Advancements in mRNA Vaccine Technology: A Review of Applications in Infectious Disease Prevention

Riaz Ahmed

ABSTRACT

During the COVID-19 pandemic, messenger RNA (mRNA) vaccine technology became extremely important in the field of medicine. Here, I review the latest updates, challenges, and future outlook for mRNA vaccines while discussing their mechanisms, development processes, and various applications. mRNA vaccines introduce synthetic mRNA to host cells, prompting them to produce specific antigens that trigger an immune response. Thanks to vaccines from Pfizer-BioNTech and Moderna, researchers discovered that mRNA can be produced quickly and is highly effective against COVID-19 infection. This advancement allows for the application of mRNA science in combating other infectious diseases and conditions, including influenza, Zika virus disease (ZVD), and certain cancers. Although mRNA vaccines show great potential, several challenges must be addressed. The requirement for COVID-19 vaccines to be stored at extremely low temperatures poses a significant issue for countries with less developed infrastructure. Innovations are underway to enhance drug stability at higher temperatures and explore new administration methods. Additionally, misinformation and public doubts surrounding vaccines have led many people to question the use of mRNA treatments, underscoring the need for transparent information sharing to help them understand these medicines. Governments are reforming regulations to accommodate the unique nature of mRNA vaccines. Agencies such as the U. S. Food and Drug Administration are establishing guidelines to ensure safety and efficacy while permitting swift distribution during emergencies. Moreover, the World Health Organization's mRNA Technology Transfer Programme aims to boost manufacturing in low- and middle-income countries and promote equitable access to these vaccines. New advancements are continually enhancing mRNA vaccine technology. The use of lipid nanoparticles and novel RNA types, alongside machine learning, is significantly improving vaccine stability, immune stimulation, and production speed. Consequently, mRNA science is advancing existing vaccines and creating new possibilities for mRNA therapeutics. In conclusion, mRNA vaccines significantly enhance vaccine technology with rapid development, adaptability, and robust immune support. Achieving the global health benefits of mRNA vaccines necessitates addressing the associated challenges through scientific innovation, investment in infrastructure, and public engagement.

Keywords: mRNA vaccines, Lipid nanoparticles, Infectious disease prevention, Vaccine stability, Regulatory challenges

Department of Medical Sciences, Military College of Signals NUST, Islamabad, Pakistan

Correspondence to:
Riaz Ahmed,
riazkhattak450@gmail.com

Additional material is published online only. To view please visit the journal online.

Cite this as: Ahmed R. Advancements in mRNA Vaccine Technology: A Review of Applications in Infectious Disease Prevention. Premier Journal of Infectious Diseases 2025;4:100004

DOI: https://doi.org/10.70389/PJID.100004

Received: 28 May 2025
Revised: 12 July 2025
Accepted: 12 July 2025
Published: 26 July 2025

Ethical approval: N/a
Consent: N/a
Funding: No industry funding
Conflicts of interest: None
Author contribution: Riaz Ahmed – Conceptualization, Writing – original draft, review and editing
Guarantor: Riaz Ahmed
Provenance and peer-review: Unsolicited and externally peer-reviewed
Data availability statement: N/a

Introduction

Important developments in vaccines have profoundly changed the direction of health around the world. First demonstrated through the use of cowpox to prevent smallpox in the late eighteenth century, and later extended by immunizing people against polio, measles, and hepatitis in subsequent centuries, immunization has continually helped fight infectious diseases.[1] Live-attenuated, inactivated, protein subunit vaccines have helped protect the public and guided vaccination programs for many years. Despite doing very well, these platforms are often slow to develop, need complicated manufacturing, and find it difficult to respond to newly discovered pathogens[2] quickly.

Thanks to messenger RNA (mRNA) vaccine technology, scientists now have a new way to design, make, and administer vaccines.[2] Developed initially in the 1990s, mRNA vaccines give host cells instructions to produce certain proteins found in pathogens, which starts an immune response.[3] Successful progress from concept to use in people came about through advances in mRNA stability, how codons are optimized, and the creation of lipid nanoparticle (LNP) delivery methods. All these advancements led to a rapid approval of mRNA vaccines for SARS-CoV-2, making Pfizer-BioNTech's BNT162b2 and Moderna's mRNA-1273 the highlights in vaccination.[3]

The sudden appearance of COVID-19 gave mRNA vaccines a unique test, showing that they can provide effective results while being flexible, mass-produced, and reliable in real-world conditions. Because of how well the mRNA vaccines have worked, there is now greater interest in applying them to more illnesses, such as cancer.[4]

The Primary Objectives of this Review

1. To provide an overview of the development and underlying science of mRNA vaccine platforms.
2. To examine the clinical success and global impact of mRNA vaccines in combating infectious diseases, especially COVID-19.
3. To evaluate ongoing research into mRNA vaccines for other infectious diseases (e.g., influenza, ZVD, respiratory syncytial virus [RSV], malaria).
4. To analyze the advantages and limitations of mRNA vaccine technology, including delivery systems, durability, and scalability.

This article explains the technology behind mRNA vaccines, explains how well they work, and considers what their impact will be on future vaccine development (Figure 1).

