Review Article

Emerging Trends in Biomaterials for Cancer Immunotherapy and Genome Editing: A Comprehensive Review

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ABSTRACT

This detailed review navigates the dynamic landscape of cancer therapeutics, shifting focus from conventional approaches to the promising frontiers of immunotherapy and genome editing. Biomaterials, including nanoparticles and hydrogels, are scrutinized for their role in enhancing therapeutic efficacy across various cancer types. Breakthroughs in biomaterial-based interventions are emphasized, with a meticulous examination of critical methodological considerations, such as safety, biocompatibility, and delivery efficiency, laying the groundwork for future research.The narrative emphasizes the need for standardization and regulatory compliance to ensure the safety and reliability of emerging therapies moving towards clinical applications. Implications for theory, practice, and future research highlight the potential of biomaterial-based approaches to offer safer and more effective cancer treatments. The integration of personalized medicine is advocated, emphasizing tailored interventions based on individual patient profiles.The review underscores the multidisciplinary collaboration across materials science, immunology, and oncology as essential for a holistic understanding and effective development of biomaterial-based therapies. Overall, this review contributes to the ongoing shift towards safer, more efficacious, and personalized cancer therapeutics by exploring innovative avenues in immunotherapy and genome editing, while emphasizing the need for a methodologically rigorous approach in translating these advancements to clinical practice.

Key words: Cancer immunotherapy, Precision genome editing, Biomaterials, CRISPR-Cas9, Combination therapies.

Cancer remains one of the most formidable challenges in modern medicine, affecting millions of lives worldwide each year [1]. Conventional therapies, such as chemotherapy and radiation, have made significant strides in treating certain types of cancer [2]. However, their limitations, such as off-target effects and drug resistance, have underscored the need for novel therapeutic approaches [3]. In recent years, cancer immunotherapy [4] and precision genome editing [5] have emerged as promising fields that hold the potential to revolutionize cancer treatment. The landscape of oncology has undergone a transformative shift with the integration of immune system harnessing and genome editing technologies, notably the revolutionary CRISPR-Cas9 system [6].

Three primary facets define this paradigm shift in cancer treatment. Immune Checkpoint Inhibitors, such as Nivolumab, pembrolizumab, atezolizumab, Durvalumab (Imfinzi), Ipilimumab (Yervoy), and Cemiplimab (Libtayo), have demonstrated success in treating various cancers, including bladder cancer, non-small cell lung cancer, head and neck squamous cell carcinoma, melanoma, renal cell carcinoma, and advanced cervical cancer, enhancing overall survival rates and response durability [7]. Adoptive T cell therapies, exemplified by Chimeric Antigen Receptor (CAR) T-cell therapy, represent a groundbreaking approach. Examples such as Daliyno (tilmesogenecel), Breyanzi (lisocabtagenedarolumab), and Tecartus (breceltinib) utilize a patient's own tumor-infiltrating lymphocytes (TILs) or engineered CAR T-cells to precisely target melanoma, large B-cell lymphoma, and mantle cell lymphoma [8].Cancer Vaccines, including Gvax (rasilmuplasmid), Papillomavirus vaccines (Gardasil, Cervarix), and personalized neoantigen vaccines, stimulate the immune system to identify and eliminate cancer cells, showcasing a personalized treatment approach [9].

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In the realm of genome editing, the CRISPR/Cas-9 system stands out as a powerful tool, exhibiting promise in correcting mutations and restraining tumor growth in cancer research and treatment. Additionally, Zinc Finger Nucleases (ZFNs), Transcription Activator-Like Effector Nucleases (TALENs), Base editing, and HDR (homology-directed repair) join the ranks of precision genome editing technologies, expanding the toolkit with their unique capabilities [10-13]. These advancements collectively hold immense potential in advancing cancer therapies, ushering in a new era of personalized and targeted interventions for improved patient outcomes.In cancer, the potential to target and correct genetic mutations implicated in tumor development offers unprecedented opportunities for precision medicine [14].

