INTERNATIONAL JOURNAL OF PHARMACEUTICAL SCIENCES
[ISSN: 0975-4725; CODEN(USA): IJPS00]
Journal Homepage: https://www.ijpsjournal.com

OPEN ACCESS

Review Article

CRISPR-Cas9 Genome Editing: Mechanisms, Applications, Challenges, and Future Horizons

Jiya Goswami*[1], Vani Varia[1], Yagnesh Modi[2], Satyajit Sahoo[3], D.B. Meshram[4]

[1.] *Student, Pioneer Pharmacy College, At & Post: Sayajipura, Ajwa-Nimeta Road, Vadodara, Gujarat, India.*
[2.] *Assistant Professor, Pioneer Pharmacy College, At & Post: Sayajipura, Ajwa-Nimeta Road, Vadodara, Gujarat, India.*
[3]. *Associate Professor, Pioneer Pharmacy College, At & Post: Sayajipura, Ajwa-Nimeta Road, Vadodara, Gujarat, India.*
[4.] *Principal, Pioneer Pharmacy College, At & Post: Sayajipura, Ajwa-Nimeta Road, Vadodara, Gujarat, India*

ARTICLE INFO

Published: 26 Sept. 2026
Keywords:
CRISPR-Cas9, Genome Editing, Single Guide RNA (sgRNA), Gene Therapy, Non-Homologous End Joining (NHEJ), Homology-Directed Repair (HDR).
DOI:
10.5281/zenodo.22967571

ABSTRACT

The Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) and CRISPR-associated protein 9 (Cas9) technology has revolutionized the process of genome editing, making the protein engineering process much more simplified and focused on RNA-directed modification. Initially described as an adaptive immune response in bacteria, CRISPR-Cas9 technology makes possible targeted therapies, plant genome modification, and model organism generation. This review article will describe how Cas9 causes double-stranded DNA breaks, delivery methods of engineered Cas9 and guide RNAs to host cells using viral and non-viral vector systems, as well as new approaches to non-replicating cell genome editing and regulation without DNA breakage. Possible safety limitations such as off-target cleavage, unexpected rearrangement of genome, presence of existing immunity to the vectors and ethical concerns about germline and zygotic editing will be addressed.

INTRODUCTION

Genome editing technology allows for accurate modifications of genome DNA sequences in living beings [1, 2]. Prior to the appearance of CRISPR technology, genome editing was achieved using tools such as zinc finger nucleases (ZFNs) and transcription activator-like effector nucleases (TALENs). However, ZFNs and TALENs technologies were limited by their cost, difficulty of protein design, and technical complexity [2, 12]. The emergence of the CRISPR-Cas9 technology has greatly reduced these obstacles, as it provides for the introduction of a highly modifiable sgRNA

***Corresponding Author:** Jiya Goswami
Address: *Pioneer Pharmacy College, At & Post: Sayajipura, Ajwa-Nimeta Road, Vadodara, Gujarat, India*
Email ✉: jiyavpgoswami1@gmail.com
Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

that targets the endonuclease to a specific locus in the genome [3, 13].

2. Objectives & Scope

2.1 Objectives

- Outline the history of CRISPR-Cas9 development starting from bacterial immune system to current gene-editing platforms [3, 13].
- Describe CRISPR-Cas9 applications in human therapeutics, crops modification, and model organism generation (M. musculus, *D. melanogaster, A.* thaliana) [4, 5, 14, 15].
- Analyze delivery systems (e.g., AAV vectors, liposomes), as well as new editing techniques (epigenetic editing, non-proliferating cells' editing) [6, 7, 16].
- Discuss issues of ethics, legality, and safety of clinical studies involving human patients and zygote editing [9-11, 17].

2.2 Scope

This review highlights the main experimental results, technical achievements, and clinical achievements described in 52 key literature sources [1-52].

