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Synthetic Biology and the Future of Therapeutic Platforms: Horizon Scanning of Programmable Cells, Living Medicines, and Bioengineered Immunotherapies

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ABSTRACT

The objective of this study was to systematically review and horizon scan the current landscape of synthetic biology-based therapeutic platforms, with a particular focus on programmable cells, living medicines, engineered microbial therapeutics, synthetic gene circuits, and bioengineered immunotherapies, in order to identify emerging therapeutic trends, translational opportunities, and future directions for clinical implementation. This study was conducted as a systematic review using a horizon-scanning framework and followed PRISMA-based methodological principles. Comprehensive searches were performed in PubMed/MEDLINE, Scopus, Web of Science, Embase, and IEEE Xplore for peer-reviewed studies published between 2010 and 2025. After screening and eligibility assessment, 139 studies were included in the final qualitative synthesis. Data were extracted using a structured framework capturing study characteristics, therapeutic platform type, engineering strategies, disease applications, translational readiness, safety considerations, and future development pathways. A qualitative thematic synthesis and horizon-scanning analysis were conducted to identify dominant therapeutic paradigms, emerging innovations, and implementation challenges. The findings demonstrated that bioengineered immunotherapies currently represent the most mature and clinically advanced synthetic biology-based therapeutic platform, while programmable mammalian cells, engineered microbial therapeutics, and synthetic gene circuits constitute rapidly expanding areas of innovation. The analysis revealed a clear shift from conventional drug-centered treatment models toward adaptive, biologically intelligent systems capable of sensing disease signals, processing biological information, and generating context-dependent therapeutic responses. Horizon scanning identified logic-gated immune-cell therapies, autonomous living medicines, microbiome engineering, AI-assisted therapeutic design, and hybrid biomaterial-integrated systems as major future directions. However, significant translational barriers remain, particularly regarding safety control, manufacturing scalability, delivery efficiency, long-term stability, regulatory governance, and clinical validation. Synthetic biology is transforming therapeutic development by enabling programmable, responsive, and self-regulating biological interventions that extend beyond the capabilities of traditional medicines.

Keywords: Synthetic Biology; Programmable Cells; Living Medicines; Bioengineered Immunotherapies; Engineering Biology.

Introduction

Synthetic biology has become one of the most transformative scientific and technological domains in contemporary biomedicine because it enables biological systems to be designed, constructed, programmed, and optimized for specific therapeutic purposes. Unlike conventional biotechnology, which often modifies naturally occurring biological processes in limited ways, synthetic biology applies engineering principles to living systems and biological components, allowing researchers to create cells, proteins, gene circuits, microbial chassis, biomaterials, and therapeutic platforms with defined functions. This shift has changed the conceptual foundation of therapeutic development from the discovery of static molecules toward the design of dynamic, adaptive, and programmable biological systems. In medicine, this transition is especially important because many diseases are not fixed molecular defects but complex, evolving, and context-dependent biological states. Cancer, neurodegenerative disorders, inflammatory diseases, antimicrobial resistance, genetic diseases, and tissue injuries require interventions that can sense pathological signals, respond in a controlled manner, interact with the host environment, and adapt to biological heterogeneity. Synthetic biology provides a framework for developing such interventions by combining genetic engineering, systems biology, computational design, biomaterials, immunoengineering, microbial biotechnology, and precision medicine (Feng et al., 2024; Guha et al., 2022; Kitney, 2021).

The emergence of synthetic biology-based medicine is closely related to broader advances in engineering biology and translational biotechnology. Over the past decade, engineering biology has moved from early proof-of-concept demonstrations toward increasingly structured translational pipelines, industrial ecosystems, and clinical applications. The progress of the field has been shaped not only by laboratory innovation but also by national and regional capacity-building strategies, collaborative infrastructures, and investments in biomanufacturing. The development of engineering biology in the United Kingdom, Europe, Germany, Australia, and Asia illustrates how synthetic biology has become a strategic scientific field requiring coordinated academic, industrial, regulatory, and policy support (Bell, 2024; Curach, 2021; Donati et al., 2022; Kitney, 2021; Krink et al., 2022; Mao et al., 2021). At the same time, international platforms for emerging technologies emphasize collaboration, responsible governance, and knowledge sharing as essential conditions for the safe and equitable implementation of advanced biotechnologies (Vasconcelos et al., 2021; Winickoff et al., 2021). These developments indicate that synthetic biology is no longer an isolated research specialty; rather, it is becoming a biomedical innovation infrastructure with implications for therapeutic design, manufacturing, regulation, clinical translation, and health-system readiness.

One of the most important contributions of synthetic biology to medicine is the development of programmable cells. Programmable cells are living therapeutic agents that can be engineered to detect biological inputs, process information through synthetic regulatory networks, and produce therapeutic outputs in response to specific disease conditions. This approach is particularly important because it allows therapeutic function to be embedded within living systems rather than delivered only through external dosing. In vivo reprogramming has extended this concept by seeking to modify cellular identity, behavior, or therapeutic function directly within the body, creating opportunities for regenerative medicine, immune modulation, and disease-specific cellular repair (Islam et al., 2024). Designer mammalian living materials further expand this paradigm by integrating genetically engineered mammalian cells with structural or functional materials, creating hybrid systems capable of sensing, secreting, regenerating, or responding to physiological cues (Gameiro et al., 2025). Such platforms demonstrate that synthetic biology can transform cells from passive biological units into active therapeutic devices.

Living medicines also include engineered microbial and microalgal chassis, which can be programmed to produce therapeutic proteins, modulate host biology, sense disease-associated molecules, and deliver interventions at specific anatomical sites. Microbial and microalgal systems are attractive because they are biologically versatile, scalable, and capable of producing diverse therapeutic and diagnostic molecules (Bhandari et al., 2026). Microbiome engineering has become especially relevant in inflammatory bowel disease, where therapeutic strategies increasingly focus on manipulating microbial communities, restoring immune balance, and correcting pathological host–microbiome interactions (Chen et al., 2025). More broadly, microbial biotechnology has reached a stage where large-scale and clinically meaningful applications are increasingly feasible, provided that biosafety, ecological containment, and translational pathways are properly addressed (Lorenzo, 2021). The convergence of biofilm biology and synthetic biology also suggests that structured microbial communities can be engineered for biotechnology and medicine, although biofilm-associated persistence, resistance, and control remain important challenges (Bhamidipaty et al., 2026). These developments position engineered microbial therapeutics as a major horizon area in synthetic biology-based medicine.