However, successful cancer immunotherapy and genome editing demand efficient and controlled delivery systems to ensure therapeutic agents reach their targets with minimal side effects [15]. This is where cutting-edge biomaterials play a pivotal role [16]. Biomaterials have emerged as essential tools to optimize cancer immunotherapy and genome editing by providing tailored platforms for drug delivery, enhancing immune response, and improving gene editing efficiency [17]. In this review article, we explore the latest advancements in harnessing the power of biomaterials for cancer immunotherapy and precision genome editing [18]. We delve into various types of biomaterials, including nanoparticles [19], hydrogels [20], and viral vectors [21], and their applications in enhancing therapeutic efficacy and minimizing off-target effects. Additionally, we discuss the challenges and future directions in the development of biomaterial-based strategies to overcome obstacles faced in cancer treatment.

METHOD AND MATERIALS

In conducting this review on "Emerging Trends in Biomaterials for Cancer Immunotherapy and Genome Editing," an extensive examination of available literature was carried out, focusing on the integration of immune system enhancement and genome editing technologies in cancer treatment. Primary sources included reputable journals, scientific databases, and authoritative publications in oncology, immunotherapy, and genome editing. The search encompassed articles published up to January 2024 to ensure the inclusion of the latest advancements. The review strategically aimed to identify pivotal studies, clinical trials, and research papers elucidating the transformative impact of immune checkpoint inhibitors, adoptive T cell therapies, cancer vaccines, and genome editing tools, with a specific emphasis on the revolutionary CRISPR-Cas9 system in the oncology landscape.

Meticulous curation of gathered information sought to present a comprehensive overview, emphasizing recent breakthroughs, emerging trends, and notable examples within each category. The narrative was enriched by incorporating specific examples related to lung cancer, breast cancer, and prostate cancer, providing a nuanced perspective on the application of these technologies across various cancer types. Beyond academic sources, reports from reputable medical and scientific organizations, scrutiny of clinical trial databases, and exploration of official regulatory publications ensured a well-rounded and evidence-based approach. The synthesis of this information aimed to provide readers with a clear understanding of the current landscape, challenges faced, and future directions in the dynamic intersection of immune system modulation and genome editing, propelling advancements in cancer therapies. The methodology placed a premium on accuracy, relevance, and the inclusion of diverse perspectives, contributing meaningfully to the ongoing scholarly conversation in this transformative field of research.

Biomaterials for cancer immunotherapy

1. Immune Modulatory Biomaterials: Immune modulatory biomaterials are ingeniously designed to manipulate the immune response, creating a favorable microenvironment conducive to the activation of anti-tumor immune cells [17]. Their pivotal role in elevating the efficacy of cancer immunotherapy is evident through their ability to deliver immune checkpoint inhibitors and immune-stimulating cytokines with precision. These biomaterials are meticulously engineered to release therapeutic agents in a sustained and controlled manner, ensuring a durable and precisely targeted immune response against the tumor[22, 23]. Nanoparticles, operating at the nanoscale, stand as formidable carriers for immune modulatory agents within cancer immunotherapy [24]. Laden with immune checkpoint inhibitors such as anti-PD-1 or anti-CTLA-4 antibodies, effectively obstruct inhibitory signals, unleashing the potent activity of tumor-specific T cells [25, 26].

The controlled and gradual release of these antibodies from nanoparticles guarantees sustained immune activation, ultimately leading to profound tumor regression. On the other hand, hydrogels, intricate three-dimensional networks of crosslinked polymers, serve as exceptional vehicles for encapsulating and releasing immune-stimulating cytokines like interleukins (IL-2, IL-12) or interferon[27,28]. These hydrogels create a localized depot of these vital cytokines precisely at the tumor site, thus fostering the recruitment and activation of immune cells, thereby significantly amplifying the anti-tumor immune response. Furthermore, the versatility of hydrogels allows for the engineering of physical support and protection for immune cells, enhancing their survival and functionality within the challenging tumor microenvironment [27]. These advancements in biomaterials hold great promise in revolutionizing the landscape of cancer immunotherapy, offering new avenues to combat cancer with increased precision and effectiveness.