3. Historical Overview & Evolution

- **Bacterial Origin of CRISPR System: Found as an adaptive prokaryotic immune** system protecting bacteria from viruses via cleavage of foreign nucleic acid molecules [3].
- Development of **Genome** Editing Technique: Conversion of the dual-RNA guiding structure into the artificial single guide RNA (sgRNA) cleaving eukaryotic DNA targets [13].
- Expanding **Model** Systems: Efficient use in genetic model organisms such as Drosophila, rodent models, and *Arabidopsis thaliana* [4, 5, 14, 15].

4. Key Topics & Technological Developments

4.1 Mechanisms of Action & Engineering

- Targeted **Guide RNA Delivery & DNA Cleavage:** Engineered guide RNA directs Cas9 enzyme to desired genomic sites [13]. Cas9 enzyme recognizes PAM sequence and creates a double-strand break (DSB) [3, 13].
- Genomic **DNA Repair: Double-stranded breaks undergo repair** through Non-Homologous End Joining (NHEJ), which results in random insertions of nucleotides at a target site and produces gene knockouts, and through Homology-Directed Repair (HDR), which involves insertion of a sequence via donor DNA [1, 2].
- Increasing Efficiency: The introduction of cloning-free CRISPR procedures and rapid construction of endogenous transcriptional reporters [18, 19].
- Genetic Modifications: Protocols enabling large fragment deletion and site-specific insertions [8].

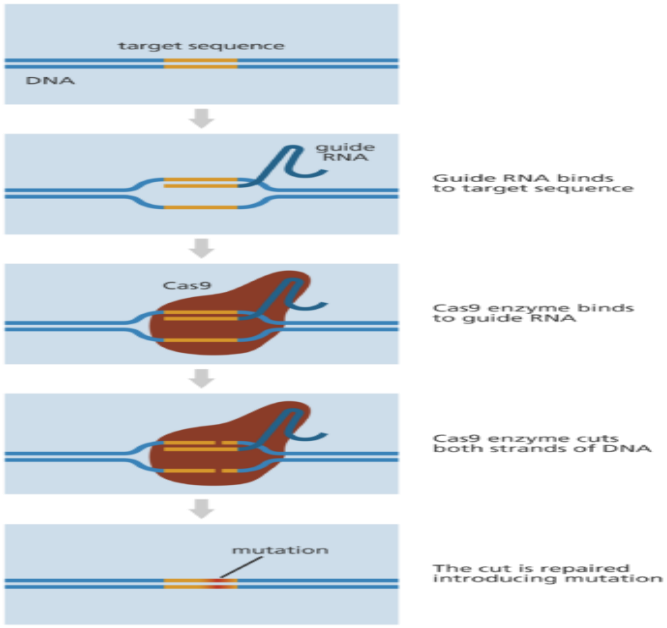


Figure 1: CRISPR-Cas9 Working Principle

4.2 Delivery Methods & Vector Systems

- Viral-Based: Pre-established AAV delivery system designed for delivery of Cas9 and guide RNAs on a tissue-specific basis [6, 16].
- In Zygote: Delivery in one step by injecting the zygote/embryo to produce knock-in and transgenic animals [5, 20].

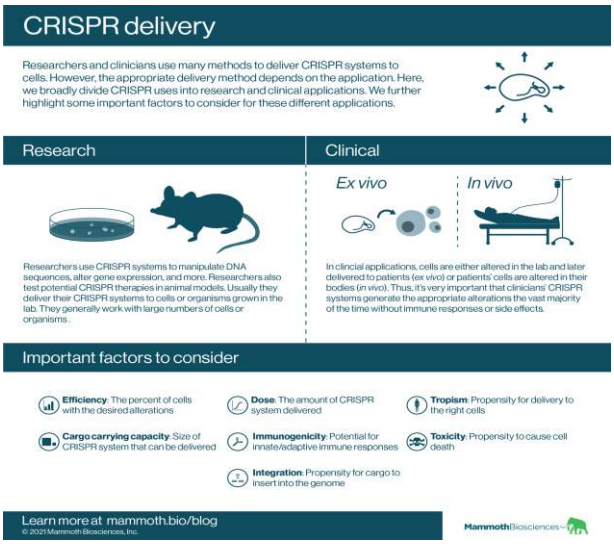


Figure 2: CRISPR Delivery Protocols

4.3 Therapeutic & Agricultural Applications

- **Organ** Transplant Therapy: Preserving the donor organs in an ex vivo fashion before the transplant surgery [21].