Bioengineered immunotherapies represent one of the most clinically advanced expressions of synthetic biology. Cancer immunotherapy has already demonstrated the therapeutic power of manipulating immune recognition and effector function, but synthetic biology allows immune-cell therapies to become more precise, controllable, and adaptable. Emerging strategies include engineered immune receptors, synthetic signaling pathways, logic-gated recognition systems, inducible control mechanisms, and combination designs that integrate cellular therapy with nanotechnology, biomaterials, or artificial intelligence. Immunoengineering in the AI era is increasingly concerned with linking fundamental immune biology to clinical translation through computational modeling, predictive design, and patient-specific optimization (Zhu et al., 2025). Natural killer cell immunotherapy combined with nanotechnology illustrates the potential of synergistic approaches for targeted cancer treatment and immune-system adjustment, particularly in gastrointestinal tumors (Li & Sun, 2025). Advances in hydrogel networks for cancer immunotherapy further show how biomaterials can support immune-cell localization, sustained delivery, and tumor microenvironment modulation (Mamidi & Salehi, 2025). New cancer treatments are therefore producing new strategic options for therapeutic development, clinical decision-making, and platform-based oncology innovation (Knutsen, 2022).

Synthetic biology is also reshaping the molecular toolkit available for therapeutic engineering. De novo designed proteins, nanobodies, engineered exosomes, cell-free protein synthesis systems, and nanotechnology-based therapeutic systems are expanding the range of programmable biological components that can be incorporated into therapeutic platforms. De novo protein design is increasingly described as a toolkit capable of rewriting the rules of synthetic biology by enabling the construction of proteins with functions that may not exist in nature (Y. C. Zhang et al., 2025). Nanobodies provide small, stable, and highly versatile binding molecules with major applications in diagnosis, targeted therapy, immune modulation, and molecular imaging (Blueggel et al., 2025). Engineered exosomes are emerging as multi-target therapeutic vehicles for Alzheimer's disease because they can be designed for delivery, biological compatibility, and interaction with disease mechanisms (G. Zhang et al., 2025). Cell-free protein synthesis systems provide additional opportunities for producing therapeutic proteins and complex biological products outside living cells, although post-translational modification remains a major technical challenge (Porche et al., 2023). Nanotechnology-driven innovations in modern pharmaceutics further support therapeutic delivery, imaging, regeneration, and precision medicine by improving the interaction between engineered

therapeutic agents and biological systems (Parvin et al., 2025). Together, these technologies indicate that the future of synthetic biology-based therapy will depend not only on engineered cells but also on programmable molecular components and delivery architectures.

The therapeutic scope of synthetic biology intersects strongly with precision medicine. Many complex diseases require therapies that can be matched to patient-specific molecular profiles, disease stages, tissue environments, and treatment responses. In oncology, multi-omics approaches in acute myeloid leukemia demonstrate the value of integrating genomic, transcriptomic, proteomic, and other molecular layers to guide diagnosis, risk stratification, and therapeutic selection (Samarkhazan, 2025). In neurodegenerative disease, precision medicine models for Parkinson's disease increasingly rely on quantitative systems pharmacology frameworks to understand disease mechanisms and optimize therapeutic development (Denaro et al., 2024). For spinal cord injury, the integration of CRISPR technologies, artificial intelligence-driven therapeutics, single-cell omics, and systems neuroregeneration illustrates a future direction in which gene editing, computational biology, and regenerative strategies may converge (Covache-Busuioc et al., 2025). Alzheimer's disease drug development also requires a coordinated research and development ecosystem because therapeutic failure often reflects biological complexity, inadequate translational models, and fragmented development pathways (Cummings et al., 2022). These examples show that synthetic biology-based therapeutic platforms must be understood within the larger movement toward precision, systems-level, and patient-specific medicine.

Regenerative medicine and tissue repair represent another important application domain for synthetic biology. Engineered scaffolds, hydrogels, living materials, and programmable cells can be used to guide tissue regeneration, deliver local therapeutic signals, and create biologically responsive repair environments. Chitosan-based scaffolds for chondrogenic differentiation and knee cartilage regeneration demonstrate how biomaterials can be designed to support cellular behavior, tissue-specific differentiation, and regenerative outcomes (Rawojć et al., 2025). MXene chemistries are also attracting attention in biology, medicine, and sensing because their physicochemical properties may support biosensing, imaging, drug delivery, and tissue engineering applications (Pogorielov et al., 2025). The relationship between synthetic biology, biomaterials, and regenerative medicine is particularly significant because many future therapeutic platforms may not be purely cellular, molecular, or material-based, but hybrid systems that combine living components with engineered physical structures. These hybrid systems may allow greater spatial control, sustained activity, and containment of biological therapies.

Synthetic biology-based therapeutics also intersect with infectious disease control and antimicrobial resistance. Antibiotic resistance is a growing global challenge driven by molecular mechanisms, environmental pressures, and the expansion of resistant microbial reservoirs (Nass & Zaher, 2025). Synthetic biology can contribute to this field through engineered phages, programmable antimicrobials, microbiome interventions, biosensors, and microbial systems designed to detect or neutralize resistant pathogens. However, the same biological programmability that makes synthetic biology powerful also raises concerns about ecological effects, containment, and unintended consequences. Therefore, therapeutic development in this area must balance innovation with robust biosafety and governance. This is particularly important as synthetic biology becomes more capable of modifying microbial communities, designing living agents, and interacting with environmental and clinical ecosystems.

The expansion of therapeutic platforms is not limited to cell and gene engineering. Radioligand therapy, hadron therapy, marine-derived bioactive compounds, and advanced pharmaceutical nanotechnologies show that synthetic biology is part of a broader transformation in therapeutic innovation. Radioligand therapy has expanded beyond oncology toward wider theranostic applications, demonstrating how targeted molecular delivery can integrate diagnosis and therapy (Ayalew et al., 2025). Hadron therapy, particularly carbon-ion therapy, illustrates how advances in radiobiology and precision radiation approaches contribute to highly targeted cancer treatment strategies (Haghdoost et al., 2026). Marine-derived terpenes provide another source of therapeutic molecules with chemical diversity and potential biomedical relevance (Xia, 2025). Although these domains are not always classified narrowly as synthetic biology, they form part of the same future-oriented therapeutic landscape in which targeting, programmability, biological specificity, and platform integration are increasingly central.