2. Cancer Vaccines: Biomaterial-based cancer vaccines have emerged as a compelling approach to augment the body immune response against cancer cells [28]. These innovative vaccines are designed to bolster antigen presentation and stimulate robust immune reactions targeting tumor-specific antigens. One avenue of this strategy involves utilizing biomaterials like liposomes, nanoparticles, and virus-like particles as carriers for tumor-specific antigens [29]. These biomaterial carriers serve a dual purpose by safeguarding the antigens from degradation and enhancing their uptake by antigen-presenting cells (APCs)[30]. This, in turn, facilitates the efficient presentation of these antigens to T cells, igniting a potent and highly specific T cell response directed against cancer cells [31].

Additionally, biomaterial-based cancer vaccines can incorporate adjuvants, substances known to enhance immune responses to antigens. Adjuvants like Toll-like receptor (TLR) agonists and cytokines are commonly integrated into these vaccines [32]. These adjuvants play a critical role in further amplifying the activation of APCs and T cells. By creating a pro-inflammatory microenvironment, they assist in the recruitment and activation of immune cells, ultimately reinforcing the immune assault on cancer [33]. This multifaceted approach harnessing biomaterials and adjuvants holds substantial promise in reshaping the landscape of cancer immunotherapy, offering innovative strategies to combat cancer more effectively and precisely.

3. Adoptive Cell Therapies: Adoptive cell therapies (ACT), a groundbreaking approach in cancer treatment, involve the isolation and manipulation of a patient's own immune cells, primarily T cells, to target and eliminate cancer cells. Notably, chimeric antigen receptor (CAR) T cell therapy has demonstrated remarkable success in specific cancer types [34-37]. Biomaterials play a pivotal role in the ex vivo engineering of CAR-T cells, functioning as delivery vehicles for CAR constructs and other genetic material into T cells [35,36]. This enables the T cells to express specific receptors (CARs) designed to recognize and engage cancer antigens effectively. Nanoparticles and viral vectors are frequently employed biomaterials, ensuring efficient gene delivery into T cells during this process. Moreover, the challenges encountered by CAR-T cells upon reinfusion into the patient's body within the complex tumor microenvironment are substantial [35-37].

To address this, biomaterials, including hydrogels and scaffolds, can be custom-designed to provide physical support and essential nutrients to CAR-T cells. This support is crucial for their survival and persistence amidst the harsh conditions of the tumor microenvironment. Additionally, these biomaterial-based scaffolds can function as reservoirs for cytokines and other immune-modulating agents, further enhancing the anti-tumor activity of CAR-T cells [34-37]. This multifaceted approach that combines the power of biomaterials with CAR-T cell therapy holds immense promise in advancing the field of cancer immunotherapy, offering novel strategies to combat cancer more effectively by equipping engineered immune cells with the tools they need to navigate and conquer the complex tumor landscape.