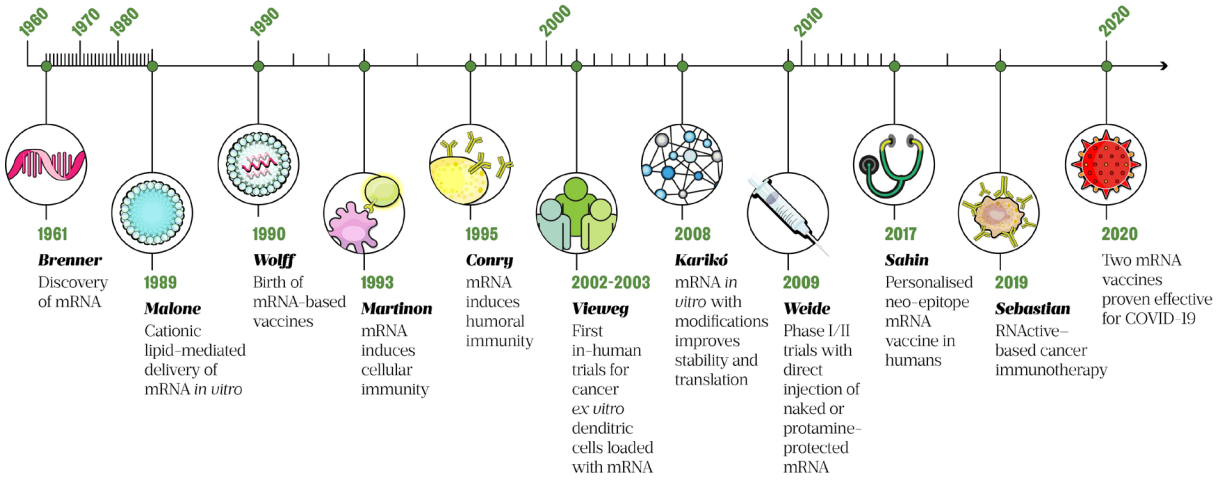

Fig 1 | Timeline of vaccine development: traditional platforms vs. mRNA vaccines[5]

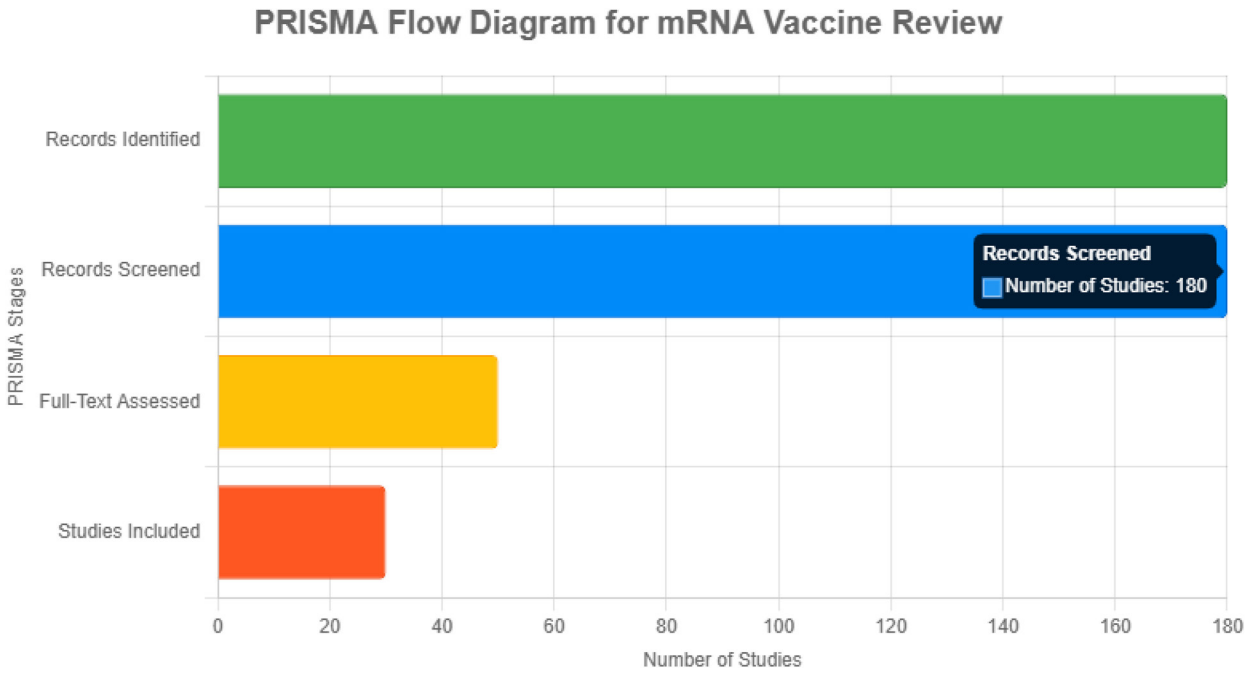

Fig 2 | PRISMA diagram

Research Methodology

This study employed a systematic narrative review to evaluate the clinical advancements and applications of mRNA vaccine technology for infectious disease prevention, excluding COVID-19, as detailed in the document. The methodology was designed to ensure a comprehensive and replicable synthesis of the literature while accommodating the heterogeneity of available data.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram illustrates the flow of studies through the systematic review process (Figure 2). The document describes a systematic narrative review with a search yielding over 180 records, followed by screening and inclusion based on specific criteria. Below is a Chart.js configuration for a flowchart-like representation, using a bar chart to show the number of studies at each stage (identification, screening, eligibility, and inclusion).

