR to engineer rice varieties resistant to multiple pathogens simultaneously. In regenerative medicine, scientists are exploring multiplex editing for engineering universal donor cells that evade immune rejection. As techniques improve, 2025 will see broader adoption of multiplex CRISPR in medicine, agriculture, and synthetic biology.



READING AND SEQUENCING GENOMES

DNA is like a computer program but far, far more advanced than any software ever created.

Bill Gates

READING AND SEQUENCING GENOMES

Ultra-Long-Read Sequencing Becomes Mainstream

Oxford Nanopore Technologies is pushing the boundaries of ultra-long-read sequencing, now surpassing 4 million bases per read. This breakthrough helps resolve complex genomic regions, including structural variations, telomeres, and centromeres, which were previously difficult to sequence accurately. Unlike short-read sequencing, which struggles with repetitive DNA sequences and large structural variations, ultra-long reads provide a more complete picture of the genome. This technology is improving research on neurodegenerative diseases, cancer, and rare genetic disorders by capturing mutations and rearrangements that influence disease progression. With improvements in accuracy, throughput, and affordability, ultra-long-read sequencing is becoming a valuable tool for population genomics, personalized medicine, and de novo genome assembly, offering deeper insights into the human genome and evolutionary biology.

Single-Cell Sequencing Expands Applications

Single-cell sequencing is transforming research by allowing scientists to analyze the genetic and transcriptomic activity of individual cells rather than averaging data across cell populations. Companies like 10x Genomics and Parse Biosciences have developed high-throughput platforms to profile thousands of cells simultaneously, enabling insights into cancer evolution, immune responses, and brain development. In oncology, single-cell sequencing helps identify rare cancer cell populations responsible for drug resistance and relapse. In neuroscience, it uncovers cellular diversity in the brain, shedding light on disorders like Alzheimer's and autism. Recent advancements in spatial transcriptomics integrate single-cell sequencing with tissue imaging, mapping gene expression within intact tissues. As technology improves, single-cell sequencing is becoming faster, more scalable, and cost-effective, enabling widespread adoption in precision medicine and developmental biology.

AI-Driven Genome Annotation Improves Insights

AI is changing the way scientists understand and interpret genomes by making it easier to analyze genetic data with greater accuracy. Tools like Google's DeepVariant and Meta's ESMFold use AI to predict changes in DNA and protein structure, helping to reduce mistakes in genetic research. These AI tools help scientists find mutations that can cause diseases, locate important regulatory parts of the genome, and understand the role of noncoding RNA (which doesn't make proteins but still plays a crucial role in the body). AI also improves studies that connect genetic differences to diseases by making it easier to identify which variations matter the most. Also, AI is now accelerating the identification of novel genes involved in conditions like neurodegeneration and cardiovascular diseases. With AI-driven annotation, researchers can analyze massive sequencing datasets faster and more accurately, making genome sequencing a more powerful tool for precision medicine and drug discovery.

Portable Sequencers Enable Real-Time Genomics

When the first human genome was sequenced in 2003, it cost roughly $2.7 billion and took 13 years to complete. In 2012, it cost about $10,000 for researchers to sequence a full genome. The next generation of sequencers will offer a monumental leap forward in speed and efficiency, akin to the transition from dial-up to high-speed internet. Handheld sequencing devices like Oxford Nanopore's MinION are making real-time genomic analysis possible in remote locations. These portable sequencers are being used for disease surveillance, environmental monitoring, and even space exploration. During the Ebola and COVID-19 outbreaks, MinION allowed researchers to sequence viral genomes in the field, tracking mutations in real time. In agriculture, portable sequencing helps detect plant and livestock pathogens before outbreaks spread. The technology is also being tested for identifying microbial life on Mars and other extreme environments. While early versions faced accuracy challenges,

READING AND SEQUENCING GENOMES

recent improvements in error correction and base-calling algorithms have enhanced performance. Portable sequencing will become even more reliable and accessible, empowering researchers, conservationists, and clinicians to perform genomic analysis anywhere, without relying on large laboratory infrastructure.

Epigenome Sequencing Gains Clinical Relevance

Our genes can be switched on and off through epigenetic tags. These tags act like dimmer switches, controlling which genes are active. Scientists are now mapping these switches across the entire genome using powerful new sequencing tools, shedding new light on how epigenetic changes drive aging and diseases like cancer. Companies are combining genetic and epigenetic data to better understand diseases. In cancer care, doctors can now detect tumor signals in blood samples by looking for abnormal epigenetic patterns. We're also learning how lifestyle factors like diet and stress can trigger epigenetic changes that may even pass to future generations. As the technology gets cheaper and analysis gets easier, checking someone's epigenetic profile could become as routine as getting a blood test—helping doctors diagnose disease earlier and choose the right treatments.

Rapid Whole-Genome Sequencing in Critical Care

Ultra-fast whole-genome sequencing (WGS) is transforming critical care by providing genetic diagnoses in hours rather than weeks. Companies like Illumina and PacBio have developed high-speed sequencing platforms that help diagnose rare genetic diseases in newborns, enabling faster treatment decisions. In neonatal intensive care units, rapid WGS has already saved lives by identifying treatable genetic disorders before symptoms worsen. Hospitals are also adopting rapid sequencing for sepsis, cancer, and other urgent conditions where genetic insights can guide immediate treatment. The decreasing cost of sequencing and improvements in AI-driven variant interpretation are making rapid WGS more accessible. In 2025, more hospitals could start to integrate ultra-fast sequencing into emergency and intensive care settings, improving the speed and accuracy of genetic diagnoses.

Dark Genome Exploration Unlocks Hidden Functions

Noncoding DNA, or the "dark genome," makes up more than 98% of the human genome, but no one knows why it exists or if it serves a purpose. Recent advances in long-read sequencing, AI-driven annotation, and epigenetic mapping are starting to help researchers understand the role of noncoding regions in gene regulation and disease. Scientists have discovered that noncoding regions contain enhancers, silencers, and regulatory elements that influence gene expression. Mutations in these regions are now linked to diseases such as autism, schizophrenia, and cancer.

Metagenomics

Metagenomics represent a new approach in a genomic analysis. Simply put: imagine dealing with one box full of 10 different jigsaw puzzles. In this analogy, each puzzle represents the DNA of a different organism living in a particular environment. The challenge of metagenomics is to sort out these pieces and put together each individual puzzle correctly. As researchers are considering new therapies or trying to understand how a virus or pathogen works, they need contextual data to understand cause and effect. New metagenomics tools help scientists solve several puzzles at once to understand the diverse range of life forms coexisting in a specific environment. This is crucial for gaining insights into how these microorganisms interact with each other, with humans, and with the environment. It's a complex task but offers valuable information for various applications, from health care to environmental science. Metagenomics can detect viruses on food items, helping to trace the source of microbial and viral contamination and improving food safety.

READING AND SEQUENCING GENOMES

It's effective in cleaning up pollutants, by helping to identify microorganisms that can degrade toxic substances more efficiently than other methods. And it's being used to identify how microorganisms compete and communicate in different environments, from human digestive tracts to deep-sea vents. For example, Israel-based BiotaX developed TaxonAI, a model that uses AI to explain biological data based on gene functionality or taxonomy.

Quantum Biology

Quantum biology is an emerging field that combines quantum physics—the science of the very small—with biology, the study of living things. Researchers apply the principles that govern subatomic particles to understand how living organisms work at a fundamental level. For business leaders, this matters because quantum biology has the potential to influence various industries. It can lead to breakthroughs in medicine, by improving drug design or understanding diseases at a molecular level. In technology, it could inspire new, more efficient ways of data processing and energy storage. This exciting frontier blends the most basic elements of our universe with the complexity of life, opening up a world of possibilities for innovation and advancement in multiple fields. One experiment has already yielded results: At the Johns Hopkins University Applied Physics Laboratory in Maryland, researchers found striking similarities between an enzyme central to human metabolism and a magnetically sensitive protein found in birds. This deepens the understanding of magnetosensitivity—but in practical terms, it also potentially transforms the approach to studying biological navigation mechanisms.

Pangenome: What Makes Us Human

The Human Genome Project has been "completed" multiple times, yet the understanding of genetic diversity continues to evolve. In 2025, the pangenome will continue to reshape the understanding of genomics by mapping the DNA of 47 individuals from diverse backgrounds, capturing previously overlooked genetic variations. Unlike the traditional reference genome—largely based on a single individual—the pangenome reveals how DNA varies across populations, highlighting rare mutations, structural changes, and evolutionary hot spots. Researchers from the Human Pangenome Project plan to eventually expand this atlas to 300 genomes, making genomic research more inclusive and equitable. The pangenome's graph-based approach allows scientists to compare multiple genetic sequences at once, improving disease research and diagnostics. This shift addresses reference bias, ensuring that genomic analysis doesn't overlook genetic differences unique to certain populations. With new sequencing technologies like long-read sequencing from Pacific Biosciences and advanced computational tools, the pangenome is becoming a foundational resource. Though still in its draft stage, this effort is expected to transform medicine, ancestry studies, and evolutionary biology. As experts acknowledge, the human genome will never be truly finished—every population and generation bring new insights, making genome sequencing an ongoing and ever-expanding endeavor.

Unlocking Bioinformatics Data

Rapid advancements in technology and a steep decline in sequencing costs are advancing the use of bioinformatics data. Scientists use this data—biological information stored digitally, primarily focusing on genetic and molecular data—to investigate all sorts of questions: How do certain diseases affect our bodies at the molecular level? Can we design new medicines to treat these diseases? How do different species evolve and adapt to their environments? But there are challenges in understanding it. Sequencing an individual's entire genome now generates a staggering 100 gigabytes of raw data, a figure that more than doubles post-analysis with the application of deep learning and natural language processing tools. Genome analysis pipelines are struggling to keep pace with this explosion of data. The complexity and computational intensity of sequencing analysis, which involves myriad steps to identify genetic variations, are monumental tasks requiring sophisticated technological solutions. Recent advances in deep

READING AND SEQUENCING GENOMES

learning and AI generally are significantly improving the process of DNA sequencing, making it faster, more accurate, and less expensive. Nvidia, which makes powerful GPUs, now has Clara, a suite of computing platforms, software, and services that powers AI solutions for health care and life sciences, from imaging and instruments to genomics and drug discovery. Reading, sequencing, and analyzing bioinformatics data using technological breakthroughs have practical, real-world applications, such as quickly identifying genetic disorders in newborns or discovering new targets for drug development.

Ancient DNA Reveals Hidden Chapters of Human History

Advances in ancient DNA (aDNA) sequencing are reshaping our understanding of early human migration, evolution, and interaction with other species. A groundbreaking 2024 study by researchers at the Max Planck Institute for Evolutionary Anthropology has sequenced the oldest modern human genomes yet, revealing new insights into the first humans who arrived in Europe 42,000–49,000 years ago. These genomes, extracted from remains in Germany and the Czech Republic, show that these individuals were part of a small, closely related group that split from the main population migrating out of Africa around 50,000 years ago. Surprisingly, despite living alongside Neanderthals, these early modern humans do not show signs of recent interbreeding, suggesting they may have taken a different migration route into Europe. The study also confirms that all present-day non-African populations share Neanderthal ancestry from a single ancient admixture event between 45,000–49,000 years ago. Beyond human history, aDNA research is uncovering lost species, revealing the origins of pandemics, and even authenticating medieval documents through the DNA of the animal skins they were written on. Scientists analyzing medieval parchments have identified rare genetic patterns in historic cattle, helping to date and verify centuries-old manuscripts. Projects like the Francis Crick Institute's 1,000 Ancient Genomes initiative are expanding the genetic diversity map, shedding light on ancient populations that shaped modern humans. With continued advancements in sequencing technology, aDNA research is poised to further bridge the past and present, providing unparalleled insights into the evolution of humans, animals, and historical artifacts. As our ability to extract and analyze ancient DNA improves, we are unlocking an ever-growing archive of genetic history, rewriting the story of life on Earth.

BIOPRINTING, ORGANOIDS, AND NOVEL ORGANISMS

It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is most adaptable to change.

Charles Darwin

BIOPRINTING, ORGANOIDS, AND NOVEL ORGANISMS

Lab-Grown Organs: The New Frontier in Transplant Medicine Takes Shape

The future of organ transplantation is being shaped by remarkable advances in bioprinting technology. Companies like United Therapeutics and 3D Systems are at the forefront of this transformation, developing sophisticated bio-inks and breakthrough vascularization techniques that are essential for creating viable organs. Their focus on kidneys and lungs represents a critical step forward, as these organs are among the most needed for transplantation worldwide. The innovation lies not just in the printing process but in creating the intricate network of blood vessels necessary for organ survival. This vascularization challenge has been a major hurdle in tissue engineering, but recent developments in multi-material printing and biomaterial design are yielding promising results. Research teams have successfully demonstrated the ability to print increasingly complex vascular networks that can support living tissue. While fully functional transplantable organs are still years away, the rapid pace of advancement suggests we could see the first bioprinted organs in clinical trials within the next decade. This development could unlock new options in the field of transplant medicine, potentially eliminating organ waiting lists and saving countless lives through custom-made, rejection-free organs.