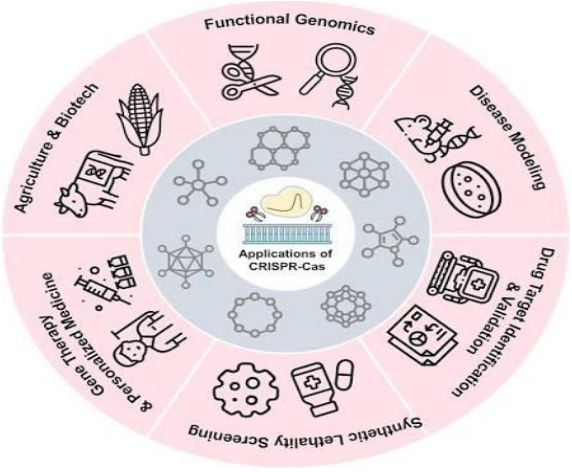
- **Non-Dividing Cells:** Targeted integration methods for gene editing in non-dividing cells without resorting to cell division (homology-independent targeted integration) [7].
- **Plant Biotechnology:** Homozygous mutant plants (crops) developed through the use of *Arabidopsis* egg cell-specific promoters in one generation [15, 22].
- **Epigenetic** Editing: Fusion of inactive Cas9 protein (dCas9) to transcription factors, thus enabling locus-specific regulation of gene expression without changes in DNA sequence [23, 24].

4.4 Ethical, Safety, & Regulatory Considerations

- Genome Integrity: Assessment of off-targets cutting events, chromosomal rearrangements, and large-scale structural deletions [9, 25].
- **Human Germline** Modification: Ethical considerations of human tripronuclei zygote and germline modifications [11, 17, 26].
- Regulation of **Clinical** Trials: Regulatory control over therapy dosages, safety regulations, and intellectual property rights in clinical human trials [10, 27, 28].

5. Future Aspects & Clinical Directions

- **Epigenetic Editing:** Development of dCas9-based gene expression regulators that regulate gene expression without producing DNA double-strand breakage [23, 24].
- Improvement of **Non-viral** Vectors: Modification of lipid nanoparticles (LNPs) to reduce immunogenicity and increase tissue-specificity outside liver cells [29, 30].
- **Clinical** Trials in Humans: Expansion of human trials of treatments for blood diseases, transthyretin amyloidosis, and immunotherapy for cancer [31-33].
- **International** Guidelines: Establishment of international regulatory guidelines for ethics and access to gene therapies [10, 27].



(Figure 3: CRISPR-Cas Applications)

5.1 Extended Clinical & Tool Categories

5.1.1 Human Therapeutics & Clinical Care

- **Genetic** Disorders of Blood: Genetic modification of stem cells outside the body for Sickle Cell Anemia and β thalassemia by disabling the enhancer of *BCL11A* gene [31].

- **In Vivo** Therapy: Genetic editing directly into the liver to treat diseases like transthyretin amyloidosis [32].
- **Donor** Organs: Ex vivo organ perfusion followed by CRISPR targeting to prevent organ rejection [21].
- **Post-mitotic Tissue** Treatment: Targeted integration techniques for post-mitotic tissues [7].

5.1.2 Agriculture & Model Organism Engineering

- Plant Tolerance **&** Productivity: Fast one-generation mutants generated through germline-specific promoter systems [15, 22].
- **Animal Model** Development: Embryonic microinjection in *Drosophila* and mouse models to establish transgenic models [4, 5, 14, 20].

