European Commission

Technology Foresight Brief

HEALING THE FUTURE

Horizon scanning for emerging technologies and breakthrough innovations in the field of cell and gene therapies

HIGHLIGHTS

→ This **Horizon Scanning** exercise was developed to support **European Innovation Council Strategic Intelligence** in the **field of health and biotechnology**, with a specific focus on **cell and gene therapies**.

→ **Seven topics** were prioritised by workshop participants: in vivo gene therapy; microphysiological pre-clinical models; stem cells in multiple applications; new tools for advanced tissue delivery; *in silico* & AI; conversion of tumour cells; and emerging genome and epigenome-based therapies.

→ **Several contextual factors** for the development of the health and biotechnology field were highlighted across the following domains: competitiveness and geopolitics; talent and expertise; cross-border and cross-sector collaboration; funding, economic and market conditions; regulatory, safety and ethical challenges; health and RDI ecosystems; and infrastructure and manufacturing.

→ **Horizon Scanning** is a qualitative foresight method, aiming at the early discovery of developments not yet on the radar of most experts.

INTRODUCTION

Project context

This brief reports on the conclusions of a Horizon Scanning exercise developed in the context of FUTURINNOV (FUTURe-oriented identification and assessment of emerging technologies and breakthrough INNOVation), a collaboration between the European Commission's (EC) Joint Research Centre (JRC) and the European Innovation Council (EIC), the EC's flagship program for deep tech, implemented by the European Innovation Council and SMEs Executive Agency (EISMEA).

Joint Research Centre

FUTURINNOV was designed to support the EIC in building strategic intelligence capacity through foresight and other anticipatory approaches. It supports activities focused on funding targets, programme design, policy feedback, and institutional governance.

The outcomes of this exercise may be used to inform future funding topics for EIC Challenges and other EC calls. They can also provide input for EIC and EC reports, as well as supporting other EU policy-making initiatives.

Methodology

Horizon Scanning is a qualitative foresight method which is aimed at the early discovery of developments not yet on the radar of most experts, decision makers, or the general public, and whose potential is not widely recognised. It is not a predictive tool, rather it encourages the exploration of novelties that offer opportunities and challenges in the medium or long-term. [1, 2, 3]

FUTURINNOV includes a series of thematic Horizon Scanning workshops that follow a tailor-made approach to this methodology. It uses a participatory detection, clustering, and sense-making process for signals, trends and contextual factors related to emerging technologies and breakthrough innovations. Each workshop is dedicated to a specific EIC Programme Manager's portfolio, or a domain deemed of interest by the EIC.

Trends and signals[1] are captured through a series of participatory exercises preceded by qualitative desk research and data and text mining. They originate from a diversity of sources, ranging from scientific publications, patents and previously funded projects to institutional websites, news, online articles, and other media.

During each workshop, through a specific methodology composed of several analytical and selection steps, participants converge on a priority list of topics. The criteria for this selection include relevance to the exercise's scope, potential impact, and overall novelty across all technology readiness levels. The final topics include technologies and innovations, as well as relevant contextual factors for their development and uptake. [2]

This brief refers to a specific workshop held online on 15 May 2025 with a focus on cell and gene therapies. It was held with a group of selected experts from academia, research and technology, business, venture capital and policy-making organisations. This diversity of institutional backgrounds, as well as various fields of specific expertise, was key to bringing different perspectives to the conversation. The resulting collective intelligence helped to build significant insights around the topics at hand.[2]

Scope and policy context

Health biotechnology is one of the established portfolios within the EIC. For this workshop, cell and gene therapies were selected as the main focus, as they represent a revolutionary advance in medicine, offering the potential to tackle previously untreatable diseases by targeting their root causes.

Considering the maturity of the field, with multiple products already authorised for use, this exercise focused on breakthroughs along the entire value chain that can increase patients' access to therapies. These include therapeutic approaches themselves and also preclinical models and manufacturing for cell and gene therapies, and developments in adapting these therapies for different diseases and organs.

The health biotechnology domain is high on policy agendas. The recent Draghi report recommended increasing and focusing public Research, Development and Innovation (RDI) investment on the field, particularly in life sciences for advanced therapy medicinal products (ATMPs). [4]

The Biotech Act was announced as part of the current European Commission's political guidelines, with the aim of reducing regulatory fragmentation, simplifying processes, and shortening time to market for innovations.

Two other important initiatives for this field are included in the political guidelines: the recently published strategy for European Life Sciences and the, upcoming, Innovation Act that will focus on

[1] The understanding of what constitutes a signal or a trend may vary [65, 66]. As it is not yet consensual, for the purposes of this project both are relevant and understood as tangible manifestations of novelty in science, technology, innovation and other fields. They can cover different maturity levels from basic research to commercial readiness. Although often used interchangeably, a signal is less consolidated than a trend.