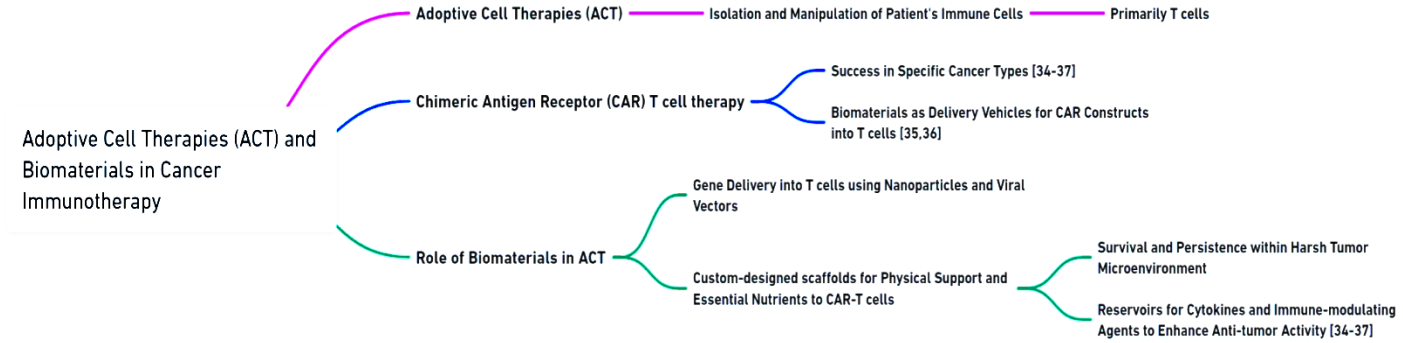

Figure 1. Biomaterials for cancer immunotherapy.

Biomaterials for Genome Editing

Biomaterials have emerged as essential tools in the field of genome editing, particularly with the advent of CRISPR-Cas9 technology. Genome editing aims to precisely modify the DNA sequence of living organisms, offering unprecedented potential for treating genetic diseases, understanding gene function, and advancing biotechnology. Biomaterials play crucial roles in facilitating efficient and targeted delivery of CRISPR-Cas9 components, protecting these components from degradation, and enhancing gene editing efficiency [12,13]. The various types of biomaterials used in genome editing are:

1. Delivery of CRISPR-Cas9 Components: Efficiently delivering the CRISPR-Cas9 system to target cells or tissues is a central challenge in genome editing, and biomaterials play a pivotal role in overcoming this obstacle [38]. These versatile carriers encapsulate and protect essential CRISPR-Cas9 components, including the Cas9 protein or mRNA and guide RNA (gRNA) molecules, ensuring their successful delivery to the desired cellular destinations [39]. Three commonly used biomaterials in this context are nanoparticles, liposomes, and viral vectors [40]. Nanoparticles made from biocompatible materials, such as lipids or polymers, have shown remarkable efficacy as carriers for CRISPR-Cas9 components. They

protect the cargo from degradation and allow for efficient uptake by target cells. Due to the large molecular weight of the Cas9 protein (approximately 4.5 kb in genetic size) and its low stability against serum enzymes and proteins, the entry of the Cas9/sgRNA or RNP complex into cells is challenging [41,42].

However, nanoparticle delivery systems, such as lipid-based nanoparticles and cationic polymer nanoparticles, have been developed to address these challenges. These delivery systems can be modified to target specific cell types, reducing off-target effects and improving gene editing precision. For instance, a DNA nanocell[NC]-based delivery system has been shown to efficiently load the Cas12a/crRNA RNP [42, 43]. Additionally, systemic nanoparticle delivery of CRISPR-Cas9 ribonucleoproteins has demonstrated effective tissue-specific genome editing. The development of nanoparticle-based technology for CRISPR-Cas9 delivery holds promising prospects for clinical gene editing, as evidenced by the completion of the first CRISPR/Cas9 clinical trial in 2016 [44]. Furthermore, various studies have highlighted the potential of nanoparticle delivery systems for the efficient and targeted delivery of CRISPR-Cas9 components. Lipid nanoparticles, polymeric nanoparticles, solid-lipid nanoparticles, nanostructured lipid carriers, and niosomes have all shown great potential in the delivery of CRISPR compounds to target cells. Additionally, polyamidoamine-aptamer modified CRISPR/Cas9 and sorafenib-loaded hollow mesoporous silica nanoparticles have exhibited targeted delivery of CRISPR/Cas9 for precise gene editing [45].

