

ADVANCING VACCINE DEVELOPMENT AND DELIVERY: THE ROLE OF GENETIC ENGINEERING

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ABSTRACT

The advent of genetic engineering has revolutionized the field of vaccine development and delivery, offering innovative approaches to combat infectious diseases and emerging health threats. Traditional vaccine platforms, while effective, often face limitations in production speed, efficacy, and adaptability. Genetic engineering enables the design of precise, scalable, and highly targeted vaccines, leveraging techniques such as recombinant DNA technology, RNA-based platforms, and synthetic biology. This review highlights recent advancements in genetically engineered vaccines, including mRNA and DNA vaccines, viral vectors, and protein subunit vaccines, and explores their role in addressing global health challenges. Furthermore, it examines the innovations in delivery mechanisms, such as lipid nanoparticles and gene-editing tools, that enhance stability, immunogenicity, and accessibility. Emphasis is placed on the implications of these technologies for rapid pandemic responses, personalized medicine, and the potential to tackle diseases previously considered untreatable. Challenges in regulatory approval, scalability, and equitable distribution are also discussed, providing a comprehensive overview of the transformative

potential of genetic engineering in vaccine science.

Keywords: *Genetic engineering, infectious diseases, vaccine*

1. Introduction

Major concerns of the global public health system are the prevention and control of infectious diseases, which pose a serious threat to world health. Infectious illness prevention and control are achieved by a variety of tactics, including social distancing, monitoring, and immunization. Vaccination is the most economical and successful strategy for treating and preventing infectious illnesses among these strategies. (Rémy et al 2015). Throughout history, extensive vaccination campaigns have effectively eliminated the extremely virulent smallpox virus. The incidence and mortality rates of many serious infectious diseases, such as polio, rotavirus enteritis, hepatitis B, diphtheria, tetanus, pertussis, cervical cancer, mumps, and others, have also been considerably reduced as a result of vaccination. (Mühlemann et al 2020). The World Health Organization (WHO) reported that between 3.5 and 5 million lives can be saved annually if immunizations are widely used. There is no denying the impact of vaccines on public health, even though their accessibility and acceptance vary among countries and regions. (Sallam et al 2021). Emerging high-risk and highly variable viruses continue to pose serious dangers and provide major global health issues, as the unpredictable COVID-19 pandemic shows. (Lazarus et al 2022).

Advances in virology, immunology, molecular biology, and related fields have transformed vaccine research. These developments have led to the development of several molecular engineering tools, such as viral vectors, molecular adjuvants, gene editing tools, protein modification tools, and molecular delivery techniques (Baay et al. 2021). With the aid of these technologies, new vaccine technology platforms have been developed, current vaccine products have been improved and enhanced, and vaccine formulations have been safer and more effective. Furthermore, molecular engineering methods have made it possible to respond quickly to newly discovered high-risk infections, averting and managing

widespread epidemics. (Nguyen et al 2021).

This review aims to present a thorough analysis of the state of molecular engineering tool research and implementation, with an emphasis on how these tools have advanced different vaccine technology platforms. It will also cover possible future research directions for vaccine technology.

2. Advances in Genetically Engineered Vaccine Platforms

2.1. Viral vectors

The use of viral vectors for gene therapy has existed since the beginning of virology. However, the ongoing development of virology has made viral vectors crucial engineering tools that enable the development of a wide range of novel vector vaccines. (Travieso et al 2022). The viral vector can transfer the antigen to host cells by inserting target antigen sequences at the right locations, which initiates a thorough immune response. (Okuda et al 2014). Because of their safety, a broad range of host cells, low vector immunogenicity, and capacity to express exogenous genes for extended periods in vivo, replication-defective viruses like adenovirus, lentivirus, and poxvirus are particularly appealing for vaccine development among the different vector tools available. (Robert-Guroff et al 2007). Because of its quicker clinical conversion rate, adenovirus vector vaccines have been a popular option during the COVID-19 pandemic. Examples of these include Russia's Sputnik V and Johnson & Johnson's Ad26.COV.S, and AstraZeneca's ChAdOx1Ncov-19. (Sadoff et al 2021). Herpesviruses, retroviruses, and influenza viruses are examples of another kind of viral transmission agent that can replicate itself. These viruses are safe and effective, and recent vaccine research is concentrating on them. (Kamel et al 2019). Chen and associates used an influenza virus vector in 2022 to create a novel COVID-19 vaccine that, when inhaled, was successful in triggering mucosal immune responses, such as humoral and resident cell immunity, as well as mucosal IgA, which in turn prevented the virus from spreading. (Chen et al 2022).