[2] For this exercise, a longlist of 205 trends and signals was compiled and assessed by the JRC and the EIC for their relevance to the workshop's scope and objectives. The list was subsequently narrowed down to a shortlist of 73 and shared in advance with participants. During the workshop, attendees discussed the contents of the shortlist, added new topics considered relevant and previously overlooked, grouped and connected related issues, and ultimately converged on a final list of topics, summarised in this report.

tackling regulatory fragmentation and simplifying hurdles for startups and scale-ups. [5, 6, 7]

The EC has put forward several other policy initiatives on biotechnology and health. These include: the EU4Health program aiming to strengthen EU health systems and crisis preparedness [8]; the European health data space regulation (EHDS), the first common EU data space dedicated to a specific sector [9]; and the health technology assessment (HTA) regulation to improve the availability for patients of innovative technologies [10].

Quick guide

This brief is organised in 3 sections:

- **trends and signals** on technologies and innovations;
- **contextual factors**, covering drivers, enablers and barriers related with their development and uptake;
- **conclusions** providing complementary insights and overarching analysis.

TRENDS AND SIGNALS

The following trends and signals were deemed as the most relevant by the workshop participants. "*In vivo* gene therapy" (see box 1) was selected by more than half of participants as top final topic and a wildcard[3].

Box 1: *In vivo* gene therapy

Gene therapy is rapidly evolving, with a shift from *ex vivo* techniques to *in vivo* delivery of therapies, directly targeting therapy-relevant cells throughout the body.

A key innovation is the development of engineered viral and non-viral vectors capable of recognising specific cell surface markers, significantly improving biodistribution and delivery precision. Clinically, this has been exemplified using T-cell targeted vectors in delivering CAR T-cells[4] for cancer immunotherapy.

Beyond oncology, the approach shows promise in treating genetic disorders and in regenerative medicine by delivering therapeutic agents directly to affected cells or tissues. The opportunities include enhanced treatment precision, broader disease applicability, less invasive treatment delivery, reduced cost, increased access, and the potential for entirely new therapeutic approaches.

However, technical complexity, safety concerns regarding off-target effects (toxicity), and regulatory hurdles remain significant challenges. Continued innovation and careful validation will be essential to fully realise the benefits of *in vivo* gene therapy.

[11, 12]

Microphysiological pre-clinical models

Microphysiological systems (MPS) hold the potential to transform biotechnology by providing efficient human-relevant pre-clinical models for basic research, drug development, and personalised medicine.

MPS are advanced *in vitro* models—such as organ-on-chip, organoids, or induced pluripotent stem cells—that reflect the structure and function of human tissues or organs. MPS can reduce reliance on animal testing and improve the predictability of clinical outcomes by providing human-relevant data for studying disease mechanisms, drug responses, and toxicological effects. Additionally, MPS can accelerate drug development and reduce costs.

An example of MPS with a potential use in disease modelling and regenerative medicine are skin organoids. They are derived from human pluripotent stem cells and can self-assemble into complex skin structures with functional features like hair follicles and innervation, offering new avenues to support therapeutic development.

Another example in gene therapy safety improvement is a dual-chamber bioreactor system that enables detailed *in vitro* assessment of tumorigenicity in gene-edited haematopoietic[5] stem cells.

The EU's *in vitro* biotechnology sector is rapidly advancing the development of novel MPS with applicability for cell and gene therapies, supported by other complementary technologies such as 3D bioprinting. Through their continuous development,

[3] Workshop participants were asked to classify one signal as a wild card. In foresight a wild card is an event or development that bears a higher potentially disruptive impact than a normal signal.

[4] CAR T-cell therapy (Chimeric Antigen Receptor T-cell therapy) is a form of immunotherapy that uses a patient's own immune cells to fight cancer.

[5] Haematopoietic commonly describes the process of stem cells in bone marrow generating all blood cell types, essential for immunity, oxygen transport, and clotting.

these technologies may also contribute to novel, innovation-friendly regulatory frameworks that recognise advanced, human-relevant models and incentivise the reduction of animal testing, while also providing alternative approaches to safety and efficacy assessment.

This transition could enhance the EU's global competitiveness while promoting more sustainable and ethical RDI practices, although challenges remain in standardisation, overall trust, and adoption.