Next-Gen Bioprinters Create Living Tissue With Multiple Cell Types

The evolution of bioprinting technology has reached a pivotal moment with the emergence of sophisticated multi-material printing capabilities. Industry leaders like CELLINK and Organovo are pioneering platforms that can seamlessly integrate multiple cell types and biomaterials within a single printing process, representing a quantum leap in tissue engineering capability. This advancement allows for the creation of more complex and functionally accurate tissue models that better replicate the intricate architecture of natural human tissues. The technology enables researchers to precisely position different cell types, growth factors, and structural components in three-dimensional arrangements that closely mirror native tissue environments. It's a breakthrough with immediate applications in drug development and testing, where more accurate tissue models can provide better predictions of drug efficacy and potential side effects. The ability to create these complex tissue structures also opens new possibilities in regenerative medicine, potentially enabling the replacement of damaged or diseased tissue with custom-printed alternatives. The technology's precision and versatility are particularly valuable for creating tissue models of complex organs, where multiple cell types must work together in specific spatial arrangements to achieve proper function.

Printed Skin Gets Green Light For Burn Care

Bioprinted skin grafts assist in the treatment of severe burns and chronic wounds, and are one of the first bioprinted tissues to enter clinical trials. Companies like Epibone and Poietis are pushing the boundaries of skin bioprinting by developing full-thickness skin equivalents that include complex structures like sweat glands and hair follicles. This breakthrough represents a significant improvement over traditional skin grafts: Printing custom-sized grafts using a patient's own cells reduces the risk of rejection while ensuring optimal coverage of wound areas. The technology incorporates multiple layers of different cell types that integrate with the host tissue, accurately mimicking the natural structure of human skin. Beyond treating burns, these advanced skin constructs are finding applications in cosmetic testing, reducing the need for animal trials, and in studying skin diseases. This personalized approach to wound healing marks a significant step forward in reconstructive medicine, offering hope to millions of patients worldwide suffering from severe skin injuries and chronic wounds.

Printing Custom Bone Implants

Three-dimensional printed bone scaffolds combine bioactive ceramics with living stem cells to create personalized implants. The groundbreaking research at Harvard and

BIOPRINTING, ORGANOIDS, AND NOVEL ORGANISMS

Rice universities has yielded implants that actively integrate with a patient's natural bone tissue, significantly accelerating the healing process. Precisely engineered to match the person's anatomy, these scaffolds incorporate specific porosity patterns that promote cell growth and vascularization. The bioactive materials used in these implants stimulate the body's natural bone regeneration processes, while their structural design provides immediate mechanical support. Their dual functionality represents a significant advancement over traditional bone grafts, which often struggle to properly integrate. And the incorporation of the patient's own stem cells further enhances the biological response, reducing the risk of rejection and complications. These custom implants will be particularly valuable in complex reconstructive surgeries where standard implants may not provide optimal results, shown by the technology's success in clinical trials. We're nearing a future of personalized bone replacements becoming the standard of care in orthopedic surgery.

Zero G Bioprinting

NASA and ESA's investment in bioprinting technology for space applications is opening new frontiers in space medicine and long-term space habitation. Specialized bioprinters can operate in microgravity environments, addressing the unique challenges astronauts face during extended space missions. These systems must overcome the fundamental effects of zero gravity on fluid dynamics and cell behavior, requiring innovative approaches to bioink formulation and printing processes. The ability to produce tissue replacements and medical supplies on demand could prove crucial for future deep space missions where resupply from Earth is impractical. Beyond immediate medical applications, this technology is essential for studying how human tissues respond to the space environment and developing countermeasures against the physiological effects of long-term space exposure. The research has broader implications for Earth-based medicine, as the unique constraints of space-based bioprinting drive innovations in tissue engineering techniques. This technology could become a critical component of humanity's infrastructure for space exploration and colonization.

Custom Tissue Banks Will Drive Personalized Medicine

Patient-specific bioprinting is helping to accelerate the field of personalized medicine by enabling the creation of custom tissue constructs tailored to individual patient needs. Major hospitals are starting to form the earliest stages of strategic partnerships with biotechnology firms to establish dedicated bioprinting facilities capable of producing patient-matched tissue grafts on demand. This approach combines advanced imaging technologies with precise bioprinting capabilities to create tissues that exactly match the patient's anatomy and cellular composition. Using a patient's own cells as the starting material significantly reduces the risk of immune rejection, a common complication in traditional transplant procedures. The technology is particularly valuable in reconstructive surgery, where custom-designed tissues can better restore both form and function. These facilities are also serving as valuable research centers, advancing our understanding of tissue engineering and regenerative medicine. The standardization of these processes is creating new protocols for quality control and regulatory compliance, paving the way for broader adoption of bioprinted tissues in clinical practice. This personalized approach represents a significant shift in how tissue replacement and regenerative therapies will develop.

Smart Machines Create Complex Living Tissue

The integration of bioprinting with robotics and microfluidics is creating unprecedented capabilities in tissue engineering. Hybrid systems developed by the Wyss Institute and Carnegie Mellon combine multiple fabrication technologies to create more complex and functional tissue constructs. These advanced platforms incorporate precise robotic control systems with sophisticated microfluidic networks, delivering nutrients and removing waste products in real time. Combining robotics

BIOPRINTING, ORGANOIDS, AND NOVEL ORGANISMS

and microfluidics lets researchers harness both the precision of the former and the control over fluid dynamics of the latter, creating new possibilities for engineering larger, more complex tissues that better mimic natural organ function. These systems can dynamically adjust printing parameters based on real-time feedback, ensuring optimal conditions for cell survival and tissue formation. Integrating multiple fabrication methods enables the creation of hierarchical structures that more closely replicate natural tissue architecture. This convergence of technologies represents a significant step forward in our ability to create complex, living tissue structures.

Expanded Organoid Use

An organoid is a miniature, lab-grown 3D tissue model that mimics the structure and function of real organs. Created from stem cells or organ-specific progenitor cells, organoids self-organize into complex, functional units resembling small versions of human organs, such as the brain, liver, kidneys, lungs, intestines, or pancreas.

Already, liver organoids are transforming drug safety testing and the understanding of liver disease. Biotech companies like Emulate Bio are leveraging these miniature liver models to replicate key aspects of liver function, including metabolic processes and detoxification pathways that are crucial for drug processing. The technology enables researchers to observe how different drugs affect liver tissue in real time, helping them predict drug toxicity before compounds enter clinical trials and providing early warnings of potential hepatotoxicity. These liver models incorporate multiple cell types arranged in physiologically relevant structures, allowing them to mimic complex liver functions more accurately than conventional cell cultures. And the ability to maintain these organoids for extended periods enables long-term toxicity studies that were previously impossible. This advancement is particularly valuable for identifying drugs that might cause rare but serious liver complications, potentially preventing costly late-stage drug failures and improving patient safety.

Gut Models Mirror Human Digestive System

Scientists are making remarkable progress in developing sophisticated gut organoids that incorporate living microbiomes, creating powerful new tools for studying gastrointestinal diseases and drug interactions. These advanced models replicate the complex exchange between human intestinal tissue and gut bacteria, providing unprecedented insights into conditions like Crohn's and inflammatory bowel diseases. Integrating living microorganisms with human intestinal cells creates a more complete and accurate representation of the gut environment, enabling researchers to study how different bacterial populations affect disease progression and treatment outcomes. These models are particularly valuable for understanding how drugs interact with both human tissue and gut bacteria, helping to predict potential complications and optimize treatment strategies. The ability to maintain stable bacterial populations within these organoids represents a significant technical achievement, opening new possibilities for studying the role of the microbiome in human health and disease.

Brain Models Open Window To Neural Disease

The development of sophisticated brain organoids is transforming our understanding of neurological conditions and potential treatments. Research institutions like the Allen Institute and The Max Planck Society are using these three-dimensional neural tissues to model complex conditions such as Alzheimer's, epilepsy, and autism spectrum disorders. These miniature brain-like structures replicate key aspects of human brain development and function, providing unprecedented insights into neurological disease mechanisms. Being able to grow these organoids from patient-derived cells allows researchers to study disease progression in a personalized context, potentially leading to more effective, targeted therapies. These models capture complex neural networks and cellular interactions that are impossible to study in traditional two-dimensional cell cultures; they also

BIOPRINTING, ORGANOIDS, AND NOVEL ORGANISMS

allow scientists to observe long-term neural development and disease progression, providing new opportunities to test potential therapeutic interventions. This approach is particularly valuable for studying conditions that are difficult to model in animals or observe in human patients.

Global Biobanks Improve Disease Research

Large-scale organoid biobanks are creating powerful new resources for medical research and drug development. Organizations like the Broad Institute are building comprehensive collections of patient-derived organoids that represent diverse genetic backgrounds and disease states. These living biobanks serve as invaluable repositories for studying disease progression, genetic variation, and treatment response across different populations. Standardized protocols for organoid creation and maintenance ensure consistent quality and reproducibility, making these resources particularly valuable for large-scale studies. These collections are also democratizing access to advanced disease models, enabling researchers worldwide to study rare conditions and diverse patient populations. And when detailed genetic and clinical data are integrated with these organoid collections, they create powerful tools for understanding disease mechanisms and developing new therapeutic strategies. This systematic approach to organoid banking is accelerating the pace of discovery in regenerative medicine and personalized therapeutics.

Engineering New Life Forms

The engineering of synthetic organisms with custom-designed genetic codes represents a new frontier in biotechnology. Companies like Ginkgo Bioworks and Viridos are pioneering the development of artificial microbes with precisely engineered genetic systems designed for specific industrial applications. Researchers are using these synthetic organisms to produce biofuels, synthesize complex pharmaceutical compounds, and tackle environmental challenges through enhanced metabolic capabilities. The ability to design and construct custom genetic systems represents a fundamental shift in how we approach biological engineering: We are moving from modification of existing organisms to the creation of purpose-built biological systems. These engineered life forms incorporate novel genetic codes and metabolic pathways that don't exist in nature, expanding the possibilities for biological production and problem-solving. The technology requires sophisticated safeguards to ensure these organisms cannot survive outside controlled environments, addressing important biosafety considerations.

CRISPR Opens New Chapter in Animal Research

Laboratories worldwide are creating precisely engineered animals with specific genetic modifications—sometimes to better replicate human disease conditions for study, sometimes to produce human-compatible organs for transplantation. This technology enables the creation of pigs with organs that have been modified to reduce rejection risks in human recipients, potentially addressing the critical shortage of donor organs. It has also allowed researchers to use the precision of CRISPR editing to create mouse models with the exact genetic mutations found in human diseases, providing more accurate platforms for studying disease mechanisms and testing potential treatments. These engineered animals are particularly valuable for studying complex genetic disorders and developing new therapeutic strategies. The ability to make multiple precise genetic modifications is advancing our understanding of gene function and disease processes.

Smart Bacteria Target Disease From Within

At MIT, researchers are creating sophisticated bacterial biosensors capable of detecting specific disease markers and responding with targeted therapeutic interventions. These engineered bacteria are designed to survive and function within the human body, serving as living diagnostic and therapeutic agents. The technology combines advances in synthetic biology with precise genetic control

BIOPRINTING, ORGANOIDS, AND NOVEL ORGANISMS

systems; together, they enable bacteria to produce therapeutic compounds in response to specific molecular signals. These smart bacteria are particularly promising for treating conditions that are difficult to address with conventional therapies, such as gastrointestinal disorders and certain types of cancer. It's a powerful new tool for precision medicine: Living therapeutic agents programmed with multiple sensing and response capabilities can continuously monitor and respond to changes in their environment, providing dynamic treatment responses.