5.1.3 Advanced Genetic & Molecular Tools

- **Epigenetic** Modulation: Catalytically dead dCas9 conjugated with transcription activators/repressors for transcriptional induction/silencing [23, 24].
- **Base & Prime Editing:** Single-base changes and replacement editing without causing double-strand breaks [34-36].

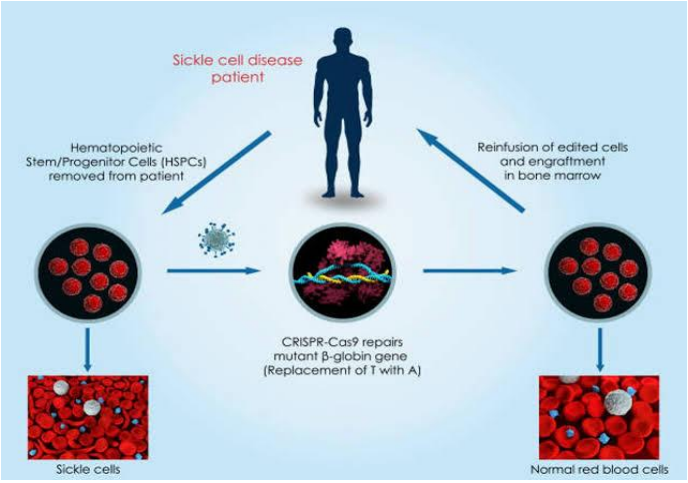
6. Challenges and Limitations of CRISPR-Cas9

- **Off-Target** Edits: Off-target cutting may occur when there is a mismatch between the sgRNA and genomic DNA sequence [9, 25].
- **On-Target Structural** Changes: Double-strand breaks may result in big deletions, chromosomal changes, or translocations at the target locus [9].
- Transport Obstacles: Encapsulation of Cas9 system elements in nontoxic organ-specific vehicles is a significant obstacle; AAVs are burdened by capacity issues, whereas LNPs have difficulty with targeting extrahepatically [6, 29, 30].
- Reaction of the **Immune** System: The prior presence of antibodies and T cells to Cas9 proteins from *S. aureus and S. pyogenes* can be detrimental for treatment clearance and immune reactions [37, 38].
- Inefficiency **in** Post-Mitotic Cell Types: Repair of DSB through HDR takes place mostly in dividing cells, hindering the replacement of genes in non-dividing post-mitotic tissues such as neurons [7].
- **Ethical and** Accessibility Issues: Financial costs restrict global availability, while the germline and embryonic edition have long-term ethical consequences [10, 11, 17, 26, 27].

7. Case Studies

7.1 Sickle Cell Disease & β-Thalassemia (Ex Vivo Stem Cell Therapy)

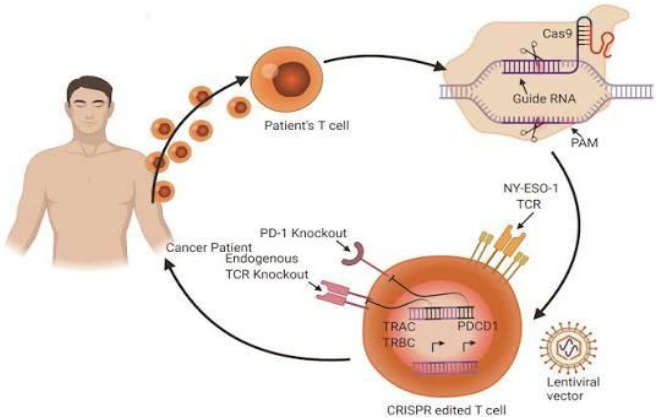
- Approach for Treatment: Ex vivo gene editing of the patient's own CD34+ hematopoietic stem and progenitor cells (HSPCs) [31].
- **Molecular Mechanism:** CRISPR-Cas9 is used to target the erythroid-specific enhancer domain of BCL11A [31]. The disruption of this enhancer prevents the transcription of BCL11A and activates the production of fetal hemoglobin HbF ($\alpha_2\gamma_2$) to prevent sickling of the red blood cells [31].
- **Clinical** Evidence: The patients showed increased levels of HbF, absence of vaso-occlusive crises, and independence of blood transfusion [31].