2. Liposomes: Liposomes, characterized by a lipid bilayer structure, play a pivotal role in genome editing, encapsulating various agents like nucleic acids and proteins. Their targeted delivery, responsiveness to environmental cues, and versatility in CRISPR/Cas9 applications make them indispensable. Key aspects in CRISPR delivery include:

- **PEGylation:** Enhancing efficiency, PEG-modified liposomes optimize CRISPR delivery by improving pharmacokinetics and minimizing immune responses.
- **Endosomal Escape:** Facilitating the release of CRISPR-Cas9 cargo into the cellular cytoplasm, liposomes ensure effective genome editing.
- **Stimuli-Responsive Design:** Tailored to environmental cues, liposomes provide spatial and temporal control over CRISPR cargo release.
- **Targeting Strategies:** Surface modifications enable precise delivery to specific cells or tissues, enhancing CRISPR/Cas9 precision.
- **Light-Sensitive Delivery:** Innovative light-sensitive liposomes, like those loaded with a photosensitizer, offer precise spatial and temporal control in CRISPR/Cas9 gene editing. Despite challenges like low transfection efficiency, the adaptability of liposome formulations allows customization for specific CRISPR requirements. Noteworthy liposome types include:
- **EG-Bearing Liposomes:** Tailored with PEG, these liposomes, like the ones carrying CRISPR components, enhance genome editing efficiency by improving pharmacokinetics and minimizing immune responses.
- **Charged Liposomes:** Positively or negatively charged liposomes, exemplified by those carrying CRISPR payloads, target specific cells, contributing to precise genetic modifications.
- **Stimuli-Responsive Liposomes:** Engineered to respond to environmental cues, liposomes, such as those used in CRISPR delivery, ensure spatial and temporal control over cargo release, enhancing gene editing precision.
- **Light-Sensitive Liposomes:** Innovations like light-sensitive liposomes loaded with CRISPR components provide high control in gene editing, allowing for flexibility and precision.
- **AD Liposomes and Cationic Lipids**: Liposomes derived from AD liposomes, as well as those using cationic lipids like DOTAP and DLin-MC3-DMA, showcase enhanced delivery efficiency in nucleic acid and CRISPR/Cas9-mediated gene editing. These liposomes optimize genome-editing efficiency by modulating endocytic pathways. [46,47].

3. Viral vectors: Viral vectors, such as adeno-associated viruses (AAVs) and lentiviruses, have a well-established history in gene therapy and are now integral to genome editing. These vectors deliver the CRISPR-Cas9 system to target cells with remarkable efficiency and offer the advantage of providing long-term expression of Cas9 and gRNA, making them particularly suitable for genetic diseases requiring sustained correction [42]. The use of viral vectors in gene therapy has seen significant progress, with nearly 70% of clinical trials utilizing viral vectors, highlighting their continued importance in the field. Despite their successes, challenges still limit their full potential, and ongoing research aims to address these limitations. Viral vectors have been employed for the treatment of various diseases, including metabolic, cardiovascular, muscular, hematologic, ophthalmologic, and infectious diseases, as well as different types of cancer [43,44].

For example, AAV-based gene therapy has been used to treat spinal muscular atrophy, a rare genetic disease that causes muscle weakness and wasting. In this case, the AAV vector was used to deliver a functional copy of the SMN1 gene to motor neurons, resulting in improved motor function and survival in patients. Another example is the use of lentiviral vectors in the treatment of HIV/AIDS. Lentiviral vectors have been used to deliver functional copies of the CCR5 gene, which encodes a co-receptor for HIV, to CD4+ T cells. This approach has been shown to protect against HIV infection in animal models and is currently being tested in

clinical trials [48]. The development of nanoparticle systems to deliver the CRISPR-Cas9 system to target cells has overcome obstacles such as the large molecular weight of the Cas9 protein and its low stability against serum enzymes and proteins. Additionally, the use of viral carrier systems has been shown to provide high efficiency in genome editing.

While viral vectors have demonstrated significant promise, ongoing research and development are focused on addressing challenges and further improving their applicability. The field of gene therapy continues to see innovative modifications and support from the pharmaceutical and biotech industries, indicating a continued commitment to advancing viral vector-based therapy. Therefore, viral vectors, particularly AAVs and lentiviruses, remain crucial tools in the landscape of gene therapy and genome editing, with ongoing efforts to enhance their efficacy and safety for clinical applications [46-48].