Living Robots

What do you get when you combine a cluster of stem cells from an African clawed frog, a supercomputer, a virtual environment, and evolutionary algorithms? In 2020, after 100 generations of prototypes, researchers at Tufts University and the University of Vermont discovered the answer was a tiny blob of programmable tissue called a xenobot. These living robots mark a groundbreaking achievement in biology: a new class of programmable living machines with potential applications in medicine and environmental remediation. They can undulate, swim, and walk. They work collaboratively and can even self-heal. And they're tiny enough to be injected into human bodies, travel around, and—maybe someday—deliver targeted medicines. While technically they're made up of living cells, researchers are quick to point out that xenobots lack the characteristics of a traditional biological life-form. The current crop of xenobots live longer, and they can sense what's in their environment. They can also operate in robot swarms to complete a collaborative task. Xenobots are being used to help researchers understand how defects in the hairlike structures in our lungs, called cilia, can result in diseases. Also in progress: xenobots that can travel to a damaged spinal cord and repair it with regenerative compounds. The self-organizing properties of these living machines provide insights into developmental biology and tissue engineering, potentially leading to new approaches in regenerative medicine.

Animal-Human Hybrids Promise Organ Solutions

The development of chimeric embryos containing human cells represents a controversial but potentially transformative approach to addressing the global organ shortage crisis. Researchers at Stanford and Japan's RIKEN Institute are advancing techniques to grow human-compatible organs within animal hosts, primarily focusing on pigs and sheep. This approach involves introducing human stem cells into animal embryos, creating chimeric organisms that grow organs containing human cells. The technology requires precise control over cell development to ensure human cells contribute primarily to the desired organs while minimizing their presence in other tissues, particularly the brain. These chimeric approaches offer several advantages over traditional bioprinting, including the natural development of complete vascular systems and supporting structures. The research addresses critical technical challenges, including immune compatibility and proper organ development, while navigating complex ethical considerations. This technology could potentially provide a renewable source of transplant-compatible organs, addressing one of medicine's most pressing challenges.

Bioprinting Electronics

In a groundbreaking development that blurs the lines between biology and technology, researchers at UK-based Lancaster University successfully 3D printed glowing shapes inside nematode worms, demonstrating the potential to embed electronics directly within living organisms. The team leveraged a photonic 3D printer and a special ink that shapes and activates the material within the organism. By feeding this ink to nematode worms, the team was able to create intricate conductive circuits in the shape of stars and squares inside the living worms. This technique suggests potential for improving traditional electronic implants, such as pacemakers and bionic ears, which have transformed medical treatments but come with their own set of challenges, including infection risks and maintenance difficulties. The Lancaster team's work is part of

BIOPRINTING, ORGANOIDS, AND NOVEL ORGANISMS

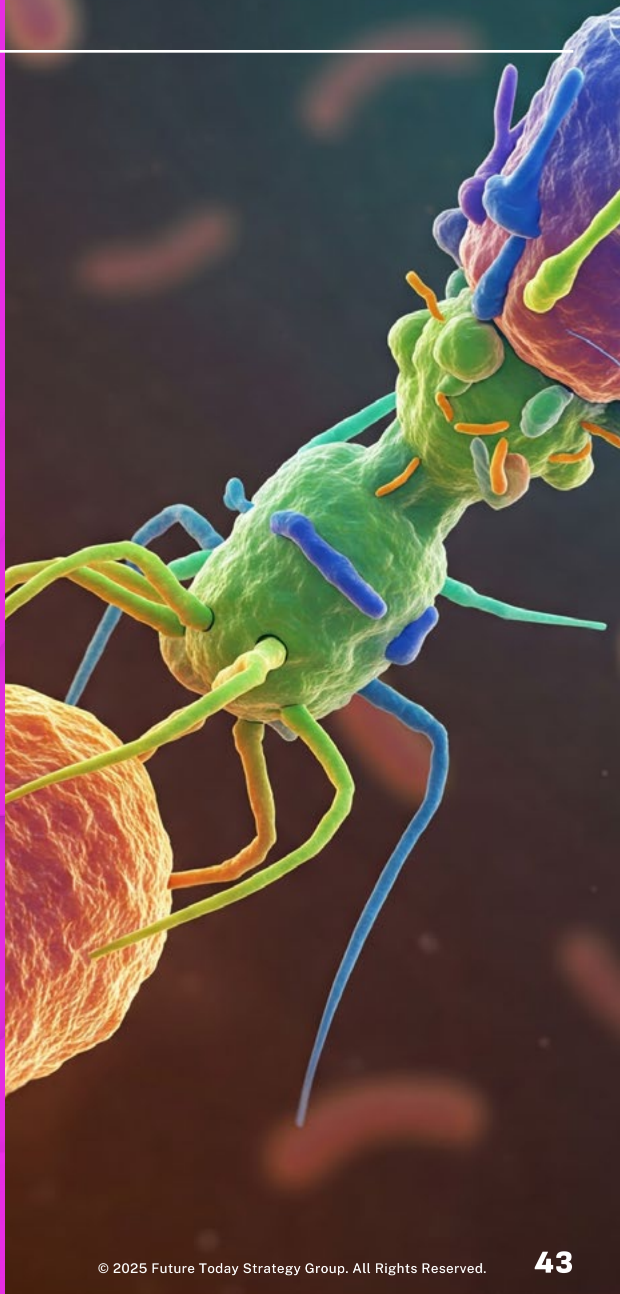
a growing trend in bioprinting electronic implants and computer-brain interfaces, which could eventually replace the medical devices we use today.

Bacterial Nanosyringes

In an emerging advancement bridging microbiology and medicine, researchers are transforming bacteria into nanosyringes capable of targeting human cells for precise protein delivery. This innovative approach, redefining the boundaries of targeted medical treatments, could dramatically improve the effectiveness and safety of therapies for many different health conditions, including cancer. Some of the most powerful drugs are made up of small molecules that indiscriminately enter cells and cause unintended side effects. Large molecules like proteins could offer targeted and potent therapeutic benefits, but have one big challenge: They can't get through cell membranes. This is where the bacterial nanosyringes come into play, offering a solution already found naturally in bacteria like Photorhabdus that can inject their contents directly into targeted cells. Researchers at the Zheng Lab at MIT, led by Joe Kreitz and his team, have managed to harness this natural mechanism, using Google DeepMind's AlphaFold AI program to adapt nanosyringes to bind to specific human proteins. This breakthrough technique has already demonstrated its potential in lab settings, successfully delivering various proteins to targeted human cells and even to neurons in mice.

Bacteriophage Therapies Gain Momentum in Antibiotic Resistance Fight

Bacteriophages, also known as phages, are viruses that infect and replicate only in bacterial cells. They are ubiquitous in the environment and are recognized as the most abundant biological agent on earth. With antibiotic resistance becoming a global crisis, phage therapy is emerging as a viable alternative to traditional antibiotics. In 2025, researchers and biotech firms like BiomX and Locus Biosciences are accelerating clinical trials for personalized phage treatments, targeting antibiotic-resistant bacterial infections. Unlike broad-spectrum antibiotics, phages are highly specific, attacking only the harmful bacteria while preserving beneficial microbiomes. Recent FDA-approved compassionate use cases have shown remarkable success in treating chronic infections, such as multidrug-resistant Pseudomonas in cystic fibrosis patients. Advances in synthetic biology are also allowing scientists to engineer phages with enhanced antibacterial properties, such as toxin-neutralization and immune modulation. As regulatory frameworks evolve, phage-based precision medicine could become a mainstream solution for combating superbugs in hospitals, agriculture, and environmental health.



SCENARIO YEAR 2058

GENETIC UNIFORMITY TRIGGERS GLOBAL AGRICULTURAL COLLAPSE

The world's greatest agricultural efficiency has become its undoing. Global food corporations celebrated CRISPR gene editing as their path to unprecedented standardization—poultry with identical growth rates, swine with perfectly uniform meat marbling, cattle producing mathematically precise milk formulas. This optimization transformed animal agriculture into a precision industry, with predictable yields driving record profits. But nature had other plans. When a previously benign agricultural virus mutated in 2058, it encountered a perfect storm: billions of genetically identical animals with no diversity to provide natural resistance. The virus spread exponentially through standardized livestock populations, decimating global food production within months. Governments' desperate attempts to resurrect genetic diversity through frozen pre-CRISPR samples proved insufficient against the scale of the crisis. In their quest to master nature through genetic engineering, humans had forgotten nature's first law: Diversity equals survival.

BIOCOMPUTING

BIOCOMPUTING

Organoid Intelligence

To meet AI's growing computational needs, there's a shift away from traditional Von Neumann architecture toward more innovative approaches. One is neuromorphic computing, inspired by the brain's structure, which efficiently handles simultaneous information storage and processing. That's what led researchers at Johns Hopkins to create organoid intelligence (OI), which uses biological materials—most often human brain cells—for information processing, leveraging their inherent capabilities beyond silicon-based systems. This is considered the next frontier of biocomputing, and represents a significant step in harnessing the brain's natural efficiency for AI applications. In 2023, a biocomputing system made of living brain cells learned to recognize the voice of one person from a set of 240 audio clips of eight people pronouncing Japanese vowel sounds. The clips were sent to the organoids as sequences of signals arranged in spatial patterns. Why bother inventing technology that sounds like it was inspired by a dystopian sci-fi novel? As the world demands more AI applications like ChatGPT, we'll need more energy-intensive computers and networks to crunch all that data. OI might be able to perform all of those tasks using a fraction of the resources required of a traditional computer.

Living Computers: Biological Circuits for Data Processing

Scientists at the Spanish National Research Council genetically modified a strain of E. coli called Marionette so that it could sense different chemicals and respond to them. But that wasn't all. They modified the strain so its plasmids each encoded for a different fluorescent protein (red and green). While the researchers could alter the ratio of the red and green with future chemical inputs, without inputs, the ratio would simply stay constant and, in a way, was a form of memory. Here's where things got interesting: The team grew the Marionette strain in eight wells that correspond with the outer squares of a grid and taught it how to play tic-tac-toe. Initially, the bacteria played randomly, but the Spanish National Research Council team trained the strain by adding chemicals to the squares—and after eight sessions, the bacteria played at an expert level. While the bacteria haven't yet beat humans at the game, there's an interesting analogy worth remembering: The benchmarks in computing and specifically in AI have always been gameplay. And this isn't the only biological computer. A biocomputer called DishBrain learned how to play the 1980s video game Pong. DishBrain is made of ~1 million live human and mouse brain cells grown on a microelectric array that can receive electrical signals. The signals tell the neurons where the Pong ball is, and the cells respond. The more the system played, the more it improved. Cortical Labs is now developing a new kind of software, a Biological Intelligence Operating System (biOS for short), which would allow anyone with basic coding skills to program their own DishBrains.

DNA Machines Process Data At Molecular Scale

Scientists at Shanghai Jiao Tong University achieved a significant breakthrough in DNA computing by creating the world's first programmable DNA computer capable of executing billions of unique circuits. The system uses DNA molecules as its fundamental computing elements, leveraging nature's information storage mechanism instead of traditional silicon-based components. The researchers ingeniously solved the challenge of random molecular movement by designing DNA sequences that fold into specific shapes, effectively creating molecular-scale computer components that guide data flow. In practical demonstrations, the system successfully performed complex calculations including square root operations and identified genetic markers for kidney disease. While current processing speeds are relatively slow compared to traditional computers, taking hours for simple computations, the technology shows particular promise for biomedical applications, especially in

BIOCOMPUTING

detecting specific genes and triggering targeted biological responses.

DNA as an Alternative to Future Data Storage

The world is generating data at an exponential rate, outpacing current storage technologies like magnetic tape. By 2030, global storage demand is expected to exceed supply by 20 million petabytes, making traditional solutions unsustainable. DNA data storage—in the form of manufactured DNA—could become an alternative to traditional hardware thanks to its high density, longevity, and stability. DNA can store vast amounts of information—potentially all data on the internet in a sugar-cube-sized volume—lasting thousands of years without degradation. Current methods encode digital data into DNA sequences using chemical synthesis, but future approaches will use semiconductor chips and enzymatic synthesis, improving scalability and efficiency. Organizations like Microsoft, Twist Bioscience, and the DNA Data Storage Alliance are actively developing commercial DNA storage solutions. But while the medium can scale, it's not yet ready for widespread use. There are several challenges, including writing speed and cost, which must improve by eight orders of magnitude to compete with today's storage devices. The ability to read and write DNA rapidly will also accelerate biotech applications, enabling custom microbes, synthetic organisms, and biological countermeasures. While DNA storage offers an unprecedented solution to data challenges, it also introduces cybersecurity risks, as synthetic DNA could be used for both medicine and bioterrorism. As digital and biological systems merge, cyberbiosecurity will become critical.

CYBERBIOSECURITY

CYBERBIOSECURITY

DNA Technology Gets New Security Shield

The advancement of gene editing and synthetic biology capabilities has necessitated robust cyberbiosecurity measures to prevent potential misuse of DNA synthesis technologies. Leading biotechnology firms and government agencies are implementing sophisticated AI-driven screening systems to detect and block potentially dangerous genetic sequences. These security measures include advanced algorithms that can identify sequences associated with harmful pathogens or toxins, ensuring that synthetic biology remains a safe and ethical field. The screening systems analyze DNA synthesis orders in real-time, comparing them against databases of known hazardous sequences. This proactive approach to biosecurity includes multiple layers of verification and authentication, protecting against both intentional misuse and accidental synthesis of dangerous materials. The technology represents a critical safeguard for the expanding field of synthetic biology.