(Figure 4: Pathway for Ex Vivo Editing of HSPCs)

7.2 Cancer Immunotherapy (Engineered CAR-T Cells)

- Approach for Treatment: T-cells from the patient or donors are first subjected to multiple rounds of CRISPR-Cas9 editing ex vivo prior to re-infusion.
- **Molecular Mechanism:** Inactivation of the *PDCD1* gene, which is responsible for producing PD-1, will hinder the development of exhaustion in T-cells due to the tumor [39]. Knockout of both endogenous T-cell receptor genes (TRAC/TRBC) and *HLA* genes allows for off-the-shelf allogenic CAR-T cells to be used without GvHD [33, 39].
- **Clinical** Evidence: Gene editing for multiple genes has led to improvements in CAR-T persistence and antitumor effectiveness [33, 39].



(Insert Figure 5: Workflow of Engineered CAR-T Cells)

8. Declarations

- **Conflict of Interest:** Authors report no conflict of interest concerning the publication of this manuscript.
- Financial Disclosure: This manuscript did not receive any specific funding.

9. CONCLUSION

The CRISPR-Cas9 technology has marked a breakthrough in molecular biology and experimental medicine [1, 2]. The problems that need solving are those of off-target cleavage, delivery of targets, immunity, and bioethical issues [6, 9, 10, 37]. Improvements in base editing, prime editing, dCas9-based epigenetic control, and non-viral delivery systems will help increase the scope of use for gene-editing therapies [23, 29, 34, 35].

REFERENCES

1. https://pubmed.ncbi.nlm.nih.gov/31021185/M Adli. The CRISPR toolbox for genome engineering and beyond. Nat Commun. 2018;9(1):1911. Accessed
2. https://pubmed.ncbi.nlm.nih.gov/29628199/D oudna, JA; Charpentier, E. The Chemistry and Biology of RNA-Guided Genome Engineering. Science. 2014;34
3. https://pmc.ncbi.nlm.nih.gov/articles/PMC45 29991/Jinek M, Chylinski K, Fonfara I, Hauer M, Doudna JA, Charpentier E. A programmable dual-RNA guided DNA endonuclease in adaptive bacterial immunity. Science. 201
4. https://www.ncbi.nlm.nih.gov/pmc/articles/P MC3730909/Bassett AR, Tibbit C, Ponting CP, Liu JL. Highly Efficient Targeted Mutagenesis of Drosophila Using the CRISPR/Cas9 System. Genetics. 2013;
5. https://www.ncbi.nlm.nih.gov/pmc/articles/P MC3961010/Yang H, Wang H, Shivalila CS, Cheng AW, Shi L, Jaenisch R. One-step generation of mice carrying gene-edited alleles by CRISPR/Cas-mediated genome engineering. Cell. 2013;153(4):
6. https://pubmed.ncbi.nlm.nih.gov/293120821/ Hung SS, Chrysostomou V, Li F, Wang JH, Williamson R, Luu CD, et al. ACRISPR/Cas9 gene editing toolbox based on adeno-associated virus vectors. Human gene therapy. 2016;27
7. https://crisprmedicinenews.com/news/crispr-replaces-dna-in-non-dividing-cells/Suzuki K, Tsunekawa Y, Hernandez-Benitez R, Yu J, Chan J, Kurita M, et al. In vivo genome editing through homology-independent targeted integration by CRISPR/Cas9. Nature. 2016;54
8. https://www.researchgate.net/publication/320 685855_Large_Genomic_Fragment_Deletion s_and_Insertions_in_Mouse_Using_CRISPR Cas9Kraft L, Kurita M, Suzuki K, Belmonte JCI. Large Genomic Fragment Deletions and Insertions in Mouse Using CRISPR/Cas9. Mamm Genome. 2017;28
9. https://pubmed.ncbi.nlm.nih.gov/30482590/K osicki C, Tomberg K, Bradley A. CRISPR–Cas9-mediated targeting and repair of double-strand breaks causes extensive chromosomal rearrangements and complex deletions. Nat Biotechnol. 2018;3
10. https://academic.oup.com/jlb/article/3/2/413/1 751234Sherkow JS. Law, arbitrary innovation, and CRISPR-Cas9. J Law Biosci. 2016
11. https://pmc.ncbi.nlm.nih.gov/articles/PMC44 43921/P Liang, Y Xu, X Zhang, C Ding, R Huang, Z Zhang, et al. Gene editing in human tripronuclear zygotes using CRISPR/Cas9 system. Protein Cell. 2015;6(5):
12. https://www.ncbi.nlm.nih.gov/pmc/articles/P MC4322718/Sander JD, Joung JK. CRISPR-Cas systems for editing, regulating and targeting genomes. Nat Biotechnol. 2014;32(
13. https://pubmed.ncbi.nlm.nih.gov/26375006/C ong L, Ran FA, Cox D, Lin S, Barretto R, Koziarski C, et al. Multiplex genome engineering using CRISPR/Cas systems. Science. 2013;339(
14. https://www.ncbi.nlm.nih.gov/pmc/articles/P MC4489958/Fujii W, Kawasaki K, Sugiura K, Naito K. Cloning-free CRISPR/Cas system enables functional cassette knock-in in mice. J Reprod Dev. 2015;61

