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Editorial

The future of precision medicine: Integrating genetic engineering into pharmacological research

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Abstract

The integration of genetic engineering into pharmacological research is transforming the landscape of precision medicine, offering the potential to revolutionize healthcare. Precision medicine focuses on tailoring treatments to individuals based on genetic, environmental, and lifestyle factors, moving beyond the traditional "one-size-fits-all" approach. This editorial highlights the pivotal role of genetic engineering in advancing precision medicine, exploring its applications in drug discovery, pharmacogenomics, and innovative therapies such as gene and cell treatments. Tools like CRISPR-Cas9 and advancements in omics technologies have accelerated the development of personalized therapies and enhanced our understanding of disease mechanisms. Despite these breakthroughs, challenges persist. Technical hurdles like off-target effects, ethical concerns surrounding germline editing, and the high costs of these technologies must be addressed. Opportunities, however, abound—ranging from artificial intelligence-driven innovations to collaborative research initiatives, which promise to streamline the development of genetic engineering applications. This convergence of disciplines is not only reshaping drug development but also expanding the therapeutic arsenal to tackle complex diseases. With sustained investment, interdisciplinary collaboration, and an emphasis on equitable access, the promise of precision medicine—treatments tailored to each individual's genetic blueprint—is rapidly becoming a reality.

The concept of precision medicine has transformed the healthcare landscape, offering the promise of tailoring treatments to individual patients based on their genetic, environmental, and lifestyle factors (Marques *et al.*, 2024). At the heart of this revolution lies the integration of genetic engineering into pharmacological research, a convergence that has the potential to redefine drug development, enhance therapeutic efficacy, and minimize adverse effects (Alzoubi *et al.*, 2023). This editorial explores the dynamic interplay between genetic engineering and pharmacology, highlights key advancements, and examines the challenges and opportunities that lie ahead in the pursuit of precision medicine. Traditional medicine has long followed a "one-size-fits-all" approach, where treatments are developed and prescribed with the assumption of universal efficacy. However, individual variability in drug responses—driven by genetic differences—has revealed the limitations of this model (Jamrat *et al.*, 2023; Sugandh *et al.*, 2023). Precision medicine seeks to overcome these limitations by utilizing patient-specific data to guide clinical decisions. Genetic engineering plays a vital role in this paradigm shift, providing the tools to manipulate and understand the genetic underpinnings of disease and drug response (Strianese *et al.*, 2020; Puccetti *et al.*, 2024).

Genetic engineering encompasses a suite of technologies that enable the precise modification of DNA sequences. Techniques such as CRISPR-Cas9, TALENs, and zinc-finger nucleases have revolutionized our ability to edit genomes with unprecedented accuracy. These tools are now being applied across various domains of pharmacological research, including drug discovery, development, and personalized treatment strategies (Hsu *et al.*, 2014; Aljabali *et al.*, 2024; Dutta, 2024a, 2024b). Genetic engineering has accelerated the pace of drug discovery by enabling the creation of more accurate disease models. For instance, CRISPR technology allows scientists to introduce specific mutations into cell lines or animal models, mimicking the genetic basis of human diseases. These models are invaluable for screening potential drug candidates and understanding disease mechanisms at a molecular level (Rubbini *et al.*, 2020; Wang and Doudna, 2023). Furthermore, genetic engineering facilitates the production of biologics, including monoclonal antibodies, recombinant proteins, and gene therapies. These biologics are increasingly becoming the cornerstone of treatments for conditions such as cancer, autoimmune diseases, and genetic disorders. Genetic engineering enables the fine-tuning of these molecules to enhance their specificity, efficacy, and safety (Banerjee and Ward, 2022; Szkodny and Lee, 2022).

Pharmacogenomics, the study of how genes influence drug responses, is a critical component of precision medicine. Genetic variations in enzymes, receptors, and transporters can significantly impact a drug's metabolism, efficacy, and toxicity. By leveraging genetic engineering, researchers can identify and validate these variations, paving the way for personalized therapies (Ahmed *et al.*, 2016; Qahwaji *et al.*, 2024). For example, variations in the CYP450 family of enzymes, responsible for metabolizing many drugs, can lead to differences in drug clearance rates among individuals. Genetic engineering tools can be used to create cell or animal models harboring these variants, enabling the study of their functional impact

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and informing dose adjustments in clinical practice (Hossam *et al.*, 2024).