Even though vaccine research has focused a lot of attention on designing vaccines using viral vectors, safety, and human

preexisting immunity are still issues. As an illustration, the first chimpanzee-based COVID-19 vaccine, which was authorized for use in several nations, has been halted because of the possibility of blood clots.(Voysey et al 2021).

2.1.1. Adenovirus Vectors

There are approximately 50 known serotypes of human adenovirus (Ad). Human adenovirus serotype 5 (Ad5) has been extensively studied as a gene delivery vector due to its ability to be produced at high titers easily. The genome of Ad5 consists of 36 kilobases (kb) of double-stranded, linear DNA. It is non-enveloped and features a capsid shell made up of hexon and penton structures. The Ad fibre protein plays a crucial role in determining the virus's tropism, as it facilitates the binding of the adenovirus to the coxsackievirus and adenovirus receptor (CAR).(Sumida et al 2005). The high transduction efficiency, high transgenic expression, and wide spectrum of viral tropism of recombinant Ad vectors make them popular. Both proliferating and non-dividing cells can become infected by them. Because the E1A and E1B viral gene regions are deleted, the majority of Ad vectors have replication defects. To make room for the transgene, the E3 genes are frequently removed as well. A common process for creating ad vectors consists of two parts. The Ad vector plasmid is first transfected into cell lines that complement E1 (the 293 cell lines are commonly utilized). Following infection, the Ad vector multiplies in the 293 cultured cells. Secondly, the vector is extracted from infected cells and ultracentrifuged to purify it.(Wohlfart et al 1988). The neutralizing reactions are dominated by antibodies directed against the hexon protein's hypervariable regions (HVRs). It has been researched to modify these HVRs and the fibre knob domain to circumvent pre-existing immunity.(Roberts et al 2006).Modifying the host immune response by lowering viral gene expression is an additional strategy. By decreasing the vector-derived immune response in infected cells, deletion of the E2 and E4 viral gene sections reduces toxicity. This vector is referred to as a second-generation advertising vector.(Gao et al 1996).Clinical trials have investigated vaccinations based on recombinant Ad vectors against solid tumors, influenza,

and HIV-1.(Chiappori et al 2013).

2.1.2. Retrovirus Vectors

The majority of retrovirus vectors are avian or murine, and they are usually replication-defective. Retroviral vector-based gene therapy has been used in clinical trials for individuals with malignant gliomas or X-linked severe combined immunodeficiency (SCID-X1).(Basile et al 2000). During preclinical testing, this safety concern also surfaced. When viral LTRs were incorporated into proto-oncogenes, cancer began. The risk of carcinogenesis may be decreased by non-integrating and self-inactivating (SIN) retroviral vectors because they preferentially incorporate close cellular gene promoters that control cell reproduction. (Maruggi et al 2009). During vector manufacturing, SIN vectors are rendered inactive and include partially erased LTRs. Because of this, SIN vectors have been suggested for SCID-X1 clinical studies. (Thornhill et al 2008).