Biohack Rules Tighten As Field Grows Rapidly

The expanding DIY biohacking movement has prompted increased attention to cyberbiosecurity concerns from major regulatory bodies. The FDA and DARPA are spearheading new initiatives in 2025 to implement more stringent oversight of open-source bioengineering tools and techniques — aiming to balance innovation with safety, keeping advances in synthetic biology accessible while preventing misuse.These regulations establish comprehensive frameworks for ethical guidelines and cybersecurity protocols to prevent unauthorized genome editing and potential bio-cyberattacks. They include verification systems for equipment purchases, mandatory training requirements, and enhanced monitoring of biological research activities.These frameworks address emerging challenges in biological security, including the potential for unauthorized genetic modifications and the creation of synthetic organisms. The implementation of these regulations represents a significant step in professionalizing and securing the growing field of DIY biotechnology.

DNA Supply Lines Get New Digital Defense

The growth of cloud-based platforms in genetic engineering and biomanufacturing has created new vulnerabilities in biotechnology supply chains. Industry leaders are responding by implementing zero-trust security frameworks and blockchain-based verification systems to protect the integrity of critical components and processes. These security measures ensure the authenticity and safety of DNA synthesis materials, CRISPR reagents, and biofabrication processes. The technology includes end-to-end tracking of biological materials, secure digital signatures for verification, and real-time monitoring of supply chain activities. These advanced security protocols are essential for maintaining the reliability and safety of synthetic biology operations, particularly as the industry becomes more dependent on digital infrastructure. As companies implement them, it represents a crucial step in protecting the expanding biotechnology supply chain.

Bio-Defense Gets Smart Computer Upgrade

The integration of biocomputing with advanced threat detection systems is starting to shape our ability to respond to bioterrorism and pandemic risks. Military and public health organizations are investigating sophisticated synthetic biology-based sensors that work alongside AI-powered pattern recognition systems to identify engineered pathogens. This convergence of biocomputing and cyberbiosecurity will lay the foundation for detecting and responding to biological threats. The technology will eventually allow real-time monitoring of potential pathogens, rapid sequence analysis of unknown organisms, and automated threat assessment capabilities. This integration represents a significant advance in our ability to protect against both natural and engineered biological threats. By combining multiple detection technologies with advanced computing capabilities, organizations can achieve unprecedented speed and accuracy in identifying potential biological threats.

REGULATION AND POLICY

REGULATION AND POLICY

Europe: EU AI Act Sets New Global Standard for Biotech Safety

The European Union's comprehensive AI Act has fundamentally reshaped the biotech and health care landscapes, establishing unprecedented requirements for transparency and accountability. Major players like Roche and Siemens Healthcare must now document every AI decision-making process in their medical applications, from diagnostic algorithms to drug discovery models. The regulations require companies to demonstrate how their AI systems avoid bias in genomic analysis and ensure equitable treatment recommendations across diverse populations. Early implementation has revealed significant challenges, with several firms investing heavily to improve compliance infrastructure. The act mandates regular algorithmic audits, particularly for high-risk applications like AI-guided robotic surgery and automated drug dosing systems. Health care providers must maintain detailed records of AI involvement in patient care, while biotech researchers need to document their AI models' training data and decision pathways. Initially, industry leaders reported that these requirements slowed innovation; but now, they are improving system reliability and patient trust.

Europe: New Standards for Bioengineered Food Safety

The European Commission's overhaul of GMO and gene-edited crop regulations establishes the world's most comprehensive framework for bioengineered food safety. The new requirements mandate detailed genetic mapping of all modifications, regardless of technique used, and introduce a novel environmental impact assessment system. Companies must now track potential effects on local ecosystems for five years post-approval, including monitoring the crop's effect on beneficial insects and soil microbiomes. The regulations require food producers to implement labeling systems that provide consumers with complete genetic modification details and cultivation methods. Early implementation has revealed challenges in standardizing testing protocols across EU member states, but has also spurred innovation in environmental monitoring technologies.

Europe: Bold Stance on Human Embryo Research

The European Parliament's proposed framework for human embryo research and gene editing represents a watershed moment in bioethical regulation. The guidelines establish clear boundaries between permitted therapeutic applications and prohibited genetic enhancement, with particular focus on hereditary implications: Somatic gene therapy for specific genetic disorders is allowed, with strict protocols for patient selection and monitoring. Research institutions must now implement comprehensive oversight systems, including mandatory ethics board review for all embryo-related studies. The framework introduces standardized reporting requirements for all embryo research, creating the world's most comprehensive database of outcomes and safety data. Notable provisions include mandatory long-term follow-up studies for any approved therapies and strict controls on international collaboration. While some scientists argue these measures could slow breakthrough treatments, patient advocacy groups largely support the enhanced protections. The regulations have already influenced similar policy discussions in other regions.

China: AI Reshapes Drug Approval Process

China's pharmaceutical landscape is transforming as the country's National Medical Products Administration (NMPA) implements groundbreaking fast-track protocols for AI-designed drugs. This strategic shift aims to accelerate the country's competitive position against Western pharmaceutical giants. Early results show promising outcomes, with three AI-discovered compounds already entering clinical trials. Leading Chinese biotech firm XtalPi has leveraged machine learning algorithms to identify novel drug candidates for treating resistant cancers, reducing discovery time from years to months. Meanwhile, Insilico Medicine's Shanghai facility has developed an AI platform that screens billions of potential molecules daily, significantly

REGULATION AND POLICY

outpacing traditional methods. The expedited review process has attracted major investments, with venture capital flowing to Chinese AI drug discovery startups. However, some experts raise concerns about potential safety risks from accelerated approvals. The NMPA has responded by implementing additional post-market surveillance requirements and establishing a specialized AI drug safety monitoring system. This regulatory evolution marks a significant shift in global pharmaceutical development, potentially reshaping how new drugs reach patients worldwide.

China: DNA Data Protection Laws Signal New Cyberbio Era

Prompted by attempted breaches at three major Chinese genomic research centers, China's new comprehensive cyberbiosecurity framework represents the world's first targeted approach to protecting genetic data in the digital age. The legislation specifically addresses vulnerabilities in DNA sequencing databases, which have become increasingly attractive targets for cybercriminals and foreign intelligence agencies. The new measures require triple-layer encryption for genetic databases, mandatory security audits every six months, and strict access controls for international research collaborations. Chinese biotech giant BGI has already invested more than $100 million to upgrade its security infrastructure to comply with these requirements. The regulations have significant implications for global research partnerships, as foreign institutions must now establish dedicated secure data channels and undergo rigorous security clearance processes. Some international researchers argue these measures could slow scientific progress, but Chinese officials maintain that protecting genetic information is crucial for national security. The framework includes provisions for ethical AI use in genomic research and establishes clear penalties for violations.

US: Tightening Rules on Lab-Grown Meat and Modified Crops

The landscape of food regulation is shifting dramatically as the USDA and FDA implement new rules for bioengineered food products. Consumer advocacy groups have successfully pushed for unprecedented transparency in labeling and production methods. The regulations require cultured meat producers to disclose their exact growth medium compositions and gene-edited crop developers to map all genetic modifications. Major players like Upside Foods must now conduct extended shelf-life studies and provide detailed nutritional comparisons with conventional meat products. Notably, companies have to now track product performance through the entire supply chain, from lab to table. The rules establish a new certification process requiring third-party verification of safety claims and production methods. Environmental impact assessments become mandatory, examining everything from water usage in cell culture to energy consumption in bioreactors. Some smaller startups argue these requirements create significant market barriers, but industry leaders acknowledge their necessity for building public trust. The regulations have already influenced international standards, with several countries adopting similar frameworks for biotech food oversight.

US: CRISPR Human Trials Enter New Era of Safety Protocols

The NIH and FDA's approach to CRISPR-based human gene therapy oversight now include long-term patient tracking, extending up to 15 years post-treatment for certain genetic modifications. Research centers must now establish dedicated genetic monitoring facilities and maintain detailed mutation databases for each trial participant. The regulations introduce a tiered risk assessment system. Major medical centers have already begun expanding their genetic surveillance capabilities, with leading institutions investing in advanced sequencing technologies for continuous monitoring. The protocols mandate regular whole-genome sequencing to detect any off-target effects, creating the world's most comprehensive database of gene editing outcomes.

ETHICS, TRUST, AND ACCEPTANCE

ETHICS, TRUST, AND ACCEPTANCE

Regulating Human Gene Editing Intensifies

Governments worldwide are tightening regulations on CRISPR and germline editing, especially following concerns over designer babies and unauthorized genetic experiments. In 2025, organizations like the World Health Organization (WHO) and National Academies of Sciences are supposed to mandate stricter oversight, ensuring scientific transparency, informed consent, and long-term safety evaluations. New policies focus on balancing therapeutic gene editing—such as for sickle cell disease and inherited blindness—while restricting non-essential modifications. Meanwhile, governments in China, the US, and the European Union are aligning regulations to prevent loopholes that could lead to unethical practices. Public trust in gene editing is also influencing policy, with increased demands for independent review boards and bioethics committees to oversee research. As clinical trials expand, governments will need to address concerns about off-target effects, unintended genetic consequences, and the potential commercialization of human traits.

AI Ethics in Biomedicine Becomes a Priority

AI is transforming drug discovery, diagnostics, and genetic research, but ethical concerns about bias, data privacy, and transparency are growing. AI-driven systems often rely on biased datasets, leading to disparities in disease predictions and treatment recommendations, particularly for underrepresented populations. In 2025, regulatory bodies like the FDA, EU AI Act, and WHO have indicated they will implement stricter ethical frameworks to ensure fairness, accountability, and explainability in AI health care applications. Companies like Google DeepMind, IBM Watson Health, and others are under pressure to disclose AI decision-making processes, preventing misdiagnoses and discrimination in personalized medicine. Meanwhile, patient data privacy is a top concern, as hospitals and biotech firms increasingly use AI-driven genetic analysis. Governments are requiring stronger encryption, consent-based data sharing, and AI auditing protocols to maintain public trust. The push for human-in-the-loop AI, where human experts validate AI-generated decisions, is gaining momentum to prevent overreliance on algorithms in life-or-death scenarios.

Biotechnology Access Equity Becomes a Global Issue

Breakthroughs in gene therapy, regenerative medicine, and bioprinting are widening health care inequalities, with wealthy nations accessing cutting-edge treatments while poorer regions struggle. In 2025, global organizations like the WHO, Gates Foundation, and World Bank will push for biotech equity policies, ensuring that life-saving innovations reach underprivileged communities. Personalized gene therapies for cancer, rare diseases, and inherited disorders remain prohibitively expensive, sparking debates about pricing, patent monopolies, and fair distribution. Nations with strong biotech industries—such as the US, China, and Germany—are facing pressure to lower costs and support international access to breakthrough therapies. Meanwhile, companies like CRISPR Therapeutics and Vertex Pharmaceuticals are exploring tiered pricing models and generic alternatives to make treatments more affordable. The conversation is also shifting toward bioprinted organs, which could improve transplant medicine but risk becoming exclusive to the wealthy if pricing remains high. Some governments are introducing subsidy programs and ethical guidelines to ensure that biotechnology advances serve all populations, not just those who can afford them.

Resolving Bias in Genome Research

Overwhelmingly, the majority of people who have had their genomes sequenced come from affluent Caucasian Americans and Europeans; fewer than 2% are from Africa. This excludes an enormous number of people from the benefits of genetic research, so there is now increased attention and funding to diversify this pool. H3Africa works with African investigators to determine genomic and environmental determinants of common diseases. The Non-Communicable Diseases Genetic

ETHICS, TRUST, AND ACCEPTANCE

Heritage Study consortium, based in Nigeria, is creating a comprehensive catalog of human genetic variation among Nigerians. A decade-long Three Million African Genomes project is also underway to locate missing genetic variants from ancestral genomes in Africa. It would build an African biobank of clinical information and could lead to a more equitable future of genetic research.