4. Gene Editing in Stem Cells: Stem cells hold immense potential for regenerative medicine and cell-based therapies Stem cells possess the unique ability to self-renew and differentiate into various cell types, making them promising candidates for regenerative medicine and cell-based therapies [49]. Precisely modifying their genes via CRISPR-Cas9 unlocks their full therapeutic potential, and biomaterials play a crucial role in achieving this effectively. Let's dive deeper into recent developmental examples across different delivery strategies:

a. Transfection Reagents: Lipid Nanoparticles (LNPs): Recent advances involve LNPs modified with cell-specific targeting ligands. For instance, researchers conjugated folate ligands to LNPs for targeted delivery to pluripotent stem cells expressing folate receptors. This led to efficient gene editing with minimal off-target effects [48].

b. Polymer-Peptide Hybrids: Novel synthetic polymers with peptide conjugation offer enhanced cellular uptake and endosomal escape. A recent study employed chitosan-based polymers conjugated with cationic peptides for CRISPR-Cas9 delivery to mesenchymal stem cells, achieving high editing efficiency with improved biocompatibility [48,49].

c. Electroporation Platforms:

- **Microfluidic Chips:** Researchers are now integrating microfluidic chips with temperature control to enhance cell viability during electroporation. A recent study used a temperature-controlled microfluidic chip for CRISPR-Cas9 delivery to neural stem cells, demonstrating improved cell survival and editing efficiency compared to conventional methods [50].
- **Conductive Hydrogels:** Development of hydrogels with specific electrical properties allows for localized, tissue-specific CRISPR-Cas9 delivery. Scientists developed a conductive hydrogel scaffold for *in vivo* delivery to cardiac stem cells residing within heart tissue. This approach facilitated targeted gene editing with minimal impact on surrounding tissues [49,50].

d. Viral Vectors:

- **Engineered AAV Vectors:** Adeno-associated viral (AAV) vectors are gaining popularity due to their safety and low immunogenicity. Recent efforts focus on enhancing their targeting capabilities. Researchers engineered AAV vectors with stem cell-specific promoters, achieving efficient and selective gene editing in human embryonic stem cells without harming neighboring cell types [51].
- Hybrid Viral Vectors: Combining different viral vectors leverages their unique strengths. A recent study used a hybrid vector combining AAV and lentiviral vectors, achieving sustained and efficient gene editing in hematopoietic stem cells with minimal insertional mutagenesis [52].

e. *In-vivo* Genome Editing: *In vivo* genome editing holds immense promise for treating genetic disorders directly within the patient's body [40]. However, delivering CRISPR-Cas9 components to target tissues or organs in a specific and efficient manner remains a significant challenge. Innovative strategies are being developed to overcome these challenges and propel the field forward.

f. Targeted Nanoparticles: These miniature cargo ships can be engineered to carry CRISPR-Cas9 components and adorned with ligands that bind to receptors unique to specific tissues. This targeted delivery approach minimizes off-target effects and enhances overall efficiency. For example, researchers at MIT crafted nanoparticles coated with folate ligands, precisely targeting receptors abundant on cancer cells, enabling gene editing specifically within tumors and laying the groundwork for personalized cancer therapies [41,42].

g. Controlled-Release Scaffolds: These biomaterials function as custodians, encapsulating CRISPR-Cas9 components and releasing them gradually over time. This controlled, sustained delivery mechanism ensures localized gene editing within the target area, amplifying the therapeutic impact. For instance, a biodegradable hydrogel scaffold loaded with CRISPR-Cas9 was employed to treat Leber's hereditary optic neuropathy, a challenging mitochondrial disease affecting the retina. This localized editing within the eye demonstrated improved vision in animal models, offering promise for conditions previously deemed untreatable [20,35,36].