A systematic search was conducted across multiple databases, including PubMed, ScienceDirect, Scopus, and the World Health Organization (WHO) Global Index Medicus, to capture both academic and policy-oriented sources. The search period spanned from January 1, 2020, to May 25, 2025, reflecting the accelerated development of mRNA vaccine research following the emergence of SARS-CoV-2. Search terms were constructed using Medical Subject Headings (MeSH) and keyword combinations to ensure thorough coverage of relevant literature.

mRNA Vaccine Technology: Mechanism and Design

Unlike standard vaccines, mRNA vaccines let the body's cells make the antigens, which helps build

DOI: https://doi.org/10.70389/PJID.100004 | Premier Journal of Infectious Diseases 2025;4:100004

immunity. Currently, when mRNA vaccines are used, a short strand of mRNA carries the code for a viral antigen (usually the spike protein), not a disabled virus or protein fragment. This mRNA instructs cells to make the antigen, causing the humoral and cellular parts of our immune system to respond.[6]

Basic Components: Synthetic mRNA and LNPs

The technology is built around two main parts: synthetic mRNA and the delivery method—LNPs. Giving the mRNA molecule pseudouridine and other nucleoside analogues improves its stability, better controls protein synthesis, and helps avoid detection by the immune system.[7] The use of modifications guarantees that the vaccine brings about a strong and safe immune response.

LNPs play different parts in the delivery of mRNA vaccines. First, they prevent the mRNA molecule from being destroyed by enzymes in the fluids of the body.[8] Further, they help mRNA enter cells by merging with the cell membrane and being taken up through endocytosis. As soon as LNPs enter the cell, they release the mRNA into the cytoplasm, where protein production begins.[9] Carefully chosen lipid molecules in the form of ionizable lipids, phospholipids, cholesterol, and PEG-lipids are usually used to produce these carriers, ensuring stability, efficient delivery, and low immune reactivity.[7]

Mechanism of Action: Antigen Production and Immune Activation

After the cell takes in the mRNA, it is released into the cytoplasm and translated into protein by the cell's ribosomes.[5] Having been formed, the proteins are handled and then revealed on the outside of the cell by MHC molecules. The presentation of these antigens triggers helper T cells, stimulates B cells to make antibodies, and increases the actions of cytotoxic T cells. As a result, the immune system remembers the pathogen and can fight it off if it is seen again.[6]

Unlike DNA vaccines, mRNA does not enter the nucleus and does not interact with our genetic material. Because it is broken down naturally by the cell soon after translation, this contributes to its safety.[9]

Types of mRNA: Nonreplicating vs. Self-Amplifying

Two basic types of mRNA vaccines are being developed: nonreplicating mRNA and self-amplifying mRNA.[8] COVID-19 vaccines made by Pfizer-BioNTech (BNT162b2) and Moderna (mRNA-1273) deliver only the needed antigen and are relatively easy to produce in large quantities. RNA vaccines contain extra genetic sequences that allow RNA to replicate inside the cell.[10] As a result, this means stronger immune responses using less mRNA, reducing material and cost.[11]

Manufacturing Process and Rapid Scalability

Making mRNA vaccines is easy because it does not require live cells. The processing of antigen protein usually starts with DNA coding, then is continued by bacteriophage RNA polymerase to create the antigen RNA.[9] The produced mRNA is purified and packed into LNPs, either by microfluidic or by batch-mixing processes (Figure 3). Because no live cultures or pathogens are used, the process is simpler, faster, and easier to standardize than traditional vaccine manufacturing.[12]

mRNA Vaccines in COVID-19: A Case Study

The COVID-19 pandemic sped up developments in vaccines and put the use of mRNA technology on the global map.[14] After scientists made the sequence for SARS-CoV-2 in early January 2020, many experts stepped up to develop vaccines that were both safe and effective. Leading in the vaccine research were two mRNA vaccines made by Pfizer-BioNTech (BNT162b2) and Moderna (mRNA-1273).[11] These vaccines were the first mRNA vaccines allowed for human use, signifying a significant moment in immunization.[12]

Development of Pfizer-BioNTech (BNT162b2) and Moderna (mRNA-1273)

BNT162b2 and mRNA-1273 were rapidly made using the SARS-CoV-2 spike (S) protein genetic sequence, which is mainly recognized by antibodies.[15] Because preclinical studies proved that the vaccine produced a strong immune reaction, clinical trials were conducted under intense worldwide scrutiny.[12] Amazingly, both vaccines were tested in Phase III trials soon after and earned Emergency Use Authorization from the U.S. Food and Drug Administration (FDA) in December 2020—after the virus's genetic sequence was released a little over 11 months ago.[2]

Two doses of mRNA at a dosage of 30 μg, spaced 3 weeks apart, were given with the Pfizer-BioNTech vaccine. Each Moderna vaccine shot delivered 100 μg after a period of 4 weeks. They each used LNPs to deliver mRNA, although the composition and storage protocols for them were not identical.[11]

Efficacy, Safety, and Real-World Effectiveness

During Phase III, both vaccines were found to be more than 94% effective at preventing symptoms related to COVID-19. This strong performance amazed many and quickly helped both the public and regulators feel more certain about mRNA technology.[16]

Many further studies globally confirmed that the vaccines are reliable in preventing both symptoms and serious infections, leading to hospitalization and death.[12] Furthermore, the vaccines protected against severe disease, even as the Alpha and Delta variants began to spread. Later, booster shots were given to strengthen immune protection against older and newer virus forms, such as Omicron.[17]

The findings showed that the safety checks were generally favorable. Most of the side effects were mild to moderate, usually lasting only a short time, for example, fatigue, headache, fever, and soreness at the injection site. Nonetheless, there were rare but major adverse effects, such as myocarditis found in young males.[18]