2.1.3. Poxvirus Vectors

Highly attenuated vaccinia virus strains have been developed, including replication-competent strains like LC16m8 and replication-deficient strains such as NYVAC, ALVAC, TROVAC, and MVA. Numerous studies have shown that vaccines based on vaccinia virus vectors can induce a strong immune response due to the high transgenic expression of foreign antigens. (Martinez et al 2007). The vaccinia virus benefits from a scalable manufacturing process for the smallpox vaccine. (Belshe et al 2013). The MVA vector is usually produced in chick embryo fibroblast (CEF) cells for large-scale manufacturing. Specifically, the vaccinia virus is employed to transfect CEF cells with a plasmid containing the recombinant transgene. After transfection, centrifugation is used to purify the recombinant vectors that multiply within the CEF cells. (Mehtali et al 2010).

Enhancements to vaccinia virus vectors continue to be developed even today.(Davison et al 1990).

2.2. DNA Vaccine

DNA vaccines provide immunogenicity through the

activation of the adaptive immune response. When a plasmid is introduced close to a cell and then picked up (either passively or through facilitation), the target antigen can be produced by the cellular machinery that recognizes and expresses the plasmid DNA. (Hewitt et al 2003). The most popular method of antigen presentation in DNA vaccination is MHC Class I because plasmids are absorbed by the cell and the antigen to be presented is subsequently produced intracellularly by the transcription and translation of the supplied DNA. (Khan et al 2013). Intracellular peptides, which are endogenous proteins in this route and are most frequently seen on MHC I, are produced sequentially by DNA vaccines and activate CD8 T cells. Additionally, the translated proteins are exocytosed at the same time and then absorbed by additional antigen-presenting cells, which then drain to nearby lymph nodes. (Hobernik et al 2018). Macrophages, dendritic cells, and other monocytes are examples of antigen-presenting cells (APCs) that endocytose and/or phagocytose extracellular materials before processing and presenting them by MHC II, which preferentially activates CD4 T cells. Th1 and Th2 are two types of CD4 T helper cells that can either further activate CD8 T cells or encourage B cell differentiation to plasma cells to produce a humoral immune response, respectively. (Tussey et al 2000). Because of their basic structure, plasmids can include many CpG patterns, just like DNA. These CpG patterns can be optimally built into DNA vaccines. A CpG motif is a recognized adjuvant that stimulates plasmacytoid dendritic cells and TLR9-bearing B cells to generate powerful Th1-type immune responses. (Bode et al 2011).

Strong T cell-mediated immune responses, which are essential for both the removal of infected cells and the prevention of tumors, have been demonstrated to be induced by the DNA vaccine. (Chang et al 2021). Fascinatingly, the DNA vaccination delivery mechanism might guide the immune responses. While intramuscular (IM) delivery produces a stronger humoral, or Th2-mediated, immune response with an advantage in antigen expression, intradermal (ID) delivery may preferentially induce the Th1-immune response by recruiting more APCs and inducing a more polyfunctional cellular immune response. (Shedlock et al 2000). This indicates

that the proliferation of CD4 T helper cells toward Th1 or Th2 is somewhat directable.(Feltquate et al 1997).

However, it has been argued that the DNA vaccine's administration method – such as gene gun versus IM depot – is probably more directed. Adjuvants can also have specific stimulatory actions that guide CD4+ T cells toward either or both Th-1 and Th-2, thus the problem appears to be merely additional.(Olive et al 2010). Finally, plasmid DNA can enable tissue production of antigens for considerably longer periods than injected protein or subunit antigens, which have a very limited half-life. This could potentially provide superior immune system priming. (Petrovsky et al 2016).

DNA vaccines are presently being studied in immunoncology. DNA cancer vaccines target cancer cells to elicit both a broad and a customized immune response, in contrast to the conventional DNA vaccination that targets infectious organisms. The tolerogenic effect is the process by which cancer cells avoid detection by the immune system. The two most well-known mechanisms are PD-1 and CTLA-4.(Makarov et al 2014).