[13, 14, 15, 16, 17, 18, 19, 20, 21, 22]

Stem cells in multiple applications

Research in stem cells is driving significant advances in multiple domains from chronic diseases to fertility treatments, and regenerative medicine. Pluripotent stem cells offer enhanced differentiation potential and closer resemblance to early embryonic development. Together with improved differentiation protocols they support personalised regenerative therapies and developmental studies.

For example, a new human embryonic stem cell-derived therapy has shown unprecedented results in type 1 diabetes: all patients maintained average blood glucose levels (HbA1c) below 7% and most were insulin-free after one year. This offers hope for restoring endogenous insulin production, potentially transforming management of severe diabetes cases beyond existing insulin therapies.

Gameto's Fertilo—an ovarian support cell therapy derived from induced pluripotent stem cells—shows promise in *in vitro* fertilization (IVF) by improving egg quality and reducing hormone use and is now entering Phase 3 trials.

These innovations collectively showcase multiple opportunities but also raise regulatory, ethical, and technical challenges related to scalability, genetic stability, and clinical validation. Pluripotent stem cells, for example, are prone to acquiring genetic abnormalities, prompting the need for new assays and relevant safety protocols.

[23, 24, 25, 26, 27, 28, 29, 30]

New tools for advanced tissue delivery

Tissue engineering and regenerative medicine innovations are being enabled by new tools and delivery platforms that facilitate precise, efficient, and biocompatible therapeutic interventions.

Among these, extracellular vesicles (EVs) and exosomes have emerged as highly promising drug delivery vehicles. These natural nanocarriers, secreted by cells, offer tissue-specific targeting, as well as superior biocompatibility compared to synthetic systems.

Engineered EVs can deliver proteins, RNAs, and drugs directly to diseased or damaged tissues, minimising off-target effects and immune responses. They are being explored for cancer, neurodegenerative disorders, and regenerative therapies. In-situ production and modulation of EVs can further enhance their precision and therapeutic potential.

Another active area of research focuses on delivering therapeutic payloads to tissues beyond the liver. Recent innovations in nanoparticle design now enable efficient *in vivo* delivery to extrahepatic organs such as the spleen and lungs. This expansion in delivery capabilities significantly broadens the potential applications of gene therapies.

In the area of cell therapy, 3D printed scaffolds provide customisable frameworks for localised, controlled tissue regeneration and drug release, integrating bioactive agents for advanced tissue repair.

[31, 32, 33, 34, 35, 36, 37, 38, 39, 40] [41]

In silico & AI

Breakthroughs in *in silico* [6], AI-driven and digital-twin approaches can transform biomedical research, diagnostics, and personalised medicine. *In silico* modelling leverages computer simulations increasingly integrated with AI and can potentially replace some traditional animal testing and clinical trials.

This approach could accelerate drug development, reduce costs, increase safety, and address ethical concerns, by simulating complex biological interactions and predicting treatment outcomes with high accuracy.

In oncology, AI-driven analysis of tumour heterogeneity integrates histology images and genomic biomarkers, significantly improving early cancer diagnosis, subtype discrimination, and personalised treatment plans.

In another example, a new AI tool can now analyse immune cell receptor genes from a single blood sample to diagnose multiple diseases simultaneously,

[6] *In silico* refers to the use of computer simulations and modelling. This approach complements traditional *in vivo* (in living organisms) and *in vitro* (in laboratory settings) approaches.

enhancing accuracy and efficiency in healthcare delivery.

Furthermore, AI-driven regenerative medicine combines predictive analytics with stem cell and tissue engineering, enabling precise, individualised therapies and accelerating tissue repair.

These technologies collectively promise to advance healthcare by enabling rapid, cost-effective, and highly personalised interventions, though challenges remain in data quality, regulatory approval, and integration.

[42, 43, 44, 45, 46, 47, 48, 49]

Conversion of tumour cells

Korean researchers have pioneered a groundbreaking treatment for colon cancer by converting tumour cells into quasi-normal cells, rather than destroying them.

This innovative approach uses a digital twin of gene networks to identify master molecular switches that can alter the differentiation path of cancer cells, possibly also reducing side effects.

In another example, scientists reprogrammed cancer cells to dendritic cells, a type of immune cell, which subsequently helped activate cancer-specific T cell responses to the remaining tumour. This approach showed durable tumour control in mouse melanoma models.

The concept of converting tumour cells holds potential for broader oncological applications. However, challenges remain: the complexity of gene networks in different cancers requires further understanding, and validation across various cancer types is needed. Additionally, extensive clinical trials and regulatory processes must be completed to ensure safety and efficacy before such treatments can be widely adopted.