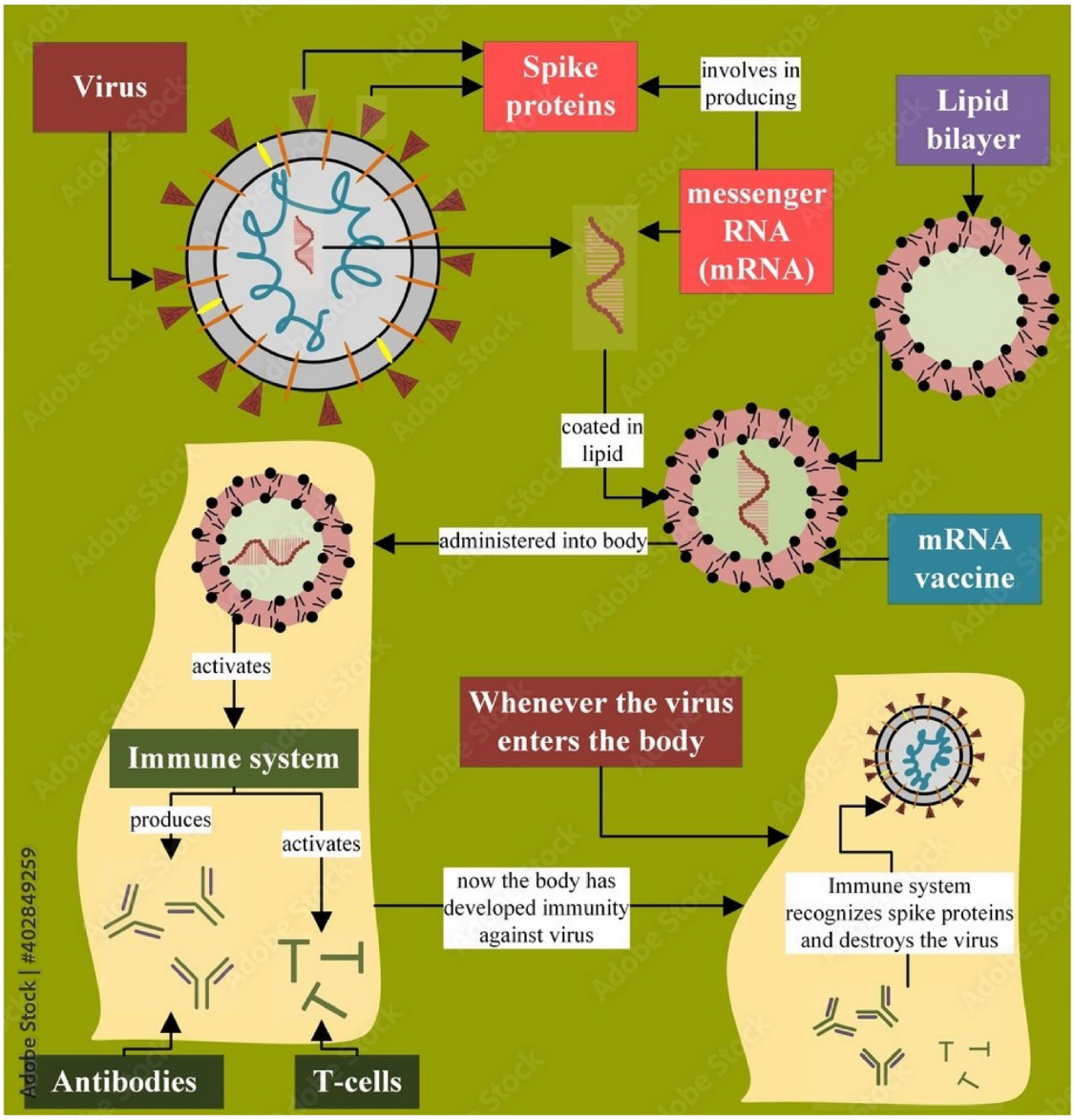

Fig 3 | Illustration of mRNA vaccine components, cellular uptake via LNPs, translation of the antigen protein, and activation of immune responses through MHC presentation[13]

Public Health Impact: Mass Deployment and Variant Response

Using mRNA vaccines as part of the COVID-19 effort greatly improved the global response. Thanks to their fast process and good performance, several countries controlled morbidity and mortality when the pandemic was most intense.[13] When many people in wealthy nations took the vaccine, the rate of infections fell, hospitals were safer, and some measures to stop the outbreak were relaxed.[18]

Even so, the virus continued to evolve. While the vaccines provided strong protection against severe COVID-19, the emergence of variants like Omicron demonstrated partial evasion of the immune response. Therefore, it became clear that constant tracking was vital and that mRNA platforms were perfectly designed for the development of boosters for each variant.[16]

Lessons Learned: Regulatory, Logistical, and Equity Perspectives

The fast approval of mRNA vaccines revealed both good and bad aspects of how global health works. Rolling reviews and adaptive trial designs expedited the drug review process, but kept safety standards the same.[16]

At the same time, important challenges with organization and equity appeared. In many parts of the world where resources are limited, keeping the Pfizer-BioNTech vaccine cold enough was a big challenge. Also, not every country could get the vaccines they needed at first, resulting in richer nations disproportionately acquiring the majority of doses and making existing health differences worse[17] (Figure 4). Ways such as COVAX tried to solve this issue, but were limited by logistics, politics, and manufacturing.[19]

DOI: https://doi.org/10.70389/PJID.100004 | Premier Journal of Infectious Diseases 2025;4:100004