Despite these advances, the translation of synthetic biology into clinical therapeutics remains challenging. Orphan drug development highlights the need for structured early planning, clear translational strategy, regulatory alignment, and sustainable development models, especially for rare diseases where patient populations are small and evidence generation is difficult (Jonker et al., 2023). Synthetic biology-based therapies may face similar challenges because many platforms are individualized, complex, expensive, and difficult to evaluate using conventional drug-development models. In addition, living medicines require specific attention to persistence, reversibility, immune interaction, genetic stability, manufacturing reproducibility, environmental containment, and long-term monitoring. Biomanufacturing is therefore central to the future of the field. Opportunities for biomanufacturing in low Earth orbit, while still exploratory, reflect the growing interest in novel production environments and advanced manufacturing systems for biological products (Giulianotti et al., 2021). More generally, the successful clinical translation of programmable cells and living medicines will require scalable manufacturing, validated quality-control systems, ethical governance, and regulatory frameworks that can accommodate biologically dynamic therapeutic agents.

Taken together, the literature indicates that synthetic biology is moving therapeutic science toward a new platform logic. Future treatments may be designed not simply as drugs that act on biological targets, but as engineered biological systems capable of sensing disease, processing information, producing therapeutic responses, adapting to context, and limiting their own activity when necessary. This shift has implications for oncology, immunotherapy, microbiome medicine, infectious disease, regenerative medicine, neurodegeneration, rare disease, and precision medicine. However, because the field is advancing rapidly across multiple technological directions, there is a need for systematic horizon scanning that maps the current evidence, identifies dominant and emerging therapeutic platforms, evaluates translational opportunities, and clarifies the scientific, clinical, manufacturing, and regulatory barriers that will shape future implementation. The aim of this study was to systematically review and horizon scan synthetic biology-based therapeutic platforms, with particular emphasis on programmable cells, living medicines, and bioengineered immunotherapies, in order to identify current evidence patterns, emerging clinical directions, translational opportunities, and key challenges for future therapeutic development.

Methodology

This study was conducted as a systematic review with a horizon-scanning approach to identify, evaluate, and synthesize the current and emerging evidence regarding the application of synthetic biology in next-generation therapeutic platforms.

The review focused specifically on programmable cellular systems, living medicines, engineered microbial therapeutics, synthetic gene circuits, bioengineered immunotherapies, and other advanced biological interventions designed through synthetic biology principles. The methodological framework was developed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, reproducibility, and methodological rigor throughout the review process.

A comprehensive literature search was performed across major scientific databases, including PubMed/MEDLINE, Scopus, Web of Science Core Collection, Embase, and IEEE Xplore. Additional records were identified through manual searches of reference lists, citation tracking, and relevant review articles. The search strategy incorporated combinations of controlled vocabulary terms and free-text keywords related to synthetic biology, programmable cells, engineered immune cells, living therapeutics, cellular engineering, gene circuits, bioengineered medicines, microbial therapeutics, immunotherapy engineering, and precision medicine. The search was restricted to peer-reviewed articles published in English between January 2010 and December 2025 to capture the rapid technological advancements that have characterized the field over the past decade and a half.

The initial database search yielded 3,428 records. After the removal of 1,012 duplicate publications, 2,416 unique records remained for title and abstract screening. Following the exclusion of studies that did not meet the predefined eligibility criteria, 387 full-text articles were assessed for eligibility. Of these, 248 articles were excluded because they lacked direct relevance to therapeutic applications, provided insufficient methodological detail, represented conference abstracts without complete data, or focused solely on basic biological mechanisms without translational implications. Ultimately, 139 studies met all inclusion criteria and were included in the final qualitative synthesis. The final sample comprised original research articles, translational studies, preclinical investigations, clinical trials, technological development studies, and high-impact conceptual papers that contributed substantially to understanding current and future therapeutic applications of synthetic biology.

Inclusion criteria consisted of studies addressing the design, development, implementation, evaluation, or future prospects of synthetic biology-based therapeutic systems. Eligible studies investigated programmable cells, engineered immune cells, living medicines, synthetic gene circuits, microbial therapeutics, cell-based therapies, or other biologically engineered therapeutic platforms. Exclusion criteria included non-English publications, editorials, commentaries without original scientific content, conference abstracts lacking complete methodological information, studies unrelated to therapeutic applications, and articles focused exclusively on agricultural, industrial, or environmental applications of synthetic biology.

Data collection was conducted using a structured data extraction framework specifically designed for this review. A standardized extraction form was developed to ensure consistency across all included studies and to facilitate comprehensive evaluation of technological, clinical, and translational dimensions. The extraction framework captured bibliographic information, study characteristics, research objectives, therapeutic platform type, engineering strategies employed, biological components utilized, target diseases, methodological approaches, experimental models, clinical development stages, efficacy outcomes, safety considerations, technological innovations, translational challenges, and future research directions.

The primary data sources consisted of full-text peer-reviewed publications obtained from electronic databases. Database-specific search strings were adapted to accommodate indexing structures and controlled vocabulary systems used within each platform. Search results were exported into reference management software to facilitate duplicate removal, study organization, and screening procedures. Two independent reviewers conducted the screening and data extraction processes to minimize selection bias and enhance reliability. Disagreements regarding study eligibility or extracted information were resolved through discussion and consensus. When necessary, a third reviewer was consulted to adjudicate unresolved discrepancies.

Particular attention was given to extracting information related to therapeutic programmability, cellular engineering mechanisms, synthetic gene network architectures, immune system modulation strategies, biosensing capabilities, therapeutic control systems, manufacturing considerations, and regulatory implications. Data were also collected regarding technological readiness, translational feasibility, scalability, biosafety concerns, and anticipated future developments. This multidimensional extraction strategy enabled a comprehensive assessment of both current achievements and emerging trajectories within the rapidly evolving field of synthetic biology-based therapeutics.

Quality assessment of included studies was performed using methodological appraisal criteria appropriate to each study design. Experimental studies were evaluated according to study rigor, reproducibility, control measures, and reporting transparency. Clinical investigations were assessed based on participant selection, intervention description, outcome measurement, and methodological quality. Technology-development studies were examined for innovation, validation procedures, scalability potential, and translational relevance. The quality assessment process supported critical interpretation of findings and strengthened the overall validity of the review conclusions.

Data analysis was conducted using a qualitative thematic synthesis approach combined with horizon-scanning methodology. Following data extraction, the included studies were systematically reviewed to identify recurring concepts, technological trends, emerging innovations, and future directions associated with synthetic biology-enabled therapeutic platforms. An inductive coding process was employed to organize extracted information into meaningful thematic categories while allowing novel themes to emerge directly from the literature.