15. https://pmc.ncbi.nlm.nih.gov/articles/PMC4511082/Wang ZP, Xing HL, Dong L, Zhang H, Han CY, Wang XC, et al. Efficient generation of homozygous mutants targeting multiple genes by using the CRISPR/Cas9 system directed by an egg cell specific promoter in Arabidopsis within a single generation. Genome Biol. 2015;16(1):1
16. https://www.sciencedirect.com/science/article/pii/S2162253126000302Xu L, Wang J, Liu Y. Engineering of AAV capsid for improved tissue tropism in CRISPR gene editing. Mol Ther. 2026;34(1):21
17. https://pubmed.ncbi.nlm.nih.gov/28879860/HMa, N Marti-Gutierrez, S W Park, J Wu, Y Lee, K Suzuki, et al. Correction of a Pathogenic Gene Mutation in Human Embryos. Nature. 2017;548(7668):
18. https://pmc.ncbi.nlm.nih.gov/articles/PMC4632001/Ratz M, Testa I, Hell SW, Jakobs S. Rapid creation of transcriptional reporters endogenously controlled in cells using CRISPR/Cas9 technology. Sci Rep. 2015;5:160
19. https://www.researchpublish.com/upload/book/CRISPRCas9%20Genome%20Editing-8103.pdfGupta M, Kumar S. CRISPR/Cas9 Genome Editing: Principles and Techniques. Monograph Series 8103. Research Publish Journals; 2020
20. https://bcsrj.com/index.php/bcsrj/article/view/17Tahir T, Ali Q, Rashid M, Malik A. Journey of CRISPR-Cas9 technology from bacterial defense system to an instrument of gene editing in animals as well as plants. Biol Clin Sci Res J. 2020;2020:e017. Available at: https://bcsrj.com
21. https://crisprmedicinenews.com/news/crispr-improves-ex-vivo-donor-organ-treatment-1/Jensen M, Smith A, Taylor R. CRISPR enhances treatment of donor organs in vitro. CRISPR Med News. 2025; Report 101.
22. https://pmc.ncbi.nlm.nih.gov/articles/PMC6315587/Chen K, Wang Y, Zhang R, Zhang H, Gao C. CRISPR/Cas systems in agricultural biotechnology and crop adaptation. Annual Review of Plant Biology. 2019;70:667-69
23. https://ingena.org.au/crisprs-next-act-what-epigenetic-editing-means-for-australias-genomics-system/Genomics Insights Group InGena. CRISPR's Next Act: The Significance of Epigenetic Editing for the Australian Genomics Ecosystem. Policy Brief. InGena; 2025.
24. https://pubmed.ncbi.nlm.nih.gov/31915817/Pickar-Oliver A, Gersbach CA. The next generation of CRISPR-Cas technologies and applications. Nat Rev Mol Cell Biol. 2019;20(8):
25. https://pmc.ncbi.nlm.nih.gov/articles/PMC9245484/Tsai SQ, Joung JK. Off-target profiling protocols: from GUIDE-seq to CIRCLE-seq. Nature protocols. 2019 Jan 2
26. https://www.hilarispublisher.com/open-access/crisprcas9-human-genome-editing-challenges-ethical-concerns-and-implications-2155-9627-1000253.pdfOtieno MO. CRISPR-Cas9 human genome editing: Challenges, ethical issues and implications. J Clin Res Bioeth. 2015;6(5):
27. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5252389Sherkow, JS, & Contreras, JL. Intellectual Property and Regulatory Frameworks for Gene Editing Technology. SSRN Electronic Journal 2025:Abstract ID 5252389.
28. https://www.nsf.gov/impacts/crisprAdvisory Board of the National Science Foundation. The Broader Impacts of Gene Editing Technologies on Science and Society. NSF Impact Reports; 2024. Accessed at: https://www.nsf.gov/
29. https://www.sciencedirect.com/science/article/pii/S1773224724000066Mendonça MC,