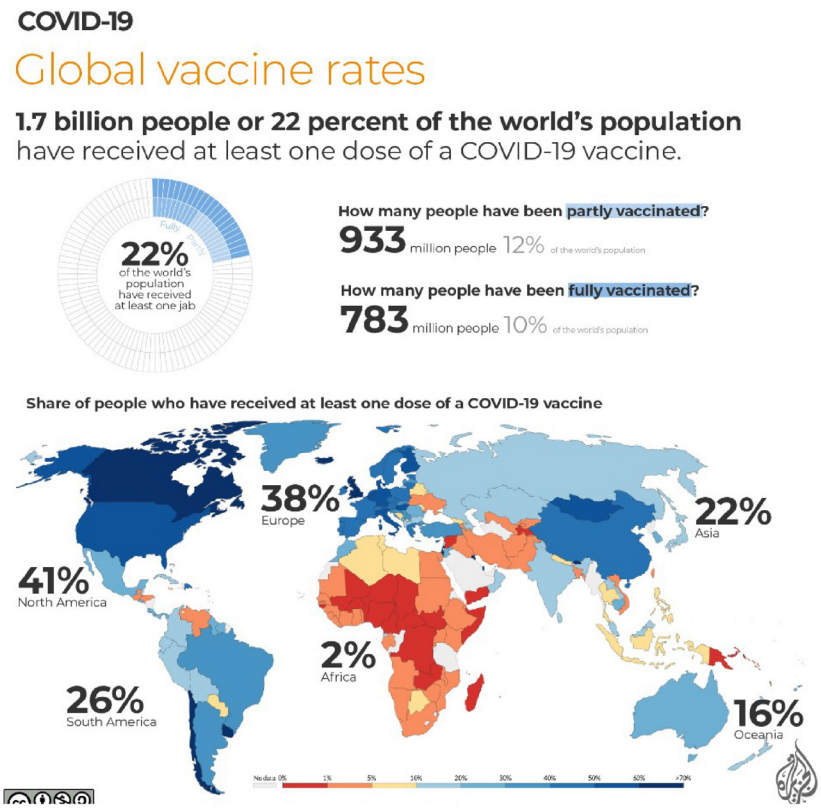

Fig 4 | Global distribution map of COVID-19 mRNA vaccines as of 2022[20]

Expanding Applications: mRNA Vaccines for Other Infectious Diseases

After the good results of mRNA vaccines for COVID-19, scientists and pharmacists are now looking to adapt this technology to a wide variety of infectious diseases. One reason is that mRNA offers simple construction, fast development, and a strong immune response, which makes it effective in addressing both old and new infections.[8]

Methods

A systematic narrative review was utilized to discuss clinical advancement and the usage of mRNA vaccine candidates against non-COVID-19 infectious diseases. The searches were conducted in PubMed, ScienceDirect, Scopus, and WHO Global Index Medicus to cover both academic and policy-driven sources comprehensively.

The examination time was between January 1, 2020, and May 25, 2025, the time when the mRNA vaccine research gained a fast pace due to the rise of SARS-CoV-2. MeSH and keyword combinations providing exhaustiveness with vaccine platforms and pathogens were mixed to create search strings. The basic Boolean search command was the following:

"mRNA vaccine" AND ("clinical trial" OR "efficacy") AND ("infectious disease" OR "RSV" OR "influenza" OR "malaria" OR "Zika" OR "tuberculosis")

Only the articles included were in English, and the preprints (e.g., bioRxiv, medRxiv) were also included because of the rapidly changing field, even though they are not peer-reviewed. A total of more than 180 records were obtained from the databases.

Screening Strategy: The primary reviewer would screen the titles and the abstracts to exclude inappropriate studies, including reviews with no new information, articles describing other immunotherapies, or articles comprising commentaries. Inclusion criteria Full texts were evaluated by inclusion criteria: the study should report the results of mRNA vaccines aimed at preventing infectious diseases in humans or similar preclinical models. Sources of duplicates and nonprimary were omitted.

Extraction of data was followed by the organization of data through thematic review as per target pathogen, development stage, and formulation of the candidate. Safety/efficacy outcome data and trial status were deciphered, where technically feasible, against publicly available regulatory filings (e.g., EMA, FDA) to ensure cross-validation.

This systematic procedure sought to provide the rigor and replicable nature of the narrative synthesis without limiting its design to fit the heterogeneity of existing data.

Methodological Rigor

In this segment, I will synthesize data from peer-reviewed publications, preprints, and regulatory sources published between 2021 and 2025. The structured search of the literature was performed with the use of PubMed, ScienceDirect, and WHO Global Index Medicus, and the following search terms were used: mRNA vaccine AND clinical trial AND ("infectious disease" OR specific pathogens). The articles had no date-related restriction and were only published in English. The narrative review format was used, and therefore, a PRISMA diagram would not be provided.

Critical Appraisal: The pieces of evidence mentioned in all of the studies are different and cover early and late-stage studies. To make it clear, each of the vaccine candidates is labelled as follows:

- **[HS]** High-stage: Late-phase (Phase II/III) or approved
- **[ES]** Early-stage: Preclinical or Phase I

Although there was no risk-of-bias instrument used, peer-reviewed and regulatory reviews recruiting human trials were preferred.

Data Synthesis: Illustrated in the table below is a brief comparison of some of the discussed mRNA vaccine candidates arranged by the pathogen targeted, phase of the trial, and reported outcomes (Table 1).