h. Engineered Viral Vectors: Repurposed viruses can be adeptly delivered into cells, with their capsids (outer shells) and promoters (genetic switches) meticulously engineered to target specific tissues. This targeted delivery strategy ensures that the editing machinery reaches its intended destination, minimizing risks and maximizing efficacy. For example, scientists modified an AAV vector with a muscle-specific promoter, not only delivering CRISPR-Cas9 but correcting a mutation causing Duchenne muscular dystrophy in muscle cells. The result: significant improvements in muscle function observed in animal models [48,49].

i. Beyond Delivery: Researchers are advancing high-fidelity Cas9 enzymes and guide RNAs with heightened specificity, reducing the risk of unintended edits. Strategies involve sustained delivery systems or inducible editing approaches to enhance the persistence of gene editing. Careful consideration of ethical implications, especially concerning germline editing and equitable access, is crucial for responsible development [20,28,52].

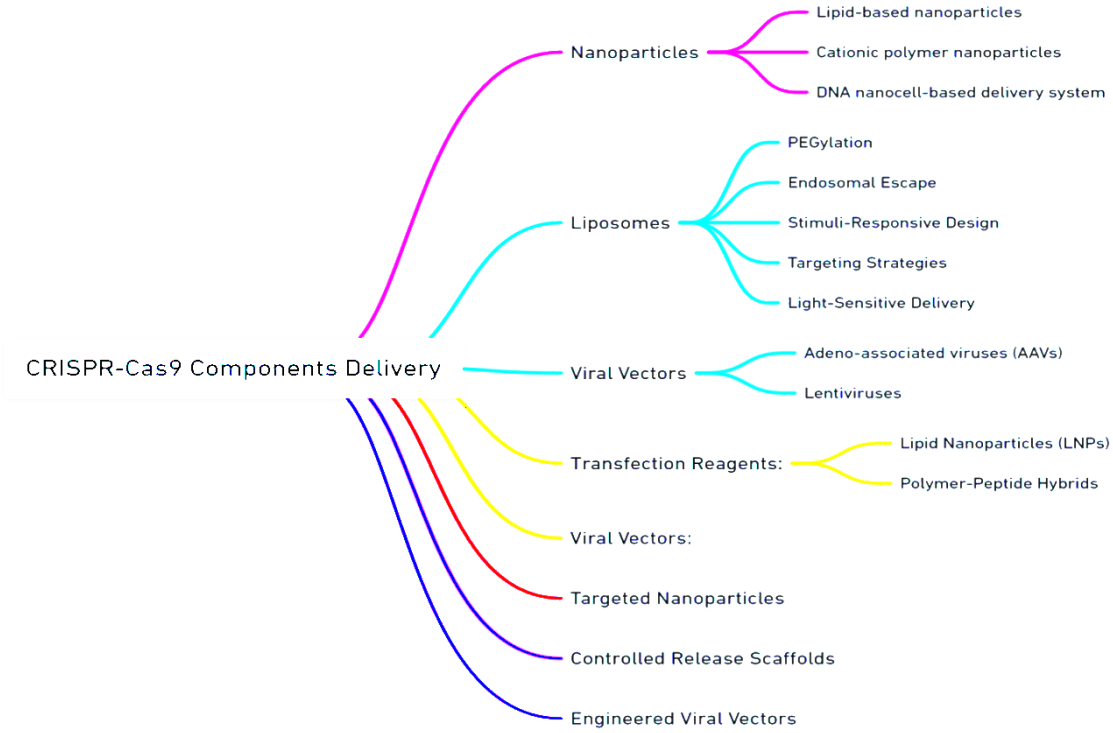

Figure 2. *In-vivo* Gene editing.

Challenges and future directions in biomaterials for cancer immunotherapy and genome editing.