2.3. Protein Subunit Vaccines

Subunit vaccines derived from pieces of microbes can overcome these obstacles. Subunit vaccinations include only the pathogen's antigenic components necessary to elicit successful immune responses. Proteins, polysaccharides, and nucleic acids can all be employed as antigens (Bill et al. 2015). Immune responses are triggered by protein subunits that contain a particular virus product rather than the entire viral particle. SARS-CoV-2 includes both structural and non-structural proteins in addition to accessory proteins. The primary structural proteins of SARS-CoV-2 are the envelope (E), membrane (M), and S proteins. (Koupae et al 2021). The proteins present in the ribonucleoprotein core of the nucleocapsid (N) and the viral phospholipid bilayer play crucial roles in the virus's function. The S-proteins facilitate viral entry and adhesion to host cells by binding to ACE2 (angiotensin-converting enzyme-2). Protein S consists of two subunits: S1 and S2. The S2 subunit is responsible for

membrane fusion, essential for the virus to enter the host cell, while the S1 subunit serves as a C-terminal receptor-binding domain (RBD) that identifies the receptor. The M proteins are involved in the development of the virion envelope. Since antibodies bind to the S protein and neutralize the virus, the spike gene sequence or protein is a critical component of SARS-CoV-2 vaccines.(Sampson et al 2021).Due to its high antigenicity and capacity to trigger strong immune responses, the S protein of SARS-CoV-2 has been recognized as a leading candidate for vaccine development across various platforms. (Zepeda-Cervantes et al 2021) (Zheng et al 2020).

Some Recombinant Spike Protein Vaccines for COVID-19

2.3.1. COVAX-19 Vaccine

A South Australian biotech company called Vaxine Pty Ltd. has developed a COVID-19 vaccine candidate known as COVAX-19, or SpikoGen. This vaccine is based on recombinant spike proteins and combines a recombinant protein antigen with the Advax-SM adjuvant.Vaxine Pvt. Ltd. utilized computer models of the spike protein and the human ACE2 receptor to demonstrate that this vaccine not only reduces COVID-19 illness but also helps prevent virus shedding and transmission.(Vihol et al 2021).

2.3.2. Nanocovax Vaccine

Nanogen Pharmaceutical Biotechnology JSC makes a protein subunit vaccination called Nanocovax in Vietnam. The vaccine, which is based on the SARS-CoV-2 recombinant spike protein, uses aluminum hydroxide as an adjuvant. When tested in animal models, the vaccine has produced high amounts of anti-spike antibodies. Nanocovax has been shown to neutralize antibody titers against the Wuhan variety and anti-spike IgG antibodies. (Jacob et al 2020).

2.3.3. Nanoparticle Vaccine

Matrix-M1 adjuvant² and a recombinant SARS-CoV-2 (rSARS-CoV-2) nanoparticle vaccine³ derived from the full-length, wild-type SARS-CoV-2 spike glycoprotein are both included in Novavax's NVX-CoV2373 protein subunit vaccine. Because it improves viral attachment to the host cell's

human angiotensin-converting enzyme 2 (hACE2) receptor, it targets the formation of antibodies and vaccines. The absence of cell-mediated immune responses, which define protein subunit vaccines, was addressed using the saponin-based matrix M1 adjuvant. (Bengtsson et al 2016).(Keech et al 2020).

2.4. mRNA vaccine

There are two RNA vaccine categories: self-amplifying and traditional mRNA-based immunizations.(Kramps et al 2017). Traditional mRNA vaccines solely encode the target antigen and are conceptually comparable to host cell mRNA molecules. SAM vaccines, on the other hand, encode a modified RNA viral genome that contains nonstructural proteins and an antigen cassette that replaces the genes encoding the structural proteins. Examples of these viruses are those produced from alphavirus single-stranded, positive sense (+)RNA molecules. (Geall et al 2012). Because of RNA template amplification in host cells, the resulting RNAs, known as replicons, express high amounts of the antigen gene. These replicons are unable to produce infectious virions and disseminate to nearby cells because they lack the genes for the viral structural proteins. The sequences of two open reading frames (ORFs) with untranslated regions (UTRs) at the 5C and 3' ends make up the alphavirus-based replicon. A viral polyprotein that is translated from the genomic (+)RNA and proteolytically broken down into four nsPs is encoded by the ORF at the 5C-end.(Fros et al 2016).