Influenza

Universal and Seasonal Vaccine Candidates: Large numbers of people continue to suffer and die from seasonal influenza epidemics around the globe.[12] Because traditional flu vaccines are made with eggs and based on predictions made several months ahead, they frequently do not match the actual viruses circulating at the time of the shot. However, vaccines based on mRNA for influenza are speedier and can be adapted easily.[21]

Table 1 | Key mRNA vaccine candidates by pathogen and development stage

Vaccine Developer	Target Pathogen	Candidate Name	Trial Phase	Key Findings	Stage Tag
Moderna	RSV	mRNA-1345	Phase III	Strong antibody titers, good tolerability	[HS]
Pfizer-BioNTech	Influenza (seasonal)	qIRV	Phase II	Multivalent coverage, adaptable composition	[HS]
CureVac-GSK	COVID-19 variant	CV2CoV	Phase II	Enhanced T-cell response	[HS]
Moderna	ZVD	mRNA-1893	Phase I	Good seroconversion in a small cohort	[ES]
University of Tokyo	Tuberculosis	TB-mRNA prototype	Preclinical	Induces IFN-γ and IL-2 in mice	[ES]
BioNTech	Malaria	BNT165b1	Preclinical	Early-stage immune profiling underway	[ES]

Moderna and Pfizer are testing several forms of seasonal mRNA influenza vaccines that are now in Phase I–III clinical trials.[18] They contain hemagglutinin antigens from several types of influenza and can be modified quickly to follow changes in the most common strains each season. Furthermore, scientists are continually working to design a single flu vaccine that protects against many strains by targeting important parts of the virus.[22]

RSV

RSV is one of the major reasons for severe breathing problems, most commonly among the very young, elderly, and those who have weak immune systems.[9] Even after years of study, there had not been any approved RSV vaccines until recently. At present, mRNA technology is central to solving previous difficulties in RSV vaccine development.[23]

Both Moderna and Pfizer have made vaccine candidates using mRNA technology, which targets prefusion-stabilized F proteins important for fighting RSV infections. Both companies have successfully taken candidates through Phase III trials.[17] Latest studies show that the vaccine is well-tolerated and promotes a strong immune response, so regulatory approval may come soon.[24]

ZVD and Chikungunya

In recent times, ZVD and Chikungunya have been spread by Aedes mosquitoes, bringing attention to the urgent requirement for vaccines against later-appearing arboviruses.[7] Preliminary studies in animals using mRNA vaccines that code for the envelope (E) proteins of ZVD have produced promising results, demonstrating strong protection against infection.[19] Similarly, results show that mRNA-based Chikungunya vaccines have stimulated an immune response and protected against infection in mice and nonhuman primates, and a few candidates now entering early-phase human testing.[25]

Tuberculosis and Malaria

Preclinical and Early-Phase Trials: Making effective vaccines for *Mycobacterium tuberculosis* and *Plasmodium* spp. continues to be one of the biggest challenges in dealing with infectious diseases.[26] Since these pathogens developed ways to avoid the immune system, traditional vaccines have failed to stop many infections.[16]

Efforts to use mRNA vaccine technology for tuberculosis and malaria are currently being started. Mice vaccinated with mRNA-encoding circumsporozoite protein have developed a detectable immune response against malaria.[27] Research in animals found that using mRNA to express many dominant antigens shows promise in eliciting both the production of antibodies and the immune system's cellular action against tuberculosis.[26]

Emerging Pathogen Platforms and Pandemic Preparedness Initiatives

MRNA technology's ability to be customized rapidly means it is very important for addressing new outbreaks.[18] The Coalition for Epidemic Preparedness Innovations (CEPI) launched the "100 Days Mission," which aims to allow the distribution of safe and effective mRNA vaccines just 100 days after detecting a new pathogen.[28]

Work is underway in these areas to support innovation, promote manufacturing equality worldwide, improve cold delivery networks, and restructure regulations. They demonstrate the value of mRNA platforms in helping to protect public health from many diseases.[13]

Stunning quantitative growth in the field of mRNA vaccines began with the emergence of COVID-19. Most candidates in 2021 targeted SARS-CoV-2, and by 2025, the pipeline has diversified to cover influenza and RSV and more ZVD, tuberculosis, and cancer. As indicated in Table 2, the number of candidates available in the clinical trial increases in each stage:

Advantages and Challenges of mRNA Vaccine Platforms

During the COVID-19 pandemic, using mRNA vaccines as the leading technology made a major change in vaccinology.[29] Nevertheless, several important challenges for science and logistics remain with mRNA vaccines, which will need to be met to maximize their impact over time.

Advantages

Rapid Design and Adaptability

An important benefit of mRNA vaccine platforms is their rapid design process. If the DNA of a pathogen is mapped, the synthesis of targeted antigen mRNA generally takes just a few days. Because the turnaround is fast, scientists are faster at responding to viruses, which helps them keep up with mutations and launch clinical testing quicker.[30]

DOI: https://doi.org/10.70389/PJID.100004 | Premier Journal of Infectious Diseases 2025;4:100004

Table 2 | Global mRNA Vaccine pipeline by phase (2021 vs. 2025)

Vaccine Target Area	Phase I (2021)	Phase I (2025)	Phase II (2021)	Phase II (2025)	Phase III (2021)	Phase III (2025)
Infectious diseases	14	37	9	24	4	11
Cancer (therapeutic)	3	15	1	10	0	5
Total	17	52	10	34	4	16

Data compiled from CEPI, WHO Technology Transfer Programme, and recent regulatory filings (2021–2025).