The development of biomaterial-based therapies presents a myriad of complex challenges that necessitate rigorous scientific investigation and innovative solutions [53]. Foremost among these challenges is the imperative to ensure safety and biocompatibility. As these biomaterials interact intimately with the patient's immune system and biological processes, a comprehensive assessment of their biocompatibility is essential to mitigate the risk of adverse reactions or immune responses [17,54]. This extends to the imperative of long-term evaluation of the effects of biomaterials, especially when employed in the context of chronic treatments, where potential impacts must be thoroughly understood [17,53,54].

Efficient delivery and precise targeting represent pivotal facets of therapeutic success. Achieving optimal outcomes hinges on enhancing the delivery efficiency of biomaterials, particularly in the often-hostiletumor microenvironments [55]. Innovative strategies must be devised to bolster the targeting specificity and improve tissue penetration, addressing the unique challenges presented by biomaterial-based therapies. The potential immunogenicity of certain biomaterials, notably viral vectors, poses a substantial concern, potentially limiting their effectiveness upon repeated administration [56,57]. Therefore, it is imperative to explore avenues for mitigating immunogenicity without compromising therapeutic efficacy [57]. This calls for the development of novel biomaterials engineered to exhibit reduced immunogenic potential or the implementation of immune-evasion strategies to enhance their clinical applicability [58].

Off-target effects, a notable challenge in gene editing therapies, where CRISPR-Cas9 may inadvertently edit unintended genomic sites, necessitate continual refinement of the specificity and accuracy of CRISPR-Cas9 systems. This ongoing pursuit aims to minimize off-target effects and bolster the safety profile of genome editing treatments [59]. Practical considerations regarding manufacturing scalability and standardization come to the forefront. Ensuring

reproducibility, quality, and alignment with regulatory standards is imperative to meet the burgeoning demand for clinical trials and future commercialization [60]. Standardization of manufacturing processes and strict adherence to regulatory compliance are pivotal for the widespread adoption of biomaterial-based therapies [61].

Moreover, the vision of personalized medicine, integral to both cancer immunotherapy and genome editing, requires the seamless integration of biomaterials with patient-specific genomic and immunological data [62]. Realizing this ambition hinges on advancements in high-throughput sequencing and bioinformatics, which are poised to play instrumental roles in optimizing biomaterial-based therapies tailored to individual patient profiles [63]. Combination therapies that harness the synergy between diverse biomaterials, immunotherapies, and gene editing strategies hold immense promise for enhancing cancer treatment. Nevertheless, unravelling the intricacies of optimal combinations and understanding potential interactions between various biomaterials and therapies poses a multifaceted scientific challenge that demands meticulous exploration [64-66]. Lastly, as biomaterial-based therapies transition from the realm of research to clinical trials, successfully navigating the complex regulatory landscape and securing approvals from regulatory agencies emerges as a pivotal step [64]. This necessitates collaborative efforts encompassing academic researchers, industry partners, and regulatory authorities to ensure the safe and efficient translation of these pioneering therapies into clinical practice [64,65].

CONCLUSION

The combination of biomaterials and breakthrough approaches such as cancer immunotherapy and genome editing are ushering cancer treatment into a new era. Biomaterials, which serve as precision transporters for immune-modulating drugs, are meticulously engineered to negotiate the complicated tumor microenvironment. Their goal, like that of architects, is to encapsulate and distribute therapeutic substances, thereby boosting the body's immunological response to cancer with precise targeting. This formulation ensures prolonged release for optimal treatment outcomes while also reducing systemic toxicity. Despite these advances, obstacles remain, particularly in biocompatibility and delivery efficiency. Researchers are actively overcoming these barriers in order to fully realize the revolutionary promise of biomaterials, recognizing the need of tailoring treatments to individual genetic profiles for personalized medicine. Global impact cancer care could be safer and more effective with this individualized approach. A thorough understanding of the transformative role that biomaterials will play in reshaping cancer care in the future and fostering innovation towards safer, more effective, and personalized treatment avenues can be gained by critically evaluating the current landscape, acknowledging its limitations and ongoing challenges, and combining it with insights into cutting-edge research.

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