Mice treated with liposome-delivered mRNA encoding the influenza nucleoprotein developed a response from antigen-specific cytotoxic T lymphocytes (CTLs). (Martinon et al 1993).

Advantage of mRNA vaccines

1. The first benefit of mRNA vaccines is how simple and quick they are to make. Delivering a transcript that encodes a target antigen or immunogen is the fundamental idea behind mRNA vaccines. The procedure is also simply scalable and cell-free, needing little platform modification throughout mRNA formulation and production. (Jackson et al 2020)
2. After transfection, an mRNA vaccine quickly expresses

the target protein (antigen) by translation from the mRNA. Since the cytoplasm, not the nucleus, is where the antigens are translated, mRNA vaccines are far more biosafe than DNA-based vaccinations since they have a lower chance of integrating into the genome. Furthermore, as mRNA is a temporary molecule that does not interact with the host genome and only contains a brief sequence that needs to be translated, it is a safer vector than DNA.(Jackson et al 2020)

3. While the host translation machinery translates mRNA vaccines and are therefore likely to yield an antigen that matches the protein's structure released from the viral genome, including the post-translational modifications, protein-based vaccinations are frequently made from bacteria. (Jackson et al 2020).

2.4.1. Production of mRNA Vaccines

In the production process, a DNA template containing the mRNA sequence is transcriptionally transcribed *in vitro*. A poly(A) sequence, a start codon, an open reading frame (ORF), a stop codon followed by a 3' UTR, and a 5' untranslated region (UTR) are all typical components of this mRNA. RNA for translation and stability as well as codon optimization have both been employed to optimize the ORF for expression. The mRNA is polyadenylated and capped to facilitate effective translation. The poly(A) sequence can be added either during or after transcription using poly(A) polymerase, and the cap can be added either way. Translation efficiency may be significantly impacted by the 5' and 3' UTR sequences. Using nucleoside triphosphates as the building blocks, a DNA-dependent RNA polymerase (often from phage T7) converts a linearized DNA template into mRNA to begin the process. The nucleosides could be either naturally occurring modified nucleosides or native nucleosides. (Liu et al 2019) (Pardi et al 2018) (Thess et al 2015).

The removal of nucleotides, enzymes, and the DNA template is crucial for mRNA purification. As recently summarized, various manufacturers have optimized their specific constructs in terms of the sequence, the nucleosides used (i.e., how modified, if they are modified), and for the

lipid nanoparticle formulations to achieve the appropriate immunogenicity, potency, and thermostability. (Zhang et al 2019).

3. Innovations in Delivery Mechanisms

3.1. Lipid nanoparticles (LNPs)

The pharmaceutical industry has seen lipid nanoparticles (LNPs) as attractive delivery systems for a range of medicinal medicines. Other industries, including medical imaging, nutrition, cosmetics, agriculture, and other cutting-edge domains like nanoreactors, have also begun to use LNPs. LNPs are currently in the news as an essential part of the COVID-19 mRNA vaccines, helping to preserve and deliver mRNA to cells.