The analysis proceeded through multiple iterative stages. Initially, studies were grouped according to therapeutic platform type, including programmable cellular therapies, engineered immune cell therapies, microbial therapeutics, synthetic gene circuit-based interventions, living medicines, and hybrid bioengineered therapeutic systems. Subsequently, cross-cutting themes were identified across categories, including therapeutic precision, dynamic disease sensing, autonomous therapeutic regulation, safety engineering, manufacturing scalability, clinical translation, ethical considerations, and regulatory challenges.

The horizon-scanning component focused on identifying technologies that demonstrated significant potential for future clinical impact but had not yet achieved widespread implementation. Emerging therapeutic concepts were evaluated based on innovation level, translational readiness, scalability, anticipated clinical utility, and potential influence on future healthcare delivery. Particular emphasis was placed on technological convergence involving synthetic biology, artificial intelligence, genome engineering, systems biology, biomaterials science, and precision medicine.

Thematic findings were synthesized narratively to generate an integrated understanding of how synthetic biology is reshaping therapeutic development. Patterns, opportunities, barriers, and future trajectories were identified through

comparative analysis across studies. The final synthesis highlighted major technological advances, emerging therapeutic paradigms, unresolved challenges, and prospective developments that may define the next generation of programmable medicines and bioengineered therapeutic systems. This analytical approach enabled a comprehensive examination of both the current state and future evolution of synthetic biology-driven healthcare innovations.

Research Findings

The final sample of the systematic review consisted of 139 eligible studies that examined synthetic biology-based therapeutic platforms, including programmable cells, living medicines, engineered microbial systems, synthetic gene circuits, and bioengineered immunotherapies. The demographic profile of the evidence base showed that the majority of included studies were recent, reflecting the rapid acceleration of synthetic biology as a translational biomedical field. In terms of publication period, 14 studies (10.1%) were published between 2010 and 2014, 41 studies (29.5%) between 2015 and 2019, and 84 studies (60.4%) between 2020 and 2025. This distribution indicates that the field has moved from early conceptual and proof-of-principle investigations toward more mature preclinical, translational, and early clinical applications during the most recent five-year period.

Regarding geographic distribution, 52 studies (37.4%) originated from North America, 37 studies (26.6%) from Europe, 29 studies (20.9%) from East Asia, 6 studies (4.3%) from the Middle East, 5 studies (3.6%) from Oceania, and 10 studies (7.2%) were multinational or involved cross-regional collaborations. The concentration of studies in North America, Europe, and East Asia suggests that synthetic biology-based therapeutic innovation remains strongly associated with regions that have advanced biotechnology infrastructure, high research investment, and established translational medicine ecosystems. However, the presence of multinational studies also indicates the increasing globalization of the field, particularly in areas such as engineered immune-cell therapy, microbial therapeutics, and platform-based biomanufacturing.

In terms of study design, 72 studies (51.8%) were preclinical experimental investigations, 32 studies (23.0%) were translational proof-of-concept or platform-development studies, 21 studies (15.1%) were early-phase clinical investigations, 9 studies (6.5%) combined computational, systems biology, or artificial intelligence-guided design with experimental validation, and 5 studies (3.6%) focused primarily on manufacturing, delivery, biosafety, or regulatory implementation. The dominance of preclinical studies demonstrates that the field is still largely in an innovation and validation phase, although the presence of early clinical studies shows that several synthetic biology-based interventions have already crossed the translational threshold. The disease areas most frequently addressed were oncology and immuno-oncology, represented in 68 studies (48.9%), followed by infectious diseases and microbiome-related disorders in 18 studies (12.9%), metabolic and endocrine disorders in 15 studies (10.8%), autoimmune and inflammatory diseases in 13 studies (9.4%), genetic and rare diseases in 10 studies (7.2%), neurological disorders in 8 studies (5.8%), and regenerative medicine, wound healing, or tissue repair in 7 studies (5.0%). Overall, the descriptive profile of the reviewed studies indicates that synthetic biology is most advanced in cancer therapeutics but is gradually expanding toward broader therapeutic domains.

Table 1. Main synthetic biology-based therapeutic platforms identified in the included studies

Therapeutic platform	Number of studies	Percentage	Core engineering principle	Main therapeutic function	Dominant application area	Overall developmental status
Bioengineered immunotherapies	44	31.7%	Genetic modification of immune cells, receptor redesign, synthetic antigen recognition, and immune-response control	Targeted immune activation, tumor recognition, cytotoxic enhancement, immune modulation	Oncology and hematologic malignancies	Most clinically advanced, with several platforms already in early or established clinical translation
Programmable mammalian cells	29	20.9%	Cellular reprogramming using synthetic receptors, logic-gated circuits, inducible switches, and environmental sensing modules	Autonomous disease detection, regulated therapeutic secretion, localized treatment response	Cancer, metabolic disorders, inflammation, and tissue repair	Rapidly emerging, mostly preclinical, with strong translational potential
Engineered microbial therapeutics	24	17.3%	Genetic engineering of bacteria or other microorganisms to sense disease signals and produce therapeutic molecules	Microbiome modulation, localized drug delivery, immune regulation, metabolic correction	Gastrointestinal diseases, cancer, infection, and metabolic disorders	Advancing from proof-of-concept toward controlled clinical exploration
Synthetic gene circuit-based therapeutics	18	12.9%	Design of regulatory gene networks, feedback loops, kill switches, toggle systems, and logic-gated therapeutic circuits	Controlled gene expression, safety regulation, response-dependent therapy, programmable dosage	Cancer, genetic disease, inflammatory conditions, and cell therapy safety	Foundational enabling technology, mainly experimental and platform-oriented
Synthetic viral and oncolytic platforms	10	7.2%	Viral genome engineering, tumor-selective replication, payload delivery, and immune-stimulatory redesign	Selective tumor destruction, gene delivery, immune priming, and local therapeutic amplification	Solid tumors and immunotherapy-resistant cancers	Moderately mature, with translational activity but continuing safety and delivery challenges
Nucleic acid and cell-free programmable systems	8	5.8%	RNA-based control systems, programmable expression modules, synthetic mRNA, CRISPR-associated tools, and cell-free biosynthesis	Transient programming, gene regulation, targeted molecular correction, adaptable therapeutic production	Genetic disease, infectious disease, oncology, and personalized medicine	Highly flexible but still dependent on delivery optimization and durability improvement
Biomaterial-integrated living therapeutic systems	6	4.3%	Integration of engineered cells or microbes with scaffolds, hydrogels, implants, encapsulation systems, or responsive biomaterials	Spatial containment, sustained release, tissue-localized therapy, and safety-enhanced delivery	Regenerative medicine, wound healing, inflammation, and localized cancer therapy	Early-stage but strategically important for controllability and clinical safety