Gene and cell therapies represent some of the most direct applications of genetic engineering in precision medicine. These therapies involve the introduction, removal, or alteration of genetic material to treat or prevent disease. For instance, CAR-T cell therapy, which modifies a patient's T cells to target cancer cells, has shown remarkable success in treating certain types of leukemia and lymphoma (Bulcha *et al.*, 2021; Yu *et al.*, 2022). Similarly, gene-editing approaches are being explored to correct genetic defects underlying monogenic disorders such as cystic fibrosis, sickle cell anemia, and Duchenne muscular dystrophy. These therapies exemplify the potential of genetic engineering to address previously untreatable conditions and highlight its transformative impact on pharmacology (Deneault, 2024).

While the integration of genetic engineering into pharmacological research holds immense promise, it is not without challenges. Addressing these hurdles is essential to fully realize the potential of precision medicine. Achieving precise and efficient gene editing remains a significant technical challenge. Off-target effects, where unintended regions of the genome are edited, can lead to undesired outcomes and safety concerns. Advances in bioinformatics and engineering of more accurate editing tools are critical to overcoming this limitation. Additionally, the complexity of polygenic diseases, where multiple genes and environmental factors interact, poses challenges for developing effective therapies. Understanding these intricate interactions requires sophisticated computational models and large-scale genomic datasets (Aljabali *et al.*, 2024; Merlin and Abrahamse, 2024). The use of genetic engineering raises ethical questions, particularly concerning germline editing, which involves modifications that can be passed to future generations. Striking a balance between scientific progress and ethical responsibility is crucial to gaining public trust and ensuring equitable access to these technologies. Regulatory frameworks for gene-edited products are still evolving. The development of clear guidelines that address safety, efficacy, and quality control is essential to facilitate the translation of genetic engineering advancements into clinical practice (Rubeis and Steger, 2018; Almeida and Ranisch, 2022). The high cost of genetic engineering technologies and therapies limits their accessibility, particularly in low- and middle-income countries. Efforts to reduce costs through innovation, scale-up, and public-private partnerships are necessary to ensure that precision medicine benefits are globally equitable (Doxzen *et al.*, 2024).

Despite these challenges, the integration of genetic engineering into pharmacological research offers numerous opportunities for innovation and impact. The proliferation of omics technologies, including genomics, transcriptomics, and proteomics, provides a wealth of data to inform precision medicine. Integrating these datasets with genetic engineering tools enables a deeper understanding of disease biology and drug response, driving the development of targeted therapies (Chakraborty *et al.*, 2024; Mohr *et al.*, 2024). Artificial intelligence (AI) and machine learning (ML) are revolutionizing pharmacological research by enabling the analysis of complex genomic datasets. These technologies can predict off-target effects, identify druggable targets, and optimize the design of gene-editing tools, accelerating the path from discovery to application (Quazi, 2022; Yadav *et al.*, 2024). Collaboration between academia, industry, and government is essential to advancing genetic engineering in pharmacology. Initiatives such as the Human Genome Project and the All of Us Research Program demonstrate the power of collective efforts in generating valuable genomic insights and fostering innovation (Heilbron *et al.*, 2021). Genetic engineering is opening new frontiers in drug development, from RNA-based therapies and CRISPR-based gene editing to synthetic biology approaches for creating novel biomolecules. These innovations are expanding the therapeutic arsenal available to tackle complex diseases (Zahedipour *et al.*, 2024).

The integration of genetic engineering into pharmacological research is driving the evolution of precision medicine, offering the potential to revolutionize healthcare. By enabling the development of personalized therapies, addressing previously untreatable conditions, and enhancing our understanding of disease mechanisms, genetic engineering is reshaping the future of medicine. However, realizing this vision requires overcoming technical, ethical, and accessibility challenges. It also demands sustained investment in research, interdisciplinary collaboration, and a commitment to equity in healthcare. As the field continues to advance, the promise of precision medicine—a world where treatments are tailored to each individual's unique genetic makeup—moves closer to becoming a reality.

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None to declare.

Data availability

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Informed consent statement

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Conflict of interest

The authors declare no competing interests.

Authors' contribution

Md. Mosharraf Hossen contributed to the conceptualization and writing of this editorial. The author has read and approved the final version of the published editorial.

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