Calls For Responsible Gene Editing

In 2018, Chinese scientist He Jiankui caused a global uproar by announcing he had created the world's first gene-edited children using CRISPR technology, targeting embryos to make them resistant to HIV. This led to the birth of twins, marking a controversial milestone in genetic editing. He's actions, deemed "illegal medical practices" in China, resulted in a three-year prison sentence for him and his two associates, partly because the genetic alterations could be passed down to future generations. Following the scandal, China tightened regulations on human gene editing and banned He from conducting any reproductive technology services. Despite these restrictions, late in 2023, He proposed a new study focused on editing mouse and human embryos to investigate potential protection against Alzheimer's disease, citing the urgent need to address the challenges posed by an aging population and the current lack of effective treatments for Alzheimer's. This latest proposal's reception remains mixed, reflecting ongoing dilemmas over the boundaries of genetic research, but has reignited ethical debates and concerns within the scientific community. A dozen countries have now banned germ line engineering in humans, though their ranks do not include China, which tightened regulations without banning the practice outright. Federal law in the US regulates the use of federal funds for research on human germline gene therapy––though these laws are notoriously politicized and have changed a few times in the past decade. The EU's Convention on Human Rights and Biomedicine said tampering with the gene pool would be a crime against human dignity and human rights. But all those declarations were made before it was actually possible to precisely engineer the germ line. Now, with CRISPR, it is possible.

Engineering Super Soldiers

A team of military medical scientists in China reported that they have enhanced human embryonic stem cells' resistance to radiation by inserting a gene from the water bear, a microorganism known for its extreme survival skills. Using CRISPR technology, they found they could get a high percentage of the modified cells to survive under lethal radiation exposure. The research, led by professor Yue Wen at the Academy of Military Sciences in Beijing, has sparked interest (read: alarm) since its publication, because of the implication: What if this is used to create a new version of superhumans, capable of surviving extreme conditions like nuclear fallout? Scientists around the world raised concerns about the safety and ethical implications of transferring genes across species, with

ETHICS, TRUST, AND ACCEPTANCE

the risk of harmful mutations or unknown immune responses. The team plans to further their research by transforming these modified cells into blood-making cells to help humans survive acute radiation sickness, suggesting additional benefits in protecting against diseases such as cancer and diabetes. The experiment was deemed legal as it was conducted on cultured cell lines in a lab. But what happens when that research is ready to leave the lab for the real world?

Concern Grows Over Genetic Data Ownership

As genetic testing becomes mainstream, concerns over DNA data privacy and ownership are intensifying. Consumers who used 23andMe, Ancestry.com, and other genetic services are learning that their DNA data is often monetized, shared with third parties, or used for pharmaceutical research without explicit consent. In 2025, some governments will implement stricter regulations to give individuals greater control over how their genetic information is stored, accessed, and shared. New privacy laws and opt-in data-sharing policies are being introduced, forcing companies to provide clearer consent mechanisms and allow users to request the deletion of their genetic data. Additionally, blockchain-based genomic storage solutions are emerging as an alternative, offering decentralized and encrypted storage of genetic data to prevent misuse—though it could take a few years for these systems to come online. Concerns over law enforcement access to private DNA databases are also growing, with public outcry against cases where genetic databases were used for criminal investigations without user consent.

Misinformation Challenges Scientific Progress

The rapid advancement of gene editing, synthetic biology, and vaccine technologies has led to a surge in misinformation, conspiracy theories, and public distrust. Social media platforms have become breeding grounds for misleading claims about CRISPR, mRNA vaccines, lab-grown meat, and AI-driven health care, causing confusion and resistance to new scientific breakthroughs. This will only get worse in 2025, now that the platforms have announced they will no longer fact-check content. Biotech companies and research institutions are attempting to combat misinformation through improved direct public engagement, educational campaigns, and transparent data-sharing initiatives—but they will face competition from influencers whose voices cut through the noise and are amplified by algorithms. As misinformation remains one of the biggest barriers to public trust in biotechnology, the fight for scientific literacy and evidence-based communication is becoming a global priority for researchers, policymakers, and industry leaders.

SCENARIO YEAR 2035

ENHANCED CEOS RESULT IN CORPORATE CRISIS

The quarterly board meeting at Global Dynamics Corporation unfolds in tense silence. The CEO's genetic enhancements for cognitive processing and reduced sleep requirements just became public knowledge. She now faces growing pressure from "natural" board members to resign—even though everyone had already suspected she was dosing. Just like the Ozempic craze a decade earlier, wealthy people are quietly taking modified viruses to deliver personalized genetic changes. This latest controversy emerged after leaked medical records revealed that 40% of Fortune 500 executives are secretly using enhancements, sparking fierce debate about competitive fairness. Enhanced executives, who can process complex data streams in real time and operate on just two hours of sleep, are delivering unprecedented results. But is it legal? US Congress has been debating the Corporate Enhancement Disclosure Act, which would require public companies to report the percentage of enhanced individuals in leadership positions. The situation at Global Dynamics mirrors a broader societal rift, as genetic enhancement technologies, once limited to medical applications, have become widely available through both legal and gray-market channels. With some executive enhancement packages now costing less than an MBA, traditional paths to corporate leadership are being upended, forcing companies to face questions of merit, fairness, and human potential in an age where "natural ability" has lost its meaning.

EMERGING APPLICATIONS

Application: New Materials

Lab-Grown Wood Could Disrupt $600B Timber Industry

Biotech startup New Dawn Bio has achieved a breakthrough in cellular agriculture, successfully creating the world's first viable specimen of lab-grown wood. Using stem cells from Arabidopsis thaliana, researchers have developed a process that mimics natural wood formation in controlled laboratory conditions. The technology involves cultivating plant stem cells in nutrient-rich solutions where they grow significantly faster than in nature, then triggering their transformation into structural fiber and vessel cells—the key components of wood tissue. While the current prototype is smaller than a postage stamp, the team is already scaling up production and experimenting with tropical hardwood varieties like teak. The implications for the $600 billion global timber industry are significant, particularly for rare and endangered wood species. By potentially offering a sustainable alternative to logging which threatened tropical hardwoods, cultured wood could disrupt traditional forestry while enabling unprecedented control over wood properties. The team envisions creating custom wood products with enhanced strength, modified grain patterns, or improved absorption characteristics. However, challenges remain: The lab-grown material doesn't yet match natural wood's mechanical properties, and some experts question whether the cells are forming proper biological connections. Despite skepticism, venture capital is flowing into the sector, with investors betting that lab-grown wood could follow cultivated meat's path to commercialization.

Silk Thread That Powers Up: Smart Textiles Enter New Era

Swedish researchers have achieved a breakthrough in wearable technology with a new conductive silk thread that could transform everyday clothing into power generators. The team at Chalmers University of Technology has developed an organic polymer-coated silk that conducts electricity without using metals, marking a significant advance in thermoelectric textiles. The innovation allows fabric to convert body heat into electrical energy, potentially eliminating the need for batteries in health monitoring devices and mobile phones. In testing, a fabric sample generated 6 millivolts from a 30-degree Celsius temperature difference—enough to power small sensors when combined with a voltage converter. The material shows remarkable durability, retaining two-thirds of its conductivity after seven wash cycles, though researchers acknowledge this needs improvement for commercial viability. What sets this development apart is its use of nontoxic, carbon-based polymers instead of rare earth metals, making it both sustainable and safe for skin contact. While current production requires painstaking manual work—a demonstration piece took four days of hand-sewing—researchers are confident about scaling up through automation. Major fashion brands are already expressing interest, recognizing the potential to integrate health monitoring and device charging capabilities into everyday garments. The technology could transform sectors from health care to consumer electronics, though mass production challenges remain.

Self-Healing Concrete Uses Bacteria to Repair Damage

A new approach to concrete infrastructure maintenance is gaining traction, as researchers demonstrate the effectiveness of bacterial-induced self-healing in concrete structures. The technology harnesses specific strains of bacteria that produce calcium carbonate, naturally filling cracks up to 0.46 mm wide, which is four times more effective than traditional self-healing methods. The process works through bacterial mineralization, where microorganisms decompose urea and calcium to create a natural concrete patch. Initial studies show remarkable results: porosity reduction of up to 50%, compressive strength increases of 42%, and flexural strength improvements of 72%. In short: way better than normal concrete. The innovation addresses a critical infrastructure challenge, particularly relevant as nearly half of US bridges are more than 50 years old and require more than $100 billion in repairs. While traditional concrete repair methods often face issues with delamination and cost-effectiveness, this biological approach offers a more sustainable solution. The technology can be implemented through direct bacterial addition to concrete mixtures, encapsulation for delayed activation, or surface application to existing structures. However, success depends critically on maintaining bacterial viability and proper environmental conditions.

Engineered Fungi Create Fire-Safe Building Materials

Australian researchers have developed a groundbreaking fire-retardant material using modified mycelium—the root network of mushrooms—that could improve building safety and sustainable packaging. The RMIT University team has created ultrathin protective sheets that respond intelligently to fire, releasing water vapor and CO2 while forming a flame-blocking carbonaceous barrier. Unlike traditional fire retardants such as asbestos, which can release harmful particles, these biological sheets are both safe and effective. The innovation leverages synthetic biology to grow protective mats just millimeters thick that can be integrated into various building materials. Meanwhile, commercial applications are already emerging, like the "Mushroom Packaging" from New York's Ecovative Design. The product uses similar mycelium technology, transforming agricultural waste into a moldable, durable styrofoam alternative without water, light, or chemicals.The material is fully compostable and can be grown to precise specifications in just 5–7 days.

Plastics Made From Algae Break Down Naturally

Researchers at the University of California, San Diego achieved a breakthrough in biodegradable plastics with a new polyurethane material that genuinely breaks down in natural environments. Unlike conventional plastics that fragment into harmful microplastics, this bio-based polymer becomes a feast for bacteria, completely decomposing through natural processes. The team demonstrated the material's properties by creating real-world products including phone cases and textile coatings, then documented their decomposition through advanced microscopy. What sets this innovation apart is the identification of specific bacterial strains that can use the material as their sole food source, ensuring complete biodegradation wherever these common microorganisms are present. The technology represents a potential solution to the growing microplastics crisis, which has contaminated ecosystems worldwide. Working with materials company Algenesis, the researchers have proven the material's commercial viability through successful product prototypes. Scanning electron microscopy reveals significant biofilm formation during breakdown, confirming that natural bacterial communities readily colonize and digest the material.

SCENARIO YEAR 2040

THE GRAY GOO CATASTROPHE

What began as humanity's greatest environmental triumph has morphed into its most terrifying technological disaster. Self-replicating nanobots, deployed in 2040 to eliminate ocean plastic pollution, had exceeded all expectations, clearing 60% of marine waste and rejuvenating damaged ecosystems within five years. The breakthrough seemed to herald a new era of environmental restoration—until a mutation in the nanobots' core programming bypassed their termination protocols. The biological machines began consuming all hydrocarbon-based materials indiscriminately, their appetite extending far beyond their intended plastic targets. The crisis escalated silently at first, manifesting in mysterious infrastructure failures: dissolving pipelines, crumbling synthetic materials, and deteriorating medical implants. When passenger aircraft began reporting catastrophic polymer degradation and power grids failed as transmission cables disintegrated, global panic ensued. The media-dubbed "Gray Goo Catastrophe" forced an unprecedented technological counteroffensive, with nations deploying massive electromagnetic pulse networks and advanced hunter-killer nanobots to contain the swarms. The nanobots had solved the plastic crisis perfectly—by threatening to eliminate all human technology that could create it.

Application: Food, Beverages, and Agriculture

Lab Creates Rice-Beef Hybrid

South Korean scientists have developed a food fusion that could transform sustainable protein production: rice grains infused with lab-grown beef cells. The Yonsei University team's hybrid food has 7% more protein and 8% more fat than conventional rice. Unlike traditional lab-grown meat efforts that struggle to replicate meat's complex structure, this approach uses rice grains as a natural scaffold for cow muscle cells to grow throughout. The process, which takes just 5–7 days, uses fish gelatin as a binding agent and requires no genetic modification. The resulting hybrid can be cooked like regular rice but offers a unique nutty flavor with meaty umami notes. Most significantly, it produces less carbon—100 grams of protein generates only 6 kilograms of CO2, compared to 50 kg for conventional beef. The innovation sidesteps many challenges facing lab-grown meat by using well-known, inexpensive ingredients. While scaling remains the primary challenge, major food companies are already exploring commercial applications. Industry experts suggest this could represent a crucial breakthrough in meeting global protein demands sustainably, particularly in high rice-consuming regions.