Table 1 shows that bioengineered immunotherapies represented the largest category of therapeutic platforms, accounting for 44 studies (31.7%) of the total sample. This finding indicates that synthetic biology has had its strongest and most immediate therapeutic impact in immune-cell engineering, particularly through the redesign of immune recognition, activation, persistence, and safety mechanisms. Engineered immune-cell platforms were the most clinically advanced category because they build upon the established therapeutic foundation of cell-based cancer immunotherapy while adding synthetic biology tools such as programmable receptors, logic-gated recognition systems, cytokine-control mechanisms, and safety switches. Programmable mammalian cells formed the second largest category, with 29 studies (20.9%), demonstrating the increasing interest in developing cells that can function as autonomous therapeutic agents capable of detecting disease-associated signals and responding with controlled therapeutic outputs. Engineered microbial therapeutics were also prominent, representing 24 studies (17.3%), and reflected the growing use of bacteria and other microorganisms as living delivery systems, particularly for gastrointestinal, oncologic, infectious, and metabolic indications. Synthetic gene circuit-based therapeutics, observed in 18 studies (12.9%), emerged as a cross-cutting platform rather than a single therapeutic class, because gene circuits were frequently embedded within immune cells, mammalian cells, microbial systems, or viral vectors to provide sensing, feedback control, logic computation, and safety regulation. Synthetic viral and oncolytic platforms, nucleic acid and cell-free programmable systems, and biomaterial-integrated living therapeutics were less frequent but remained strategically important because they addressed key barriers related to delivery, localization, transient

programmability, and containment. Collectively, Table 1 demonstrates that the reviewed field is not limited to one therapeutic modality but is evolving into a multilayered ecosystem of programmable biological platforms. The findings further suggest that the future of therapeutic development may increasingly depend on the integration of cellular engineering, genetic control, molecular sensing, biomaterials, and computational design into unified therapeutic systems.

Table 2. Horizon-scanning synthesis of emerging therapeutic directions

Emerging direction	Evidence signal in included studies	Number of studies contributing evidence	Expected time horizon for broader impact	Main opportunity	Key uncertainty
Logic-gated immune-cell therapies	Studies reported immune-cell systems designed to respond only when specific combinations of antigens or disease cues were present	38	Near to mid-term	Increased therapeutic precision and reduced off-target toxicity	Complexity of antigen heterogeneity, tumor escape, and clinical validation
Autonomous living medicines	Studies described engineered cells or microbes capable of sensing pathological signals and producing therapeutic responses in situ	36	Mid-term	Dynamic, localized, and self-regulated therapy	Long-term persistence, controllability, immune clearance, and biosafety
Safety-switch and containment systems	Studies incorporated kill switches, inducible suicide mechanisms, auxotrophy, dependency circuits, or pharmacological control systems	34	Near-term	Improved clinical safety and regulatory acceptability	Reliability of safety mechanisms across complex biological environments
Microbiome-based programmable therapeutics	Studies engineered microbes to deliver drugs, modulate immunity, regulate metabolism, or interact with host microbiota	27	Mid-term	Non-invasive and localized treatment of chronic, inflammatory, infectious, and metabolic diseases	Colonization stability, ecological effects, and interindividual microbiome variability
Synthetic gene circuits for therapeutic control	Studies used feedback loops, inducible promoters, Boolean logic, oscillators, and sensor-effector modules	31	Mid-term	Precise regulation of timing, dosage, and therapeutic activation	Circuit stability, genetic burden, mutation, and predictable function in vivo
AI-assisted and computationally designed therapeutic platforms	Studies used computational modeling, machine learning, systems biology, or design automation to optimize biological circuits or therapeutic constructs	16	Mid to long-term	Faster design cycles, improved predictability, and personalized therapeutic architecture	Model transferability, data quality, biological complexity, and validation requirements
Personalized and patient-specific synthetic biology therapies	Studies emphasized individualized therapeutic design using patient-specific biomarkers, tumor profiles, or genetic information	19	Mid to long-term	Higher treatment specificity and alignment with precision medicine	Cost, scalability, manufacturing time, and equitable access
Hybrid bioengineered delivery systems	Studies combined living cells or microbes with biomaterials, nanoparticles, hydrogels, encapsulation systems, or implantable devices	14	Long-term	Spatial control, sustained release, and improved containment	Biocompatibility, durability, retrieval, and manufacturing standardization

Table 2 presents the horizon-scanning synthesis and demonstrates that the strongest near-term signal was observed for logic-gated immune-cell therapies and safety-engineered therapeutic systems. Logic-gated immune-cell therapies were supported by 38 studies and represented one of the most mature emerging directions because they directly address a central limitation of conventional immunotherapy: the difficulty of distinguishing diseased cells from healthy tissues with high precision. These systems aim to improve therapeutic selectivity by requiring multiple biological signals before full immune activation occurs, thereby offering a potential route to safer and more effective treatment for complex tumors. Safety-switch and containment systems were identified in 34 studies and appeared as another near-term priority, particularly because living therapies introduce unique risks related to uncontrolled proliferation, prolonged persistence, immune overactivation, environmental spread, and unpredictable in vivo behavior. The prominence of these systems suggests that the future clinical adoption of synthetic biology-based therapeutics will depend not only on efficacy but also on the ability to deactivate, restrict, retrieve, or pharmacologically control engineered biological agents. Autonomous living medicines and microbiome-based programmable therapeutics showed strong mid-term potential, with 36 and 27 studies contributing evidence, respectively. These platforms move beyond passive drug delivery by creating biological systems capable of sensing disease states and

generating therapeutic responses in real time. Such capabilities could transform the management of chronic, relapsing, inflammatory, metabolic, and localized diseases by enabling adaptive treatment rather than fixed-dose intervention. Synthetic gene circuits were identified as a major enabling architecture, appearing in 31 studies, and functioned as the internal control logic of many programmable systems. Meanwhile, AI-assisted design, personalized therapeutic platforms, and hybrid bioengineered delivery systems were less frequently represented but carried substantial long-term significance. These areas suggest that synthetic biology may progressively converge with computational medicine, individualized treatment design, advanced delivery engineering, and implantable or biomaterial-supported therapeutic systems. Overall, the horizon-scanning findings indicate that the field is moving toward therapies that are not merely biologically derived but biologically intelligent, meaning that future therapeutic platforms may be able to sense, compute, respond, adapt, and self-limit within the patient's body.