Reaching the full potential of RNA-based vaccines can be facilitated by using LNPs as delivery methods since they shield the big encapsulated nucleic acid molecule from nuclease destruction.(Reichmuth et al 2016)

Different applications of RNA-based vaccines against infectious diseases and cancer have resulted from the diverse functions that RNA plays in both preventive and therapeutic applications. Numerous studies that have examined LNPs as delivery methods for conventional and self-amplifying mRNA against a range of infectious illnesses have demonstrated strong and quick immune activation in various animal species. (Lutz et al 2017) (Bahl et al 2017) (Pardi et al 2018)

For example; the **mRNA-1273** mRNA vaccine was given against COVID-19 via this delivery system in phase three manufacture by Moderna Therapeutics/National Institute of Allergy and Infectious Diseases (NIAID). (Baden et al 2020)

3.2. Electroporation

Electroporation (EP) is a process that employs short electric pulses to temporarily and reversibly permeabilize the cell membrane. This temporary state allows for the enter of large molecules, such as nucleic acids, into cells, either in vivo (within a living organism) or in vitro (in a controlled environment). Over the past decade, this method has advanced from a

purely experimental technique to one that is actively used in various clinical trials aimed at transferring medications and nucleic acids to specific target organs. (Sardesai et al 2011).

In the investigations by Petkov et al. and Lambert et al., BALB/c and CB6F1 mice were immunized intramuscularly with DNA vaccines against influenza and HIV-1, respectively, using a **BEX CUY21EDITII** electroporator. (Petkov et al 2022). (Lambert et al 2016).

4. Gene editing tool: CRISPR/Cas9 for vaccine development

CRISPR/Cas9-based gene-editing technology has been extensively used in vaccine research due to its high efficiency, specificity, versatility, flexibility, simplicity, and low cost when compared to other viral genome editing techniques. This has proven to be an effective and potent strategy for the future development of genetically engineered vaccines, in addition to studies on gene function, gene therapy, and virus-host interaction. (Okoli et al 2018)

Guide RNA (gRNA) and the Cas9 nuclease, which breaks DNA, make up the CRISPR/Cas9 functional system. The Cas9 nuclease is directed by the gRNA to bind to the specific sequence 5'-NGG-3' upstream of the Protospacer adjacent motif (PAM) and then initiate the Cas9 nucleases' double-strand break (DSB) activity. Variants of the Cas nuclease enzyme cause variations in the PAM sequence. In the functioning mechanism, the Cas9 creates the double-strand break (DSB) at three base pairs upstream of PAM, and the gRNAs use sequence complementarity to determine the specificity of the target DNA. The DSB initiates two cellular DNA repair mechanisms: homology-directed repair (HDR), which results in gene knock-in (KI), and non-homolog end joining (NHEJ), which results in gene disruption or knock-out (KO). By using donor DNA as a template to rectify gene mutations, the HDR pathway activates and repairs the DSB when a foreign sequence (donor DNA template) is introduced into the first cell stage using Cas9 and gRNA. (Asmamaw et al 2021). NHEJ, a strong, error-prone, common, and quick DNA repair process, often carries out the repair of DSB when it happens in cell DNA. Throughout the cell cycle, this route

remains constant. HDR is another parallel route that is only active during the cell cycle's S and G2 stages. The "core complexes" that identify the damaged DNA regions and their "unique processing factors" that repair the DSB involve both the NHEJ and HDR processes.(Symington et al 2011).

The human immunodeficiency virus (HIV) was prevented from replicating in the host cells by editing and modifying its DNA using the CRISPR/Cas9 system. The lengthy terminal repeats of HIV-1 act as a promoter to propel viral genome integration and replication into host genomes. One treatment approach to lessen HIV replication in host cells is to edit the LTR sections. The U6 promoter was used to guide the design of the gRNA expression vector. Two target locations, T5 and T6, were chosen to be edited in the HIV-1 virus's LTR sections. In addition to eliminating and preventing the expression of latently integrated HIV-1 provirus from the host genomes, this approach dramatically decreased HIV-1 expression and replication in the host cell lines. To target the replicative factors of HIV-1 in latently infected Jurkat C11 cell lines, the researchers employed modified Cas nuclease, *Staphylococcus aureus* (SaCas9), with eight tested gRNAs. This resulted in a significant decrease in HIV replication and production in the host cell lines without any off-target effects. (Ebina et al 2013).