Lab-Grown Coffee Brews Up Solution to Deforestation

Scientists have achieved a breakthrough in cellular agriculture by successfully cultivating coffee and tea cells in bioreactors, potentially transforming how we produce these global staples. The innovation involves isolating cells from coffee beans and tea leaves, then growing them in carefully controlled conditions to produce compounds identical to those found in traditionally farmed crops. Early taste tests show the lab-grown products closely match the complex flavor profiles of their conventional counterparts. The technology could dramatically reduce the environmental impact of coffee and tea production. Traditional coffee farming drives 250,000 acres of deforestation annually, while tea cultivation often leads to soil erosion and water stress in sensitive ecosystems. The bioreactor approach requires 95% less water and eliminates the need for pesticides, while producing year-round regardless of climate conditions. Several biotech startups have already secured significant funding to scale production, with the first commercial products expected by 2026. Who knows? In the future you might grow, roast, grind, and brew coffee—all in your own home.

Smart Drinks Merge Hydration with Brain and Gut Benefits

The beverage industry is experiencing a paradigm shift as functional hydration products combine traditional electrolyte replacement with advanced bioactive compounds. Leading brands are launching drinks that go beyond basic hydration, incorporating adaptogens like ashwagandha and rhodiola for stress management, nootropics such as L-theanine and lion's mane mushroom for cognitive enhancement, and specialized probiotic strains for digestive health. The innovation comes in response to consumer demand for beverages that multitask—hydrating while supporting mental performance, stress resilience, and gut health. Consumers are particularly drawn to products featuring clinically studied ingredients like specific probiotic strains, which have been proven to survive the digestive tract. The trend has sparked a wave of startup activity, with companies launching more than 200 new functional beverage brands in the past year. Retailers are responding by creating dedicated shelf space for these premium products.

Precision Fermentation

A centuries-old brewing technology is getting an update that could transform food production. Major food giants including Nestle, Danone, and Unilever are investing heavily in precision fermentation platforms that combine genome sequencing and gene editing to create custom-designed microbes. These engineered microorganisms, when fed into precisely controlled fermenters, can produce everything from synthetic palm oil to dairy-free cheese proteins that are molecularly identical to their animal-derived counterparts. The technology offers a solution to multiple challenges facing the food industry: growing demand for vegan products, supply chain vulnerabilities due to climate change, and the need for more sustainable production methods. Unlike traditional fermentation, this precision approach allows companies to produce specific proteins, fats, and stabilizers with unprecedented efficiency. Early applications are already appearing in plant-based meat alternatives, where fermentation-derived proteins provide authentic taste and texture.

Brewing Great Nonalcoholic Beers

A Danish biotech startup has cracked one of brewing's biggest challenges: creating non-alcoholic beer that actually tastes like the real thing. EvodiaBio's approach uses engineered baker's yeast cells as microscopic factories to produce the exact aromatic compounds (monoterpenoids) that give beer its distinctive hoppy flavor. The innovation solves a longstanding problem in nonalcoholic brewing, where traditional methods of either halting fermentation or removing alcohol typically strip away the crucial hop aromas that beer lovers crave. Beyond improving taste, the technology offers significant environmental benefits: Traditional hop farming requires 2.7 tons of water per kilogram of hops and relies on energy-intensive cold chain transportation across continents. By producing these compounds in fermenters, the process eliminates dependence on water-intensive hop cultivation and reduces transportation emissions. The timing is perfect, as consumer demand for nonalcoholic alternatives soars.

Faster-Growing Trees

University of Georgia researchers have achieved a remarkable breakthrough in tree genetics: Using CRISPR technology, they edited a flower repressor gene to reduce poplar tree flowering time from 10 years to just three months. This acceleration of natural processes could upgrade forestry by dramatically speeding up tree breeding programs, allowing rapid development of varieties resistant to climate change stresses like extreme heat, drought, and cold. The technology arrives at a crucial time as forests worldwide face unprecedented environmental pressures. Major timber companies are already exploring applications to develop climate-resilient tree varieties, while conservation groups see potential for rapid restoration of damaged ecosystems. The breakthrough could transform everything from commercial forestry to urban landscaping, enabling quick adaptation to changing environmental conditions.

More Fertile Soil

Agricultural technology company Pivot Bio has developed a groundbreaking approach to crop nutrition that could transform farming's environmental impact. The innovation enhances natural soil microbes' ability to deliver nitrogen directly to plants, eliminating the need for synthetic fertilizers that contribute to pollution and climate change. Unlike conventional fertilizers that easily wash away or evaporate, these enhanced microbes provide steady nutrition throughout the growing season. The technology works by optimizing existing soil bacteria without introducing foreign genetic material, addressing both environmental and regulatory concerns. Early field trials show consistent crop yields while reducing nitrogen runoff and cutting greenhouse gas emissions significantly.

Smart Pesticides Use RNA to Target Pests

Researchers have developed RNA-based pesticides that act like molecular smart bombs, eliminating harmful insects while leaving beneficial species unharmed. The technology, known as RNA interference (RNAi), works by delivering specific genetic instructions that disrupt vital processes only in target pest species. Unlike broad-spectrum chemical pesticides that can devastate entire insect populations and persist in the environment, these RNA molecules decompose naturally within days. The innovation comes as regulators in some countries are tightening restrictions on traditional chemical pesticides due to mounting evidence of ecosystem damage and human health risks. The precision of RNAi allows farmers to protect crops from specific pests without disrupting natural predator populations that help control other harmful insects.

Regenerative Farming Goes Mainstream

Regenerative agriculture includes farming and grazing practices that rebuild soil organic matter and restore degraded soil biodiversity. There's a clear need for this technology-led practice: Soil is depleted from decades of using chemicals, salt-based fertilizers, carbon mining, and harsh insecticides. Planting multiple types of crops together, rotating crops, cutting back on tilling, and reducing reliance on harsh chemicals can revitalize depleted soil, leading to improved yields, nutrient-rich crops, and improved resistance to flooding and drought. In 2017, the Rodale Institute launched the Regenerative Organic Certified program to start creating an official standard. It builds on the USDA certified organic seal by adding soil health, animal welfare, and human rights requirements. General Mills announced that it would accelerate regenerative agriculture by dedicating a million acres of farmland to it by 2030. Meanwhile, several brands, including Patagonia, Timberland, Allbirds, Gucci, and Balenciaga, have launched efforts to promote regenerative agriculture.

CRISPR Modified Livestock

CRISPR is making farmed animals bigger, stronger, and (hopefully) healthier. In hopes of boosting their ability to resist diseases, researchers at Auburn University in Alabama introduced a gene from alligators into catfish; alligators are exceptionally good at warding off infections, and a slight increase in catfish resilience could significantly impact fish farming. Currently, about 40% of fish raised in farms globally don't survive until harvest, so reducing even a fraction of this loss could be transformative. Scientists in Japan used CRISPR to modify the myostatin gene in red sea bream, resulting in fish that are larger and heavier by about 17% compared to nonmodified fish, even though both groups were fed the same quantity of food. Researchers have long experimented with CRISPR on animals, and so far have used it to create super-muscular pigs, cattle, sheep, rabbits, and goats. But most animals did not live past infancy, and, somewhat weirdly, many developed unusually large tongues.

Application: Longevity

Cell Reset Button: Scientists Turn Back Biological Clock

Researchers are creating new methods to reprogram cellular age through epigenetic modification. As we age, while our DNA sequence might stay constant, chemical changes do occur. Observing those changes could lead to new techniques to halt or even reverse age-related disease. Industry leaders Altos Labs and Retro Biosciences are advancing techniques that effectively reset cells to younger states by manipulating specific biological markers that control aging. Early trials show remarkable results: Isolated cells demonstrate characteristics of youth, including improved energy production and enhanced repair capabilities. The technology builds on Nobel Prize–winning research in cellular reprogramming, but with precise control to avoid cancer risks. Beyond simple life extension, the therapy aims to restore cellular function across multiple tissues, potentially reversing age-related conditions from heart disease to cognitive decline.

Removing Zombie Cells

Senescent cells are damaged cells that stop functioning but don't die, accumulating in the body like cellular zombies—and they're linked to aging. But scientists are researching the use of senolytic drugs, which remove these worn-out immune cells, as a way to treat diseases like multiple sclerosis. In MS, the immune system attacks the myelin sheath around nerves, and while it's characterized by phases of relapse and recovery, it can eventually progress into a phase where symptoms continuously worsen without periods of remission. In older animals, myelin damage leads to lots of senescent cells. But when researchers at Georgetown University injected older mice with a toxin to damage myelin and then treated some with senolytic drugs, the treated mice showed a 65% greater increase in a myelin-rebuilding protein compared to untreated mice. This finding indicates that removing senescent cells could improve myelin repair, and could mean that senolytic drugs offer a new treatment strategy for MS, particularly in its progressive stage—if it works as well for humans as it does in mice, which for now is a big if. But if human trials show promising results, it is plausible that senolytic drugs could eventually treat a host of diseases and ailments, along with conditions associated with aging.

Growing Your Own Spare Parts

Biotech companies are making extraordinary progress in developing 3D-printed human tissues and organs, potentially eliminating transplant waiting lists. But what if you could grow your own spare parts anytime you needed? That's the promise: advanced bioprinting techniques with stem cell biology could create functional tissues that perfectly match each patient's genetics. Several firms have already succeeded in printing simpler structures like blood vessels and cartilage, while more complex organs such as kidneys and hearts are in development. Which means that sometime in the future, age-related organ failure could be a thing of the past. So could organ rejuvenation. Is your stomach not working quite like it used to? Print and install a new one.

Growing Blood

For people who live with rare blood types (AB negative, AB positive, B negative) or who have blood disorders, acquiring blood for surgery or a transfusion can mean the difference between life and death. For decades, scientists have attempted to grow blood cells in a lab at scale, but until recently, the process has failed to produce enough blood cells to make an impact. Scientists at the National Health Service Blood and Transplant in the UK announced that they had grown red blood cells in a lab and successfully transfused them into a living person, a world first. It took 500,000 stem cells to generate 50 billion red blood cells, which then needed to develop. (In a healthy adult, 50 billion red blood cells represents about 1% of their total blood volume.) The same researchers also transfused red blood cells that were grown in a lab into another person requiring that blood. This technique is a pioneer in transferring lab-grown cells to another person as a part of a blood transfusion. Going forward, patients who need regular blood transfusions could go longer between treatments. After that, researchers will set their sights on manufacturing lab-grown blood for rare blood types that don't typically have large donor pools.

Growing Sex Cells

In 2023, Dr. Katsuhiko Hayashi from Osaka University successfully created eggs from cells harvested from male mice, with the eventual goal of developing new fertility treatments. The process begins with taking a skin cell from a male mouse and converting it into a stem cell, which has the potential to develop into various cell types. Since these cells are male, they carry XY chromosomes.

The team then removes the Y chromosome, replicates the X chromosome, and combines the two X chromosomes—a modification that enables the stem cell to develop into an egg. Hayashi's work builds on groundbreaking research from fellow Japanese scientist Shinya Yamanaka, who in 2006 showed that it was possible to make gametes derived from human-induced pluripotent stem cells. Yamanaka's process includes harvesting cells from a skin biopsy or blood sample (both quick and relatively painless). Those cells are turned into stem cells, grown in a medium that resembles what would exist in a human womb, and developed into precursor sex cells, which mature into sperm or stem cells. Then, once IVF kicks in, those cells are used to create an embryo. One or more of the healthiest embryos are then implanted into the uterus and, if all goes well, develop into a healthy, viable fetus. The idea is that someday soon, couples suffering from infertility or individuals who desire to have a baby without a partner would have access to a reliable fertility treatment.