Scalable Manufacturing

Contrary to the usual practice, mRNA vaccines are produced without using cultured cells. With this method, production becomes easier and supports fast growth in cases of public health emergencies.[13] Since the platform is modular, changing the DNA of the antigen does not affect the production setup, allowing for fast reactions to emerging variants or other pathogens.[31]

Reduced Risk of Genomic Integration

The main reason mRNA vaccines are considered safe is that their DNA does not join with the DNA of the person receiving the vaccine. Protein translation destroys the mRNA, which is shown in the cytoplasm. Because they stay outside the nucleus, this vaccine is not expected to cause insertional mutagenesis or oncogenic changes.[22]

Challenges

Cold-Chain Requirements and Stability

It is very challenging to handle these vaccines, as they tend to degrade quickly and storage must stay extremely cold. Pfizer-BioNTech initially needed the vaccine to be kept at −70°C, but now more stable forms have been developed. Still, meeting these standards significantly challenges delivering vaccines in regions where infrastructure to maintain a cold chain is lacking, making it possible that some parts of the world are left behind.[32]

Adverse Events and Rare Safety Signals

Though mRNA vaccines were shown to be very safe in clinical trials and real-world studies, a few rare side effects have turned up with their large-scale use. Young men who received mRNA COVID-19 vaccines have sometimes been affected by myocarditis and pericarditis.[21] This demonstrates the need to closely watch and monitor medicines after they are used, to spot and assess safety issues and direct future decisions on medicine use.[15]

Duration of Immunity and Need for Boosters

Experts are also concerned about how long mRNA vaccines offer protection from COVID-19. Studies show that the effectiveness of vaccines against COVID-19 seems to decrease as time goes on, particularly when new virus variants appear.[25] For this reason, health experts are discussing whether vaccines will need periodic updates and how long the immunization schedules may last against new strains.[22]

Future Directions and Innovations

After the success in fighting COVID-19, more research is now active to solve existing problems and find new ways to use mRNA vaccines.

Thermostable Formulations and Needle-Free Delivery

Very recently, work toward thermostable mRNA vaccine formulations has been carried out with mixed success. Whereas typical LNP formulations must be stored at −20°C or −70°C, a number of freeze-dried LNP formulations and polymeric carriers have also been found to be stable at 4–25°C up to 6 months. as an example, formulations with trehalose and ionizable lipids (e.g., SM-102 analogue) displayed enhanced stability at room temperature without affecting immunogenicity.[33,34]

Some platforms vary widely in thermostability performance, however. Unless optimized with cryoprotectants, freeze-dried formulations tend to have a decreased transfection efficiency after they have been reconstituted.[35] Also, although microneedle patch technologies promise thermostable delivery, validations at the clinical level are limited.[36]

Consequently, even though thermostable mRNA vaccines have the potential to reshape worldwide vaccine equity, particularly in low- and middle-income countries (LMICs), there still remains a need to standardize the analytical comparability, confirm the potency retention, and meet prequalification criteria by the WHO. Strong comparative research as well as harmonization in the regulatory framework will play a central role in hastening these next-generation platforms to market.[37]

Multivalent and Combination Vaccines

Being flexible, the mRNA platform can contain and express several different antigens at the same time. The result allows for the development of vaccines that cover several kinds of pathogens at once. Vaccines of this kind are very useful for infectious diseases, such as the flu, since they evolve rapidly, and for infectious diseases coupled together, such as HIV and tuberculosis, which require coordination between the immune system's actions.[18]

Cancer and Personalized Vaccines Crossover

The precision and adaptability of mRNA technology have caught the interest of researchers in oncology. Although novel for cancer, these new therapies are based on knowledge gained from infectious disease vaccines, which educate and strengthen the immune system to combat infections.[38]

Integration into Global Immunization Programs and Low-Income Settings

For mRNA vaccines to always play a role in global immunization, it is necessary to solve issues involving cost, infrastructure, and where products are made.[39] Under the mRNA Technology Transfer Hub led by the WHO, work is being carried out to help set up local production in LMICs.[40] By supporting regional independence and fair

Table 3 | Future research prioritization matrix for mRNA vaccine innovations

Research Area	Potential Impact	Technology Readiness	Status Indicator
Thermostable LNP formulations	High	High	High impact/high readiness
saRNA – malaria	High	Medium	High impact/medium readiness
Microneedle patches for mRNA delivery	High	Medium	High impact/medium readiness
Multivalent mRNA vaccines (e.g., Flu + RSV)	High	Medium	High impact/medium readiness
Personalized mRNA cancer vaccines	High	Low	High impact/low readiness
mRNA vaccines for TB	Medium	Low	Medium impact/low readiness
Oral or aerosolized mRNA delivery	Medium	Low	Medium impact/low readiness

use of technology, the aim is to broaden access to help the world handle future pandemics.

Regulatory Convergence and Intellectual Property Waivers

Post-WTO Ministerial 13 Developments: An important move in the international policy arena was made at the WTO Ministerial Conference 13 in June of the year 2025. Isolated discussions were held regarding broadening the definition of the 2022 TRIPS waiver, which had exclusively applied to COVID-19 vaccines, to include mRNA technology for other pandemic-related vaccines, therapeutics, and diagnostic tools. No binding resolution was agreed upon, but the numerous participants, such as South Africa, India, Indonesia, and others, demanded an expedited exchange of knowledge as well as time-bound waivers of IP during the state of crisis.

At the same time, global regulatory agencies, such as the WHO, EMA, and FDA, have made attempts to unify the emergency-use pathways of the mRNA products. These encompass the development of a mutual recognition process, convergence of stability testing practices, and the provision of data-sharing systems to minimize redundancy in the vaccine approval process.

Regulatory convergence is critical in preventing future pandemic bottlenecks. These changes in policy may be very beneficial in terms of creating more equal access to mRNA vaccines, particularly in LMICs that do not have their own innovation ecosystem in place.