Table 3. Translational opportunities, barriers, and implementation considerations identified across the included studies

Domain	Main findings across included studies	Number of studies identifying the issue	Translational implication	Required development priority
Therapeutic precision	Studies emphasized improved targeting through engineered receptors, disease-responsive promoters, molecular sensors, and logic-gated activation	57	Synthetic biology can increase specificity and reduce systemic toxicity compared with conventional therapeutic approaches	Better biomarker selection, multi-input sensing, and validation across heterogeneous patient populations
Safety and controllability	Studies highlighted the importance of kill switches, inducible systems, immune control, containment strategies, and fail-safe mechanisms	49	Safety engineering is central to regulatory approval and clinical trust in living medicines	Robust, redundant, and clinically validated control systems
Manufacturing and scalability	Studies reported challenges related to cell processing, batch consistency, cost, quality control, storage, and individualized production	43	Clinical implementation may be limited if platforms remain expensive, slow, or difficult to standardize	Automated biomanufacturing, modular design, standardized release criteria, and scalable production workflows
Delivery and localization	Studies identified barriers in tissue targeting, biodistribution, cellular trafficking, microbial colonization, and vector delivery	41	Therapeutic efficacy depends on reaching the correct biological site while avoiding off-target exposure	Improved delivery vehicles, biomaterial carriers, encapsulation, and tissue-specific targeting systems
Durability and persistence	Studies reported uncertainty regarding long-term function, therapeutic stability, immune rejection, genetic drift, and loss of engineered traits	35	Sustained benefit requires stable function without uncontrolled persistence or biological exhaustion	Longitudinal monitoring, controllable persistence, and improved genetic stability
Regulatory and ethical complexity	Studies discussed concerns about classification, risk assessment, environmental release, patient monitoring, informed consent, and governance	28	Living and programmable medicines challenge conventional regulatory categories	Adaptive regulatory frameworks and transparent clinical governance models
Integration with precision medicine	Studies emphasized the role of patient-specific biomarkers, genomic profiles, tumor signatures, and individualized therapeutic design	24	Synthetic biology platforms may become highly compatible with personalized medicine	Data integration, rapid design-to-manufacture pipelines, and equitable access models
Clinical evidence maturity	Studies noted that many platforms remain preclinical or early clinical, with limited large-scale efficacy and safety data	62	The field has strong innovation momentum but still requires stronger clinical validation	Larger trials, standardized outcome measures, comparative effectiveness studies, and real-world monitoring

Table 3 summarizes the major translational opportunities and barriers identified across the included studies. The most frequently identified issue was clinical evidence maturity, reported in 62 studies, indicating that although synthetic biology-based therapeutic platforms are scientifically promising, many remain at the preclinical or early clinical stage. This finding is important because it shows that the field is innovation-rich but evidence-maturing; therefore, the next phase of progress must involve rigorous clinical testing, standardized outcome measurement, long-term safety monitoring, and comparative evaluation against existing therapeutic modalities. Therapeutic precision was identified in 57 studies and emerged as one of the strongest advantages of synthetic biology. The ability to design therapeutic agents that respond to specific molecular

inputs, antigen combinations, inflammatory cues, metabolic states, or local tissue conditions represents a major departure from traditional pharmacological models. Instead of delivering a fixed therapeutic effect systemically, synthetic biology platforms can theoretically produce conditional, localized, and context-dependent responses. Safety and controllability were identified in 49 studies, reinforcing the idea that living medicines require a different safety paradigm from conventional drugs. Because engineered cells and microbes may proliferate, persist, evolve, or interact dynamically with host biology, safety mechanisms must be embedded into the therapeutic design rather than treated as external monitoring procedures alone. Manufacturing and scalability were reported in 43 studies and represented a major practical barrier, especially for patient-specific cell therapies and complex engineered biological systems. Without scalable manufacturing, reproducible quality control, and cost-efficient production, many promising platforms may remain limited to specialized centers or small patient populations. Delivery and localization were also central concerns, appearing in 41 studies, because even highly sophisticated therapeutic constructs may fail clinically if they cannot reach, survive, or function within the intended biological environment. Durability, regulatory complexity, ethical oversight, and integration with precision medicine were additional recurring themes that shaped the translational landscape. Taken together, these findings show that the future success of synthetic biology therapeutics depends on the simultaneous optimization of efficacy, safety, delivery, manufacturability, regulation, and clinical validation. The field is therefore best understood not simply as a collection of experimental therapies, but as a developing therapeutic infrastructure that requires coordinated progress across biological engineering, clinical medicine, biomanufacturing, regulatory science, and health-system implementation.

Overall, the findings of this systematic review indicate that synthetic biology is transforming therapeutic development by enabling the design of programmable, responsive, and living therapeutic systems. The evidence shows that bioengineered immunotherapies currently represent the most advanced clinical application, while programmable mammalian cells, engineered microbial therapeutics, synthetic gene circuits, and hybrid living systems represent major emerging directions. The reviewed studies consistently demonstrate that synthetic biology can expand therapeutic functionality beyond conventional drug action by enabling sensing, computation, feedback regulation, localized activity, and adaptive therapeutic response. However, the evidence also shows that the field remains unevenly developed, with strong preclinical innovation but more limited large-scale clinical validation. The most important barriers include safety control, delivery, persistence, manufacturing scalability, regulatory classification, and long-term monitoring. Despite these limitations, the horizon-scanning synthesis suggests that synthetic biology-based therapeutics are likely to become increasingly central to the future of precision medicine, particularly in oncology, immune-mediated diseases, microbiome-related disorders, metabolic conditions, and genetically defined diseases. The findings support the conclusion that programmable cells, living medicines, and bioengineered immunotherapies are not isolated technological trends, but interconnected components of a broader shift toward therapeutic platforms that can be designed, controlled, and adapted according to biological context.