Silva AL, Almeida RM. Nano-medicine strategies for the delivery of nucleic acids and components of CRISPR. Eur J Pharm Sci. 2024;192:

30. https://pmc.ncbi.nlm.nih.gov/articles/PMC10916045/A, R., S., B. and D. R. L. In vivo delivery paradigms for Cas endonucleases. Nature Biomedical Engineering, 2024;
31. https://pubmed.ncbi.nlm.nih.gov/30664785/Frangoul H, Altshuler D, Cappellini MD, Chen YS, Domm J, Eustace BK, et al. CRISPR-Cas9 Gene Editing for Sickle Cell Disease and β-Thalassemia. N Engl J Med.
32. https://pubmed.ncbi.nlm.nih.gov/33283989/Gillmore JD, Gane E, Taubel J, Kao J, Fontana M, Maitland ML, et al. In vivo gene editing of transthyretin amyloidosis using CRISPR-Cas9. N Engl J Med. 202
33. https://innovativegenomics.org/news/crispr-clinical-trials-2025/Stadtmauer EA, Fraietta JA, Davis MM, Cohen AD, Weiss BM, Integrated Oncology Group, et al. CRISPR-engineered T cells in patients with refractory cancer. Science. 2020;367(64
34. https://pubmed.ncbi.nlm.nih.gov/29339778/Gaudelli NM, Komor AC, Rees HA, Packer MS, Badran AH, Bryson Chung, et al. Programmable Base Editing of A·T to G·C in Genomic DNA without DNA Cleavage. Nature. 2017;551(768
35. https://pubmed.ncbi.nlm.nih.gov/30995964/Anzalone AV, Randolph PB, Davis JR, Sousa AA, Koblan LW, Levy JM, et al. Search-and-replacement genome editing without double-strand breaks or donor DNA. Nature. 2019;576(7785
36. https://pubmed.ncbi.nlm.nih.gov/31666940/Komor AC, Badran AH, Liu DR. Base editing: Deaminase reactions of cytosine and adenine in genomic DNA. Cell. 2019;179(3
37. https://www.hilarispublisher.com/open-access/immunological-barriers-to-in-vivo-gene-editing-using-bacterial-endonucleases.pdfAdelman ER, Huang G, Wood C. Immunological barriers to in vivo gene editing using bacterial endonucleases. J Clin Cell Immunol. 2018;9(5):1000300
38. https://pmc.ncbi.nlm.nih.gov/articles/PMC7765739/Charlesworth CT, Deshpande PS, San severe AI, Dejene BT, Gomez-Ospina N, Mantri S, et al. Pre-existing adaptive immune responses to Cas9 proteins in humans. Nat Med. 2019;25(2):249-5
39. https://www.researchgate.net/publication/387444991_A_Review_of_Research_on_CRISPRCas9_Gene_Editing_Technology_in_Disease_TreatmentSharma R, Patel K. Review of the Research in CRISPR/Cas9 Gene Editing Technology for Disease Treatment. J Med Res Synth. 2024;5(1):45-58. Retrieved
40. https://pmc.ncbi.nlm.nih.gov/articles/PMC7171402/Jiang F, Doudna JA. Innovations in the structural biology of CRISPR-Cas9 systems. J Cell Mol Med. 2020;24(
41. https://www.nature.com/articles/s41392-023-01309-7B Zhang, L Wang, C Liu. Engineered Cas9 Variants and High-Fidelity Derivatives for Precision Medicine. Signal Transduct Target Ther. 2023;8(1):120.
42. https://www.nature.com/articles/s41588-024-01758-yAnzalone AV, Koblan LW, Liu DR. Recent advancements in prime editing and search-and-replace genetics. Nat Genet. 2024;56(3
43. https://www.nature.com/articles/s41581-022-00636-2Kuroda T, Tanaka M, Sato Y. Therapeutic strategies targeting genes in diseases of the kidney and metabolism. Nat Rev Nephrol. 2022;18(11):
44. https://www.frontiersin.org/journals/pharmacology/articles/10.3389/fphar.2025.1552741/fullLiu Y, Zhao X, Chen Z. Pharmacology and pharmacokinetics of genome editing therapies. Front Pharmacol. 2025;16:1552