[50, 51, 52]

Emerging genome and epigenome-based therapies

Developments in genome and epigenome-based treatments are driving novel, safer and more effective therapeutic options. Epigenetic editing therapy stands out as a promising approach, enabling precise alteration of epigenetic marks at specific genetic *loci*. This method surpasses conventional broad-spectrum drugs by allowing targeted regulation of gene expression, with applications ranging from neurodegenerative diseases to diabetes and cancer. By modulating genes involved in disease pathways without altering the DNA sequence, epigenetic editing offers durable and reversible interventions. However, challenges in delivery, off-target effects, and ethical considerations still need to be addressed.

The Sleeping Beauty (SB) transposon system is another example of a new generation of non-viral gene delivery tools. Unlike traditional viral vectors, SB integrates therapeutic genes into host genomes with lower immunogenicity and manufacturing costs, reducing risks such as immune reactions and insertional mutagenesis. Enhanced SB variants now offer improved efficacy and biosafety, making them promising for gene therapy and synthetic vector development, though precision in genomic integration and regulatory approval remain key challenges.

Recent advances in CRISPR systems, including base and prime editing, although not selected by participants, were significantly represented in signals' longlist and fit in this category. They enable precise single-nucleotide changes without double-strand breaks, reducing off-target risks. Prime editing, notably, expands the scope of possible edits, offering refined correction of pathogenic mutations. New CRISPR variants include CAS13 that introduces a novel RNA-targeting mechanism distinct from traditional DNA-editing CRISPR systems.

[39, 40, 53, 54, 55, 56]

Other topics

Four other topics were highlighted by individual workshop participants during the final voting.

Connected with the signal highlighted in Box 1, *in vivo* CAR T-cell engineering leverages gene therapy vectors to modify T-cells within a patient. This approach expands therapeutic applications, particularly in oncology and autoimmune diseases, by enhancing accessibility and scalability. [57]

Originally used in blood cancers, CAR T-cell therapies are now in early trials targeting a diverse set of tissues and diseases, including solid tumours and autoimmune conditions like diabetes and multiple sclerosis, showing promising safety and efficacy. Senolytic and stem cell therapies further expand regenerative and immunomodulatory treatment options. [58, 59, 60]

Mitochondrial transplantation is an approach that introduces functional mitochondria to replace damaged ones. Unlike traditional therapies, this directly addresses mitochondrial dysfunction, possibly providing therapeutic benefits for conditions like

cardiogenic shock and Parkinson's disease. This technique enhances cellular energy production and promotes tissue regeneration, offering a promising alternative to existing treatments. [61, 62]

RNA therapeutics are rapidly advancing through CRISPR-Cas13 RNA editing (mentioned before), improved lipid nanoparticle (LNP) delivery, and exosome-based systems. These innovations enable targeted RNA knockdown, precise gene therapy, and enhanced mRNA vaccine efficacy, expanding treatment options for genetic disorders, cancer, and infectious diseases beyond the liver and to multiple tissues. [39, 56, 63, 64]

CONTEXTUAL FACTORS

The following topics result from an aggregation of participants' insights regarding contextual factors influencing the development and uptake of cell and gene therapies in the broader context of health biotechnology.[7]

Competitiveness and geopolitics

Geopolitical competition is driving global investment and innovation in biotechnology, reshaping the competitive landscape. Strengthening the EU's strategic autonomy in health biotechnology is essential to reduce dependencies, enhance resilience, and reinforce its position as a global leader in science, technology, and health security.

Talent and expertise development

Effort is needed to identify and nurture scientific talent within EU universities in order to strengthen innovation and broaden the pool of available experts. At the same time, education systems across the EU may need to adjust curricula to equip the next generation of skilled workers with the key competencies required for advancing biotechnology across the supply chain.

Cross-border and cross-sector collaboration

Strengthening cross-border cooperation in the EU and fostering partnerships between sectors is key. It is important to foster more public-private research partnerships and strengthen the connection between academia/industry and policy makers/regulators.

Funding, economic and market conditions

Biotechnology innovation requires targeted funding mechanisms that support high-risk and high-reward research. Significant investment is needed to cover the high costs of RDI clinical trials, regulatory approval processes and compliant production infrastructure, often prohibitive to academia or SMEs. Market viability remains uncertain, especially for niche applications, highlighting the need for harmonised IP rights and supportive market frameworks across Europe.

Regulatory, safety and ethical challenges

Regulatory demands can limit the capacity of researchers and early-stage enterprises to translate scientific discoveries into clinical applications. Imposing compliance frameworks used in the pharmaceutical sector to cell and gene therapies can create disproportionate burdens on clinical institutions, exceeding the requirements of established patient-safe practices.