Discussion and Conclusion

The present systematic review and horizon-scanning analysis examined the current landscape and future trajectory of synthetic biology-based therapeutic platforms, with particular emphasis on programmable cells, living medicines, engineered microbial therapeutics, synthetic gene circuits, and bioengineered immunotherapies. The findings revealed that bioengineered immunotherapies currently represent the most mature and clinically advanced therapeutic category, while

programmable mammalian cells, engineered microbial systems, synthetic gene circuit technologies, and hybrid living therapeutic platforms are rapidly emerging as transformative areas of biomedical innovation. Furthermore, the review demonstrated that the future of therapeutics is increasingly moving beyond conventional pharmacological interventions toward biologically intelligent systems capable of sensing, computing, responding, and adapting within complex physiological environments.

One of the most significant findings of this review was the predominance of bioengineered immunotherapies within the current therapeutic landscape. This observation reflects the remarkable success of immunotherapy over the past decade and the increasing integration of synthetic biology tools into immune-cell engineering. The dominance of this category is consistent with reports highlighting the rapid evolution of immunoengineering and the growing capacity to redesign immune cells for enhanced specificity, safety, and efficacy (Zhu et al., 2025). The integration of synthetic receptors, programmable signaling pathways, and logic-gated activation systems has fundamentally changed how immune cells interact with tumors and pathological tissues. Similarly, advances in natural killer cell engineering combined with nanotechnology have demonstrated the value of integrating multiple technological disciplines to enhance immune targeting and therapeutic precision (Li & Sun, 2025). The prominence of bioengineered immunotherapies observed in the present review therefore reflects both the scientific maturity of the field and its strong translational momentum.

The findings also demonstrated that programmable mammalian cells constitute one of the most promising emerging therapeutic directions. Studies included in the review consistently suggested that mammalian cells can be engineered to function as autonomous therapeutic agents capable of detecting disease-associated signals and generating regulated biological responses. These findings align with recent developments in in vivo cellular reprogramming, which have expanded the possibilities for manipulating cellular identity and function directly within living organisms (Islam et al., 2024). Similarly, the development of designer mammalian living materials illustrates how engineered cells can be incorporated into multifunctional therapeutic systems capable of sensing environmental stimuli and producing therapeutic outputs in a controlled manner (Gameiro et al., 2025). Together, these advances support the notion that future therapies may increasingly rely on living cellular systems rather than static pharmaceutical compounds.

Another important finding concerned the growing role of engineered microbial therapeutics and microbiome engineering. The review identified substantial evidence supporting the therapeutic potential of engineered microorganisms in the treatment of inflammatory, infectious, metabolic, and oncological diseases. This trend is consistent with recent reports emphasizing the capacity of microbiome engineering to modify host physiology, regulate immune responses, and restore biological homeostasis (Chen et al., 2025). Furthermore, the emergence of microbial and microalgal chassis for therapeutic protein production highlights the versatility of engineered biological systems as both therapeutic agents and manufacturing platforms (Bhandari et al., 2026). The increasing attention given to microbial biotechnology across multiple healthcare domains reflects broader predictions that engineered microorganisms will become central components of next-generation medicine (Lorenzo, 2021). The integration of biofilm engineering and synthetic biology further expands these possibilities by enabling the creation of structured biological systems with enhanced functionality and stability (Bhamidipaty et al., 2026).

The review also identified synthetic gene circuits as a foundational technology underlying many emerging therapeutic platforms. Although gene circuits were often embedded within larger therapeutic systems rather than functioning independently, they appeared repeatedly as critical mechanisms for therapeutic control, safety regulation, and biological

computation. This finding supports recent arguments that synthetic biology is increasingly shifting from simple genetic modification toward the engineering of sophisticated biological information-processing systems (Y. C. Zhang et al., 2025). The capacity to construct regulatory networks that respond dynamically to environmental signals enables the creation of therapies that can adapt to changing physiological conditions. Such capabilities represent a significant departure from traditional therapeutic paradigms, which typically rely on fixed dosing schedules and externally controlled interventions.

A major theme emerging from the horizon-scanning component of the review was the movement toward autonomous living medicines. The reviewed studies increasingly described therapeutic systems capable of sensing disease states and responding automatically through the production of therapeutic molecules or modulation of biological pathways. These findings reinforce the argument that synthetic biology is enabling a transition from passive treatment approaches toward active biological therapies that function continuously within the patient (Feng et al., 2024). The growing sophistication of biological sensing, molecular recognition, and feedback-control mechanisms suggests that future living medicines may operate as self-regulating therapeutic systems. Such developments align closely with broader trends in engineering biology that emphasize programmability, adaptability, and system-level integration (Bell, 2024; Kitney, 2021).

The results further demonstrated that precision medicine is becoming increasingly intertwined with synthetic biology-based therapeutics. Many studies highlighted the importance of integrating genomic, transcriptomic, proteomic, and other multi-omics datasets to guide therapeutic design and patient stratification. This observation is consistent with recent advances in acute myeloid leukemia research, where multi-omics approaches have enhanced understanding of disease heterogeneity and informed therapeutic decision-making (Samarkhazan, 2025). Similarly, quantitative systems pharmacology models developed for Parkinson's disease demonstrate the growing importance of systems-level approaches in precision therapeutic development (Denaro et al., 2024). The convergence of synthetic biology with precision medicine is particularly evident in efforts to combine CRISPR technologies, artificial intelligence, and regenerative approaches for complex disorders such as spinal cord injury (Covache-Busuioc et al., 2025). These developments suggest that future therapeutic platforms will likely be individualized, adaptive, and highly responsive to patient-specific biological contexts.

Another noteworthy finding was the increasing convergence between synthetic biology and advanced biomaterials. The review identified multiple examples of therapeutic systems that combined engineered cells with hydrogels, scaffolds, encapsulation technologies, or living materials. These hybrid platforms offer significant advantages by improving localization, containment, durability, and therapeutic control. Advances in hydrogel-based cancer immunotherapy provide strong evidence that biomaterials can significantly enhance immune-cell performance and therapeutic efficacy (Mamidi & Salehi, 2025). Similarly, developments in chitosan-based scaffolds for cartilage regeneration demonstrate how engineered materials can create supportive environments for tissue repair and regeneration (Rawojć et al., 2025). The growing interest in MXene-based biomedical technologies further supports the expansion of multifunctional therapeutic systems that integrate biological and material engineering principles (Pogorielov et al., 2025). These findings indicate that future therapeutic platforms may increasingly rely on the integration of living and non-living components to achieve optimal clinical outcomes.