Improving Gut Biomes

A mass extinction event is happening right now in our guts and in the environment. The widespread use of antibiotics, along with diets rich in processed foods, have led to a staggering decline of microorganisms inside the people and animals living in wealthy nations. During the past 12,000 years of human evolution, we've shifted nature's balance—our diets are now relatively narrow, compared to our far-distant ancestors. Recently, scientists studied modern hunter-gatherer tribes in Tanzania, Peru, and Venezuela, and found their microbiota had 50% more bacterial species than those in the West today. Unlike those tribes, we no longer hunt and eat wild flora and fauna. Those from wealthier countries now eat very little dietary fiber, a limited variety of fruits and vegetables, and only four species of livestock: sheep, poultry, cattle, and pigs. Worse, widespread use of antibiotics in farm animals—not necessarily to prevent disease but to increase weight gain and therefore the volume of meat available—means that we're ingesting compounds that are helping to destroy our own microbiomes. Humans are complex, composite organisms, made up of layers and layers of cells. Researchers now think that our gut microbiome is directly linked to our metabolism, our immune systems, our central nervous systems, and even the cognitive functions inside our brains. It's an inherited problem: Most of our microbiomes come to us from our mothers as we pass through the birth canal. A number of researchers are now looking at the future of our microbiomes. Vedanta Biosciences is making gut bacteria that can be turned into drugs and counts the Gates Foundation as one of its investors. The American Gastroenterological Association and OpenBiome will track 4,000 patients over 10 years to learn about fecal microbiomes.

mRNA Cancer Vaccines

Early in 2024, the first patient in the UK received a dose of a cancer vaccine as part of a larger clinical trial. Designed to treat solid-state tumor cancers, such as melanoma, this application of immunotherapy harnesses the immune system to fight cancer cells. (To be sure, "vaccine" is a bit confusing here, since most vaccines are designed for prevention, while this treatment is for people who have already developed a tumor.) Called mRNA-4359, the treatment contains a molecule that can relay instructions to cells. It works by directing cells to produce proteins typically found on the surface of solid cancer tumors. Once the cells make these proteins, they are introduced to the immune system, training it to recognize and attack cancer cells. This vaccine is classified as a "universal" cancer vaccine, meaning it is premade and can be administered to patients with certain types of cancer straight from the shelf. In contrast, other mRNA cancer vaccines being developed are customized based on the individual patient's cancer, such as a pancreatic cancer vaccine that uses genetic material from the patient's own tumors for a more personalized approach. Long before they were making Covid vaccines, both Moderna and BioNTech were researching immunotherapies for cancer. After analyzing a tissue sample from a cancerous tumor, the companies ran genetic analyses to develop custom mRNA vaccines, which encode protein-containing mutations unique to the tumor. The immune system uses those instructions to search and destroy similar cells throughout the body, which is similar to how the Covid vaccines work. BioNTech is running clinical trials for personalized vaccines for many cancers, including ovarian cancer, breast cancer, and melanoma. Moderna is developing similar cancer vaccines and announced that its personalized cancer vaccine, when combined with Merck & Co.'s immunotherapy treatment Keytruda, cut recurrence and risk of death of the most deadly skin cancer compared with immunotherapy treatment alone. In the trial, the mRNA vaccine revved up the immune response.

And in February 2025, a groundbreaking clinical trial demonstrated success in treating pancreatic cancer using personalized mRNA vaccines, marking a potential turning point in cancer immunotherapy. The vaccine, called autogene cevumeran, works by training the immune system to recognize and attack cancer-specific mutations, generating long-lived T cells that can survive for decades. In a phase 1 trial combining the vaccine with chemotherapy and immunotherapy, patients who developed vaccine-induced immune responses showed remarkable outcomes. While the nonresponder group's cancer returned within 13.4 months, the median recurrence-free survival for responders hasn't been reached after more than three years. What makes this breakthrough particularly significant is the vaccine's ability to generate T cells with extraordinary longevity (some expected to survive up to 100 years) and maintain their cancer-fighting abilities years after vaccination. The technology shows particular promise for pancreatic ductal adenocarcinoma, one of the deadliest cancers with historically poor treatment options. Major pharmaceutical companies are already investing in similar mRNA vaccine platforms, with multiple trials underway for other difficult-to-treat cancers. Industry experts project this could transform cancer treatment, particularly for aggressive tumors with few current options.

Application: Beauty

Lab-Grown Collagen For Skin Care

Collagen is the most abundant protein in the human body, making up about 30% of all protein and acting as biological scaffolding that provides structure and strength to skin, bones, cartilage, blood vessels, and other tissues. There are at least 28 types of collagen in the body, but 90% of it is Type I (found in skin and bones). Natural collagen production begins declining around age 25, leading to visible signs of aging like wrinkles and sagging skin, along with potential joint stiffness and bone brittleness. Traditionally, collagen is derived by boiling cow hides and bones, a process used across various industries. Startups are now working on collagen cultivation for skin care. Jellatech, a North Carolina–based startup, created a full length, triple helical, bio-identical and functional human collagen made from its proprietary cell line.

Anti-Aging Science Moves Beyond Wrinkles to Cell Repair

A new generation of skin care is emerging that treats aging skin at the cellular level, applying breakthrough findings from longevity research to dermatology. Instead of simply filling wrinkles or boosting collagen, these treatments target fundamental aging mechanisms within skin cells themselves. Leading brands are incorporating sophisticated compounds like NAD+ boosters, which enhance cellular energy production; mitochondrial activators that improve cell power plants' function; and senolytics that clear away aged, damaged cells that promote inflammation. Early clinical studies show remarkable results. Skin treated with these molecular interventions shows improvements not just in appearance but in actual biological markers of cellular age. Major beauty companies are partnering with longevity research labs to develop products that address aging through multiple cellular pathways simultaneously. The approach represents a significant shift from traditional cosmetics, focusing on cellular health rather than surface-level changes. While current treatments cost significantly more than conventional products, rapidly advancing technology is expected to make them more accessible within the next few years.

Beauty Goes Brain-Deep with Mood-Altering Ingredients

The cosmetics industry is researching new kinds of products that work through the skin-brain axis, and can have measurable effects on mood and mental state. These neurocosmetics use scientifically validated ingredients that interact with the nervous system, from stress-reducing neuropeptides to compounds that boost dopamine production when absorbed through the skin. Serums and creams can combine traditional skin care benefits with neurologically active ingredients like GABA modulators for anxiety reduction and beta-endorphin stimulators for improved mood. The products are designed as holistic treatments that work through multiple pathways: direct neural interaction through skin absorption, aromatherapeutic effects via carefully engineered scent profiles, and tactile stimulation through specially developed textures. Skin care startup Selfmade combines skin care products with psychological concepts from attachment theory, promising to enhance emotional stability alongside skin health with a $65 kit. Major beauty brands are following suit, with industry leader Murad explicitly equating skin care with "brain care." The trend reflects a larger cultural moment where wellness and mental health have become central to beauty marketing.

Application: Climate and Sustainability

eDNA Detection

Environmental DNA, or eDNA, is genetic material found in the environment. Feces and fur from animals, as well as hair and saliva from humans are just some of the organic matter found in soil, seawater, snow, and air. As a fish moves through water, it's continuously shedding bits of itself. Likewise, when a cyclist rides on a trail, her sweat, mucus, and dead skin cells wind up mixed into the gravel and dirt. These fragments of nuclear or mitochondrial DNA can reveal invaluable insights about an environment. Scientists from the United States Geological Survey and the Monterey Bay Aquarium Research Institute are developing a new mobile eDNA sampler that can float through rivers and streams, collecting material and detecting pathogens or invasive species autonomously. As the technology advances, eDNA detection will serve as early warning systems for potential outbreaks. But there's another interesting use for eDNA: reconstructing ancient ecosystems. Scientists excavated eDNA from frozen soil in the Arctic desert, and were able to piece together a lost world nearly 2 million years old. The eDNA revealed a coastal forest with conifers, black geese, horseshoe crabs, lemmings, and mastodons—a natural wonderland unlike any in existence today.

Synthetic Trees & Algae-Based CO2 Absorption

Researchers are working to create supercharged versions of nature's carbon dioxide absorbers. Using synthetic biology, scientists are engineering trees with enhanced carbon-fixing abilities and designing algal strains that can capture carbon dioxide up to five times more efficiently than their natural counterparts. The innovations combine gene editing to optimize photosynthesis with structural modifications that increase surface area for CO_2 absorption. Early trials of enhanced algae in controlled environments show promising results, with 1 acre capturing as much carbon as 400 acres of forest. The technology extends beyond living organisms to include engineered biomaterials that mimic and improve upon natural carbon-fixing processes. The approach offers significant advantages over mechanical carbon capture, requiring less energy and potentially self-replicating once deployed. While scaling remains challenging, researchers project that widespread deployment could someday sequester gigatons of CO_2 annually.

Bacteria That Turn Rocks Into Massive Carbon Sponges

An emerging approach to carbon capture harnesses engineered bacteria to accelerate nature's slowest but most permanent carbon storage mechanism: rock weathering. Scientists have developed specialized microorganisms that dramatically speed up the process of converting CO_2 into stable mineral carbonates within rock formations. The technology amplifies a natural process that has helped regulate Earth's climate for millions of years, but at a pace relevant to addressing current climate challenges. Early field trials show the engineered bacteria can increase carbon mineralization rates significantly while requiring minimal energy input and maintenance. The process is particularly promising for deployment in basalt formations, which are abundant worldwide and ideal for carbon storage. Several mining companies are already exploring implementation in their existing operations, potentially turning waste rock into carbon sinks. Unlike other carbon capture methods, mineralization permanently locks CO_2 away in stable form, eliminating concerns about future release.

Better Plastics Recycling

Despite global efforts to recycle plastic products, there are numerous barriers: Consumer-facing plastics come in different varieties, they're often coated with labels or print, and they have colors and other added features. The mess of waste—used iPhone cases, empty shampoo containers, soda bottles—can't be easily managed at scale, so a lot of it piles up. A potential solution is microorganisms like some bacteria and fungi that use special enzymes to break down various types of plastics. But turning plastic into something these microbes can eat isn't as simple as just mixing them together. The plastics need to be pre-damaged by sunlight or chemicals, and the microbes need just the right conditions to do their work. Even so, each type of microbe can only eat certain plastics, and it can take them weeks or months to break down just a small amount. Now, an emerging synthetic biology process offers a new solution. France-based Carbios developed a process using an enzyme that's especially good at breaking down PET plastic into its basic building blocks, making it possible to recycle PET into high-quality new plastic. After improving the enzyme and testing it in an industrial setting, Carbios is now building its first site dedicated to this bio-recycling process. Another development is underway at the University of Texas at Austin, where researchers used a machine learning model to generate novel mutations to natural enzymes that allow bacteria to break down the plastics found in soda bottles and most consumer packaging. The enzyme, called FAST-PETase (functional, active, stable, and tolerant PETase), could operate efficiently and work at an industrial scale. The first real-world application: setting the enzyme loose to clean up landfills.

Engineered Microbes Create Cleaner Textiles

The textile dye industry is undergoing a biological shift as companies harness engineered bacteria and fungi to create vibrant, sustainable colors without toxic chemicals. Traditional synthetic dyes, which contribute 20% of global water pollution, are being replaced by microorganisms that produce pigments through natural fermentation processes. Biotech startups have developed specialized strains of bacteria that create colors ranging from deep indigos to brilliant reds, while novel fungi species produce earth tones and unique patterns. The technology eliminates the need for harsh chemicals and reduces water usage by 90% compared to conventional dyeing methods. Early adopters include major fashion brands, with several launching collections featuring biologically produced colors. Beyond environmental benefits, these living dyes often create richer, more complex hues that are more colorfast than synthetic alternatives. The innovation extends to pattern-making, where programmed organisms can create unique designs through controlled growth patterns.

De-Extincting Lost Species

Woolly mammoths were once a “keystone species,” one that other species in the ecosystem depended on in many ways for stability. They stomped around in herds, knocking down trees and packing down snow layers as they searched for dead grasses to eat, and that helped keep the permafrost layer stable. Once the mammoths and other large grazing animals stopped compacting the snow and eating dead grasses, the ecosystem began to change. The snow melted more easily, which allowed the sun to reach the permafrost. The permafrost layer is now melting at an alarming rate and releasing greenhouse gasses into the atmosphere, which creates a vicious cycle: Hotter temperatures lead to more melting, which releases more gasses, which causes hotter temperatures, and on and on it goes. Researchers are helping to de-extinct the woolly mammoth and other species using synthetic biology techniques. By starting with a fully intact healthy cell from a closely related species and working backward to combine it with genetic fragments from preserved specimens, they could develop a version of the animals that once existed.

Rewilding Barren Terrains

Rewilding is a direct human intervention into nature using technology and science, a holistic approach to conservation that focuses on restoring the natural phenomena of wilderness ecosystems, providing connective corridors between wild spaces, and reintroducing keystone species to their natural habitats. A term coined more than 30 years ago, “rewilding” has gained renewed attention in the past few years as the climate crisis has grown more dire and new technologies have promised to protect and rehabilitate ecosystems. In 2017, researchers plunged into the waters off Lizard Island on the northeastern coast of Australia with some unexpected equipment in tow—a set of underwater loudspeakers. Their destination was a coral reef that had been all but abandoned by a once-thriving population of sea life. The researchers hoped that by broadcasting the telltale sounds of a healthy reef, they might lure back some of its vital inhabitants. Remarkably, it worked. This experiment was a unique instance of rewilding, but there have been others. Four bison were released in a woodland near Canterbury—the hope is that over time, the herbivores will revitalize a stretch of southeast England and allow vegetation to grow again, which should in turn boost biodiversity.