5. Applications in Global Health

The scientific community around the world is showing renewed interest in vaccine research and development. This is primarily due to four factors: (1) the absence of effective treatment for numerous debilitating infections; (2) the rise of bacteria that are resistant to multiple drugs; (3) the necessity of enhancing the safety of the more conventional licensed vaccines; and (4) the enormous potential for novel vaccine research and design with the convergence of omics sciences, including immunomics, proteomics, genomics, and vaccines. (Bagnoli et al 2011).

The vaccine industry continued its standard cycle of discovery, development, and distribution until the end of 2019. Then, a sudden and unheard-of global public health emergency struck, upending lives, economies, and society

as a whole. In Wuhan, China, SARS-CoV-2, or severe acute respiratory syndrome coronavirus 2, first appeared. A variety of COVID-19 clinical outcomes can arise from exposure to SARS-CoV-2, ranging from asymptomatic infection to severe acute respiratory distress and death. (Zhou et al 2020).

It is extremely difficult to develop vaccines for diseases that are common in low-resource environments because they require extensive biologics manufacture, immunologic characterisation, and the management of organisms with complex life cycles. In the impacted areas, these initiatives are hindered by inadequate clinical trial infrastructure and a lack of finance. However, the chances of success have increased due to developments in immuno-profiling, antigen and antibody screening, and manufacturing methods. Within the next ten years, promising vaccine candidates for HIV, RSV, TB, malaria, and *Shigella* may become widely used. Furthermore, monoclonal antibodies and strong, reasonably priced long-acting medications may soon be able to treat these illnesses in low-income nations. Using modular biomanufacturing to facilitate regional production and cut costs, as well as embracing people-centered care techniques, are future challenges. To improve vaccination efficacy, more study on pathogen life cycles, antigen selection, and immunopathogenesis is still necessary. The diseases that plague low-resource areas can be eradicated and made extinct with the help of modern instruments and technologies. (Heaton et al 2020).

5. Challenges and Future Directions

The rapid pace of genetic engineering necessitates robust regulatory frameworks to ensure vaccine safety and efficacy. Ethical concerns, particularly regarding gene-editing technologies, must also be addressed. Regulatory agencies must adapt to evaluate the unique aspects of genetically engineered vaccines, ensuring they meet rigorous safety and efficacy standards without unnecessary delays. Manufacturing genetically engineered vaccines at scale remains a challenge, particularly in low-resource settings. Infrastructure for large-scale production and the availability of raw materials, such as lipid nanoparticles, are often limited. Strategies

to ensure equitable access, including technology transfer, global collaboration, and investment in local manufacturing capabilities, are critical to address these challenges and prevent disparities in vaccine distribution. Public skepticism toward genetically engineered vaccines highlights the need for transparent communication and education. Misinformation and distrust can undermine vaccination efforts, necessitating community engagement and proactive efforts to inform the public about the safety and benefits of these vaccines.

Future research should focus on improving the stability, storage, and delivery of mRNA and DNA vaccines, such as developing thermostable formulations that eliminate cold-chain requirements. Advances in delivery technologies, including self-amplifying RNA systems and next-generation nanoparticle carriers, could further enhance vaccine efficacy. Additionally, exploring the potential of artificial intelligence and bioinformatics to optimize vaccine design and predict immune responses will enable more precise and effective vaccine platforms.

6. Conclusion

Genetic engineering has revolutionized vaccine science, offering unprecedented speed, precision, and adaptability in combating infectious diseases and emerging health threats. Innovations in mRNA, DNA, and viral vector vaccines, as well as novel delivery systems, have proven transformative, particularly during the COVID-19 pandemic. These advancements promise to address neglected diseases, enhance personalized medicine, and improve global health outcomes. However, challenges such as scalability, equitable distribution, and public acceptance remain critical. Continued research, collaboration, and investment are essential to maximize the potential of genetic engineering and ensure vaccines are accessible to all, paving the way for a healthier and more prepared future.

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