Ensuring safety across all stages—development, trials and application—is critical for accelerated approvals. As mentioned earlier, cooperation between industry, academia, and policymakers is key to developing smarter regulation that safeguards ethical and safety concerns without hindering RDI of potentially effective therapies.

Clear ethical frameworks are also needed to support responsible sharing of safety and efficacy data while protecting privacy and security.

Additionally, the absence of dedicated regulation for emerging areas such as xenotransplantation[8] poses significant challenges, highlighting the need for an anticipatory governance approach.

Health and RDI ecosystems

Fragmented healthcare and data systems, along with commercialisation challenges hinder the integration of biotech into effective and scalable health solutions

[7] These factors were analysed using an adapted version of the Triangle of the Future framework [67] a foresight method that maps three competing forces: the pull of the future, the push of the present, and the weight of history. It can be used as a stand-alone method or in conjunction with others. For this project, the authors explored 3 types of contextual factors connected with those three temporal dimensions: drivers which are high-level factors that trigger or shape significant contextual changes and pull technological development and uptake into the future; enablers, or opportunities, that are present-day conditions that create a fertile ground for innovation to occur and therefore push technologies forward; and barriers, or challenges, that can be seen as past and present constraints ("weight") that hinder technological development and uptake.

[8] Xenotransplantation is the transplantation of living cells, tissues, or organs from one species to another, typically from animals to humans, to treat diseases or replace damaged biological functions.

across the EU. Additional efforts are needed to increase and implement standardisation in biotechnology experimentation. Central repositories for preclinical and clinical data—particularly safety data— could foster knowledge sharing and therefore new scientific and innovation breakthroughs.

Infrastructure and manufacturing

Advancing biotechnology requires modern and adaptable manufacturing processes together with robust infrastructure to deliver therapies at scale. Platform approaches to manufacturing and development pipelines with modular components allow for more rapid translation, improvements, and adaptions. Health biotechnology is also entering new frontiers, including space and other extreme environments, where resilient systems are essential. Although primarily aimed at outer-Earth exploration, biotechnology RDI conducted in space may also yield valuable applications back on Earth.

CONCLUSIONS

The rapid evolution of biotechnology is reshaping modern medicine and healthcare, with groundbreaking advances in gene therapy, human-relevant cellular models, and tissue-specific delivery systems leading the way. The following conclusions summarise the main findings of this exercise.

Transformative advances in gene therapy and delivery

In vivo gene therapies—particularly those using engineered viral and non-viral vectors—offer promising avenues for precisely targeting cells in cancer, genetic disorders, and regenerative medicine; however, their clinical availability remains limited. Realising their full potential will likely require a technological breakthrough, particularly in safe and efficient delivery systems, vector design, and immune evasion strategies.

Human-relevant cellular models

Microphysiological systems, could revolutionise cell and gene therapy by providing human-relevant models for disease study and drug development. These innovations could reduce reliance on animal testing, accelerate drug discovery, regulatory approvals, and support personalised medicine, although they raise challenges in standardisation and wide adoption.

Innovations in stem cell research and tissue engineering

Advances in stem cell research are driving breakthroughs in regenerative medicine and fertility treatments. New tools like engineered EVs enhance safety and precision in therapeutic delivery, while 3D-printed scaffolds support localised tissue regeneration, furthering the potential for personalised interventions. However, regulatory, and ethical issues can hinder their development.

Integration of AI and *in silico* approaches

AI-driven and *in silico* diagnostics could boost biomedical research by enabling rapid, accurate, and cost-effective therapy development, predictions of treatment outcomes and disease diagnostics. Data quality and regulatory acceptance remain challenges.

Competitive landscape

Global investment and geopolitical competition are reshaping biotechnology. Strengthening the EU's strategic autonomy, nurturing talent, and fostering cross-sector collaboration are essential for competitiveness.

Regulatory, standards, ethical, and infra-structure challenges

Ensuring fit-for-purpose regulatory frameworks, ethics, implementable standards, and modern manufacturing infrastructure is crucial for accelerating the translation of scientific breakthroughs into practical, scalable healthcare solutions. Addressing funding gaps, market viability, skills shortage, and harmonisation of IP rights is also necessary to ensure sustainable growth.

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The information and views presented here are those of the authors and do not necessarily reflect the official opinion of the European Commission.

The findings of this exercise resulted from a participatory process involving a group of internal and external experts representing a diversity of fields and backgrounds. The methodologies applied have limitations and the results do not aim to cover all developments and topics on the field.

Most trends and signals are referenced to the sources where they were originally detected, although some concepts included in the final texts result from the analysis and contributions of the participants.

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