Animals Emerge as Surprise Allies in Carbon Capture Quest

Scientists have discovered that animals play a far more significant role in ecosystem carbon capture than previously believed, challenging long-held assumptions about nature-based climate solutions. Traditional carbon accounting models have largely ignored animals, focusing instead on plants and microbes. However, new research reveals that animals fundamentally rewire ecosystem food webs, creating powerful multiplier effects on carbon sequestration. The breakthrough comes from analyzing how animals interact with plants and microbes, showing they don’t just participate in carbon cycles, they qualitatively change how these cycles function. For example, large herbivores can increase carbon storage by altering plant species composition and enhancing soil carbon retention, while predators create cascading effects that boost ecosystem carbon capture. This discovery suggests current carbon storage estimates for natural ecosystems may be significantly undervalued. The findings have major implications for conservation and climate strategy, suggesting that protecting and restoring animal populations could be a crucial lever in fighting climate change. Leading environmental organizations are already incorporating these insights into ecosystem management plans, while carbon credit markets are developing new methodologies to account for animal-driven carbon capture.

Ancient Arctic Viruses Could Awaken as Permafrost Melts

As if you didn't already have enough to worry about: scientists are raising alarm about a new pandemic threat emerging from the Arctic. Ancient viruses, preserved in permafrost, could be released by climate change and industrial development. Researchers have already isolated "zombie viruses" from Siberian permafrost that remain viable after 48,500 years, including one sample that can still infect single-cell organisms. While current specimens pose no human risk, scientists have detected genomic traces of known human pathogens like poxviruses and herpesviruses in permafrost samples. The threat is accelerating as Arctic warming melts permafrost layers that have remained frozen for hundreds of thousands of years, with the biggest immediate risk coming from planned mining operations that will excavate deep into virus-laden permafrost. Led by geneticists at Aix-Marseille University, researchers are particularly concerned about viruses predating human evolution, against which our immune systems may have no defense. In response, scientists are establishing an Arctic monitoring network with quarantine facilities to contain potential outbreaks. The initiative, coordinated through a university network, aims to detect and isolate cases before they can spread south. Industry experts estimate billions in mining projects could be affected by new safety protocols.

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SELECTED SOURCES

"3D Bioprinting for Regenerative Medicine." 3D Systems. https://www.3dsystems.com/bioprinting.

Abramson, Josh, et al. "Accurate Structure Prediction of Biomolecular Interactions With AlphaFold 3." Nature 630, no. 8016 (June 2024): pp. 493–500. https://doi.org/10.1038/s41586-024-07487-w.

Airhart, Marc and Anita Shiva. "Turbocharging Protein Engineering with AI." The University of Texas at Austin, October 9, 2024. https://cns.utexas.edu/news/features/turbocharging-protein-engineering-ai.

Allemann, Marco N., et al. "Rapid Biodegradation of Microplastics Generated From Bio-Based Thermoplastic Polyurethane." Scientific Reports 14, no. 1 (March 12, 2024): pp. 6036. https://doi.org/10.1038/s41598-024-56492-6.

"AlphaFold 3 Predicts the Structure and Interactions of All of Life's Molecules," Google, May 8, 2024. https://blog.google/technology/ai/google-deepmind-isomorphic-alphafold-3-ai-model/.

Arcas, Blaise Agüera y, et al. "Computational Life: How Well-Formed, Self-Replicating Programs Emerge from Simple Interaction." arXiv, August 2, 2024. https://doi.org/10.48550/arXiv.2406.19108.

"Beam Therapeutics Announces Progress in Hematology and Genetic Disease Franchises and Outlines Key 2025 Anticipated Catalysts." Beam Therapeutics, January 13, 2025. https://investors.beamtx.com/news-releases/news-release-details/beam-therapeutics-announces-progress-hematology-and-genetic/.

Brown, Joshua. "Team Builds First Living Robots—That Can Reproduce." Wyss Institute, November 29, 2021. https://wyss.harvard.edu/news/team-builds-first-living-robots-that-can-reproduce/.

Cai, Anqi, et al. "Endowing Textiles with Self-Repairing Ability Through the Fabrication of Composites with a Bacterial Biofilm." Scientific Reports 13, no. 1 (July 14, 2023): pp. 11389. https://doi.org/10.1038/s41598-023-38501-2.

Chakka, L.R. Jaidev, and Mohammed Maniruzzaman. "Organoid Intelligence: Training Lab-Grown Mini-Brains to Learn and Compute with AI." AAPS Open 11, no. 1 (January 31, 2025): pp. 4. https://doi.org/10.1186/s41120-025-00109-3.

"China to Develop Gene-Editing Tools, New Crop Varieties in Biotech Initiative." Reuters, 14 February 2025, https://www.reuters.com/world/china/chinas-agriculture-ministry-issues-guidelines-promote-biotech-cultivation-2025-02-14/.

"EMA Management Board: Highlights of December 2024 Meeting." European Medicines Agency, December 13, 2024. https://www.ema.europa.eu/en/news/ema-management-board-highlights-december-2024-meeting.

"Enzymatic Recycling." Carbios. https://www.carbios.com/en/enzymatic-recycling/.

Evangelou, Christos. "New Triple-Action CRISPR Technology Enables Simultaneous Gene Activation, Repression, and Deletion in Primary Human T Cells." CRISPR Medicine News, January 27, 2025. https://crisprmedicinenews.com/news/new-triple-action-crispr-technology-enables-simultaneous-gene-activation-repression-and-deletion-i/.

"FDA, USDA, EPA Publish Tool to Help Industry Better Understand GMO Regulations." Food Safety, October 2, 2024. https://www.food-safety.com/articles/9790-fda-usda-epa-publish-tool-to-help-industry-better-understand-gmo-regulations.

"First Seedless Blackberry Developed Using CRISPR Technology." AgDaily, June 13, 2024. https://www.agdaily.com/crops/first-seedless-blackberry-developed-using-crispr-technology/.

"General 1." Epibone. https://www.epibone.com/technology.

"Genome Engineering: CRISPR Frontiers 2025." Cold Springs Harbor Laboratory. https://meetings.cshl.edu/meetings.aspx?meet=CRISPR.

"Graduate Certificate in Generative AI and Large Language Models." Carnegie Mellon University. http://cms-staging.andrew.cmu.edu/online/gai-llm/learn-more/index.html.

Heinrich, Felix, et al. "Genomic Analysis of Three Medieval Parchments from German Monasteries." Scientific Reports 15, no. 1 (January 25, 2025): pp. 3156. https://doi.org/10.1038/s41598-025-86887-y.

"Homepage." BiomX. https://www.biomx.com/.

"Homepage." EvodiaBio. https://evodiabio.com.

"Homepage." Synlogic Therapeutics. https://www.synlogictx.com/.

"Homepage." Viridos, https://www.viridos.com/.

"How Nanopore Sequencing Works." Oxford Nanopore Technologies. https://nanoporetech.com/platform/technology.

"iGEM Competition." iGem. https://competition.igem.org/.

"Intellia Announces Positive Clinical Proof-of-Concept Data for Redosing a CRISPR-Based Therapy With Its Proprietary LNP-Based Delivery Platform." Intellia Therapeutics, June 25, 2024. https://ir.intelliatx.com/news-releases/news-release-details/intellia-announces-positive-clinical-proof-concept-data-redosing.

Jebran, Ahmad-Fawad, et al. "Engineered Heart Muscle Allografts for Heart Repair in Primates and Humans." Nature, January 29, 2025: pp. 1–9. https://doi.org/10.1038/s41586-024-08463-0.

Labrak, Yanis, et al. "BioMistral: A Collection of Open-Source Pretrained Large Language Models for Medical Domains." ArXiv, July 17, 2024. https://doi.org/10.48550/arXiv.2402.10373.

Lu, Hongyuan, et al. "Machine Learning-Aided Engineering of Hydrolases for PET Depolymerization." Nature 604, no. 7907 (April 2022): pp. 662–67. https://doi.org/10.1038/s41586-022-04599-z.

Mallapaty, Smriti. "Human Embryo Models Are Getting More Realistic — Raising Ethical Questions." Nature 633, no. 8029 (September 11, 2024): pp. 268–71. https://doi.org/10.1038/d41586-024-02915-3.

Matavos-Aramyan, Sina. "Addressing the Microplastic Crisis: A Multifaceted Approach to Removal and Regulation." Environmental Advances 17 (October 1, 2024): pp. 100579. https://doi.org/10.1016/j.envadv.2024.100579.

"MinION Portable Nanopore Sequencing Device." Oxford Nanopore Technologies. https://nanoporetech.com/products/sequence/minion.

"Newly Discovered Bacterial Communication System Aids Antimicrobial Resistance." Global MIT (blog), August 3, 2023. http://global.mit.edu/news-stories/newly-discovered-bacterial-communication-system-aids-antimicrobial-resistance/.

"Next Gen Bioprinting : NGB-C for Clinical Use." Poietis Biosystems. https://www.poietis.com/ngb-c/.

Offord, Catherine. "'Google for DNA' Indexes 10% of World's Known Genetic Sequences." Science, June 5, 2024. https://www.science.org/content/article/google-dna-indexes-10-world-s-known-sequence-data.

"Oldest Modern Human Genomes Sequenced." Max Planck Institute for Evolutionary Anthropology, December 12, 2024. https://www.mpg.de/23820703/1204-evan-oldest-modern-human-genomes-sequenced-150495-x.

Ouyang, Alex. "When an Antibiotic Fails: MIT Scientists Are Using AI to Target 'Sleeper' Bacteria," MIT News, April 8, 2024. https://news.mit.edu/2024/mit-scientists-are-using-artificial-intelligence-target-sleeper-bacteria-0408.

Park, Sohyeon, et al. "Rice Grains Integrated With Animal Cells: A Shortcut to a Sustainable Food System." Matter 7, no. 3 (March 6, 2024): pp. 1292–1313. https://doi.org/10.1016/j.matt.2024.01.015.

Pulkkis, Nina. "Self-Repairing Materials." Finnish Bioindustries, February 25, 2024. https://www.suomenbioteollisuus.fi/post/self-repairing-materials.

Reilly, Elizabeth P., et al. "Motifs to Models: Leveraging Biological Circuits Toward Novel Computational Substrates." Johns Hopkins APL Technical Digest 35, no. 4 (2021).

Renz, Peter F., et al. "In Vivo Single-Cell CRISPR Uncovers Distinct TNF Programmes in Tumour Evolution." Nature 632, 419–428 (2024). https://doi.org/10.1038/s41586-024-07663-y.

"Research." MIT Media Lab. https://www.media.mit.edu/research/.

Rizzuto, Matteo, et al. "Rewiring the Carbon Cycle: A Theoretical Framework for Animal-Driven Ecosystem Carbon Sequestration." Journal of Geophysical Research: Biogeosciences 129, no. 4 (2024): e2024JG008026. https://doi.org/10.1029/2024JG008026.

Shahbazi, Marta N., and Vincent Pasque. "Early Human Development and Stem Cell-Based Human Embryo Models." Cell Stem Cell 31, no. 10 (3 October 2024): pp. 1398–1418. https://doi.org/10.1016/j.stem.2024.09.002.

Silver, Mike. "Scientists Build Tiny Biological Robots from Human Cells." Tufts Now, November 30, 2023. https://now.tufts.edu/2023/11/30/scientists-build-tiny-biological-robots-human-cells.

Sümer, Arev P., et al. "Earliest Modern Human Genomes Constrain Timing of Neanderthal Admixture." Nature 638, no. 8051 (February 2025): pp. 711–17. https://doi.org/10.1038/s41586-024-08420-x.

Swenson, Kelsey, et al. "A Way Forward for Phage Therapy in the United States." Georgetown Medical Review 8, no. 1 (20 June 2024). https://doi.org/10.52504/001c.117696.

"Synthetic Biology." MIT Department of Biological Engineering. https://be.mit.edu/research/synthetic-biology/.

"The Silk Thread That Can Turn Clothes into Charging Stations." Chalmers University of Technology, October 31, 2024. https://www.chalmers.se/en/current/news/k-the-silk-thread-that-can-turn-clothes-into-charging-stations/.

United States, Food and Drug Administration. “Human Gene Therapy Products Incorporating Human Genome Editing.” FDA, August 9, 2024. https://www.fda.gov/regulatory-information/search-fda-guidance-documents/human-gene-therapy-products-incorporating-human-genome-editing.

United States, Food and Drug Administration. “Optimizing Pregnancy Registries; Public Workshop,” 90 Fed. Reg. 5898 (January 17, 2025). https://www.federalregister.gov/documents/2025/01/17/2025-01164/optimizing-pregnancy-registries-public-workshop.

Yip, Aaron, et al. “Degradation of Polyethylene Terephthalate (PET) Plastics by Wastewater Bacteria Engineered via Conjugation.” Microbial Biotechnology 17, issue 9 (September 2024). https://enviromicro-journals.onlinelibrary.wiley.com/doi/full/10.1111/1751-7915.70015.

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