The findings also highlighted the importance of emerging molecular engineering technologies such as nanobodies, engineered exosomes, de novo proteins, and cell-free systems. These technologies expand the therapeutic toolkit available to synthetic biology and create opportunities for highly targeted interventions. The versatility of nanobodies for diagnostics and therapeutics supports their growing role in precision medicine applications (Blueggel et al., 2025). Similarly, engineered

exosomes are increasingly recognized as promising therapeutic vehicles capable of delivering molecular payloads while interacting effectively with biological systems (G. Zhang et al., 2025). The emergence of de novo protein design represents an especially significant development because it allows researchers to construct biological functions that extend beyond naturally evolved proteins (Y. C. Zhang et al., 2025). Meanwhile, advances in cell-free protein synthesis systems provide alternative manufacturing and therapeutic strategies, although technical challenges remain regarding post-translational modifications and scalability (Porche et al., 2023).

While the therapeutic opportunities identified in this review are substantial, the findings also revealed several persistent translational barriers. The most commonly reported challenge concerned the relative immaturity of clinical evidence. Although innovation within synthetic biology is advancing rapidly, many therapeutic platforms remain at the preclinical or early clinical stage. Similar concerns have been raised regarding therapeutic development in neurodegenerative diseases, where promising biological mechanisms frequently encounter obstacles during clinical translation (Cummings et al., 2022). The gap between laboratory success and clinical implementation remains one of the most significant challenges facing the field.

Safety and controllability emerged as additional critical concerns. Living medicines possess unique capabilities, but they also introduce risks related to persistence, uncontrolled proliferation, immune activation, environmental release, and genetic instability. Consequently, many reviewed studies emphasized the importance of engineered safety mechanisms, containment systems, and kill-switch technologies. These concerns are particularly relevant in the context of microbiome engineering and microbial therapeutics, where interactions between engineered organisms and natural ecosystems must be carefully managed (Chen et al., 2025; Nass & Zaher, 2025). The findings suggest that future therapeutic success will depend not only on therapeutic efficacy but also on the ability to maintain reliable biological control.

Manufacturing and scalability represented another major barrier identified across the reviewed literature. Unlike conventional pharmaceuticals, many synthetic biology-based therapies require complex biological production systems, individualized manufacturing workflows, and stringent quality-control procedures. Previous studies emphasizing the development of engineering biology infrastructure and industrial capacity have similarly identified manufacturing as a critical determinant of future success (Curach, 2021; Donati et al., 2022; Krink et al., 2022). Emerging concepts such as advanced biomanufacturing and novel production environments may contribute to overcoming these barriers, although significant technological and economic challenges remain (Giulianotti et al., 2021).

The review also demonstrated that artificial intelligence, computational biology, and systems-level modeling are becoming increasingly important within synthetic biology. These technologies can facilitate therapeutic design, predict biological behavior, optimize therapeutic constructs, and support clinical decision-making. The growing integration of AI within immunoengineering and regenerative medicine reflects a broader trend toward computationally guided therapeutic development (Covache-Busuioc et al., 2025; Zhu et al., 2025). As biological systems become more complex and personalized, computational approaches will likely become essential for translating synthetic biology innovations into clinically viable therapies.

Overall, the findings suggest that synthetic biology is fundamentally reshaping the therapeutic landscape by introducing a new generation of programmable, adaptive, and biologically intelligent interventions. The convergence of cellular engineering, immunotherapy, microbiome science, biomaterials, nanotechnology, artificial intelligence, and precision

medicine is creating unprecedented opportunities for disease treatment. Consistent with broader assessments of engineering biology, the reviewed evidence indicates that the field is transitioning from an innovation-driven phase toward a translational and implementation-oriented era (Bell, 2024; Feng et al., 2024). If current scientific, manufacturing, and regulatory challenges can be successfully addressed, programmable cells, living medicines, and bioengineered immunotherapies may become central pillars of future healthcare systems.

This review has several limitations. First, the rapidly evolving nature of synthetic biology means that new therapeutic technologies and clinical developments may emerge shortly after publication, potentially affecting the comprehensiveness of the findings. Second, the review included only English-language publications, which may have excluded relevant evidence from other linguistic contexts. Third, the majority of included studies were preclinical investigations, limiting the ability to draw firm conclusions regarding long-term clinical efficacy and safety. Fourth, substantial heterogeneity existed across therapeutic platforms, disease applications, methodological designs, and outcome measures, making direct comparisons difficult. Finally, horizon-scanning approaches inherently involve interpretation regarding future developments, and some anticipated therapeutic trajectories may evolve differently than currently predicted.

Future research should prioritize longitudinal clinical studies evaluating the safety, efficacy, durability, and real-world performance of synthetic biology-based therapies. Greater attention should be devoted to comparative effectiveness studies that evaluate programmable therapeutic systems against conventional treatment approaches. Researchers should also investigate strategies for improving biological containment, controllability, and reversibility in living medicines. Additional studies are needed to explore the integration of artificial intelligence, multi-omics technologies, and synthetic biology for personalized therapeutic design. Furthermore, future investigations should examine ethical, legal, economic, and social implications associated with large-scale deployment of programmable biological therapies across diverse healthcare systems.

Healthcare organizations, biotechnology developers, and regulatory authorities should collaborate early during therapeutic development to facilitate safe and efficient clinical translation. Investment in advanced biomanufacturing infrastructure and workforce training will be essential to support future implementation of living medicines and programmable therapeutic systems. Clinical practitioners should prepare for increasing integration of engineered biological therapies into treatment pathways by developing expertise in precision medicine, cell-based interventions, and emerging biotechnology platforms. Regulatory agencies should establish adaptive evaluation frameworks capable of addressing the unique characteristics of dynamic and programmable therapies. Finally, multidisciplinary collaboration among clinicians, engineers, biologists, data scientists, ethicists, and policymakers should be strengthened to ensure that future therapeutic innovations are safe, effective, accessible, and aligned with societal needs.

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Authors' Contributions

Authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

AI use statement

Artificial intelligence tools were used only to support language editing, translation refinement, formatting, and consistency checks. The authors take full responsibility for the accuracy of the data, analyses, interpretations, citations, and final content of the manuscript.

Ethical Considerations

This study was conducted using interview and questionnaire data. Participation was voluntary, and the confidentiality of participants' responses was preserved. The research procedure was designed to avoid harm to participants and to respect the principles of informed participation and academic integrity.

Transparency of Data

Reasonable requests for research materials should be directed to the corresponding author, subject to university policies and participant confidentiality.

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