45. https://www.nature.com/subjects/cas9-endonucleaseNature Research Editors. Annotations on structure and function of Cas9 endonuclease. Nature Subject Collections. 2025. Available at: https://
46. https://ingena.org.au/publications/2025-breakthroughsInGena Research Group. The gene therapy advances of 2025 demonstrate the future of genomics in practice. InGena Publications. 2025. From: https://
47. https://pubmed.ncbi.nlm.nih.gov/31150758/Gao L, Cox DBT, Yan WX, Manteiga JC, Schneider MW, Yamano T, et al. Engineered miniature Cas12f and compact Cas nucleases. Science. 2019;365(6
48. https://pubmed.ncbi.nlm.nih.gov/31223254/Knott GJ, Doudna JA. CRISPR-Cas system paves way for future genetic engineering. Science. 2018;
49. https://pubmed.ncbi.nlm.nih.gov/29231142/Cox DB, Gootenberg JS, Abudayyeh OO, Franklin B, Zheng L, Zhang F. RNA editing with CRISPR-Cas13. Science. 201
50. https://pmc.ncbi.nlm.nih.gov/articles/PMC5889534/Gootenberg JS, Abudayyeh OO, Kellner MJ, Joung J, Collins JJ, Zhang F. Applications of the CRISPR-Cas System to Diagnostic Microbiology. Science. 2018
51. https://pmc.ncbi.nlm.nih.gov/articles/PMC7533657/Nelson CE, Wu Y, Gerson AL. Safety and efficacy parameters for CRISPR-based therapeutics in vivo. Nat Rev Drug Discov. 2020;19(11):755
52. https://pmc.ncbi.nlm.nih.gov/articles/PMC7447629/Dever DP, Porteus MH. Strategies to deliver genome editing components to stem cells. Hum Gene Ther. 2020;31(15):810-82.

HOW TO CITE: Jiya Goswami*, Vani Varia, Yagnesh Modi, Satyajit Sahoo, D.B. Meshram, CRISPR-Cas9 Genome Editing: Mechanisms, Applications, Challenges, and Future Horizons, Int. J. of Pharm. Sci., 2026, Vol 4, Issue 9, 3393-3402. https://doi.org/10.5281/zenodo.22967571