Prioritizing Future Research

Impact vs. Readiness Matrix: This will help to drive investment and partnership, and a traffic-light matrix is shown below, to classify the major mRNA vaccine research directions in the future, according to their potential impact on the health of the population and their level of technology readiness (TRL). Every research direction has a ranking in both dimensions of high, medium, and low (Table 3):

Conclusion

Using mRNA vaccine technology is a great step forward in immunology and fighting infectious diseases. This article described the two main components of mRNA vaccines—synthetic mRNA and LNPs—how they work, the groundbreaking development of the first COVID-19 vaccines, and their increasing use against other types of infections. As well, it discussed the main strengths of the platform, which are fast design, flexible manufacturing, and safety, while also pointing out ongoing challenges of meeting cold-chain needs, observing and addressing adverse events, and developing longer-lasting immunity for patients.

They have updated the world of vaccine production by making it faster and more targeted for new viruses. COVID-19 is not the only target for these vaccines, since researchers are also focused on further work on different types of vaccines, stable formulations, needle-free delivery, and new ways to design vaccines for cancer. Because of these advances, the platform can help both ordinary and emergency vaccine strategies.

The full benefits of this can only be achieved if we keep investing in research while making sure the rules protect both people and innovation. Strengthening the local manufacturing and supply chains in countries with lower and middle incomes is very important for global equity. By fostering international cooperation and ensuring equitable access, mRNA technology has the potential to support global health security.

References

1 Aga AM, Kelel M, Gemeda MT. Recent advances in mRNA vaccine development. Preprints; 2023. https://doi.org/10.20944/preprints202308.0245.v1

2 Erman M. FDA sets new COVID booster guidelines requiring trials for approvals for healthy adults. Reuters; 2025. Available from: https://www.reuters.com/business/healthcare-pharmaceuticals/fda-sets-new-covid-booster-guidelines-requiring-trials-approvals-healthy-adults-2025-05-20/

3 Al Fayez N, Nassar MS, Alshehri AA, Alnefaie MK, Almughem FA, Alshehri BY, et al. Recent advancement in mRNA vaccine development and applications. Pharmaceutics. 2023;15(7):1972. https://doi.org/10.3390/pharmaceutics15071972

4 Chen N. Exploring mRNA vaccines: current insights and future potential. Integrating Pulse; 2025. Available from: https://integratingpulse.com/articles/exploring-mrna-vaccines-insights-potential/

5 Pharmaceutical Journal. Understanding mRNA vaccine technologies. London: Royal Pharmaceutical Society; 2021. Available from: https://pharmaceutical-journal.com/article/ld/understanding-mrna-vaccine-technologies

6 Aljabali AA, Bashatwah RM, Obeid MA, Mishra V, Mishra Y, Serrano-Aroca Á, et al. Current state of, prospects for, and obstacles to mRNA vaccine development. Drug Discov Today. 2023;28(2):103458. https://doi.org/10.1016/j.drudis.2022.103458

7 U.S. Food and Drug Administration. mRNA vaccines: mechanism, efficacy, and safety. Silver Spring, MD: FDA; 2024. Available from: https://www.fda.gov/media/185127/download

8 Szabó GT, Mahiny AJ, Vlatkovic I. COVID-19 mRNA vaccines: platforms and current developments. Mol Ther. 2022;30(5):1850–68. https://doi.org/10.1016/j.ymthe.2022.02.016

9 Jin L, Zhou Y, Zhang S, Chen SJ. mRNA vaccine sequence and structure design and optimization: advances and challenges. J Biol Chem. 2024;301:108015. https://doi.org/10.1016/j.jbc.2024.108015

10 Batisani K. The role of mRNA vaccines in infectious diseases: a new era of immunization. Trop Dis Travel Med Vaccines. 2025;11(1):1–8. https://doi.org/10.1186/s40794-025-00246-3
11 Cao Q, Fang H, Tian H. mRNA vaccines contribute to innate and adaptive immunity to enhance immune response in vivo. Biomaterials. 2024;310:122628. https://doi.org/10.1016/j.biomaterials.2024.122628
12 Fang E, Liu X, Li M, Zhang Z, Song L, Zhu B, et al. Advances in COVID-19 mRNA vaccine development. Signal Transduct Target Ther. 2022;7(1):94. https://doi.org/10.1038/s41392-022-00950-y
13 Adobe Stock. mRNA vaccine mechanism about the human body. Adobe Stock; 2020. Available from: https://stock.adobe.com/images/mrna-vaccine-mechanism-in-relation-to-human-body/402849259
14 Haghmorad D, Eslami M, Orooji N, Halabitska I, Kamyshna I, Kamyshnyi O, et al. mRNA vaccine platforms: linking infectious disease prevention and cancer immunotherapy. Front Bioeng Biotechnol. 2025;13:1547025. https://doi.org/10.3389/fbioe.2025.1547025
15 Paczkowska A, Hoffmann K, Andrzejczak A, Pucek WF, Kopciuch D, Bryl W, et al. The application of mRNA technology for vaccine production—current state of knowledge. Vaccines (Basel). 2025;13(4):389. https://doi.org/10.3390/vaccines13040389
16 Khormi AH, Qohal RM, Masrai AY, Hakami KH, Ogdy JA, Almarshad AA, et al. Emerging trends in mRNA vaccine technology: beyond infectious diseases. Egypt J Chem. 2024;67(13):1567–74. https://doi.org/10.21608/ejchem.2024.337883.10838
17 Fatima M, Park PG, Hong KJ. Clinical advancements in mRNA vaccines against viral infections. Clin Immunol. 2024;271:110424. https://doi.org/10.1016/j.clim.2024.110424
18 Kollewe J. 'Medicine is going personalised': Moderna's UK boss on the coming vaccine revolution. The Guardian; 2024. Available from: https://www.theguardian.com/business/2024/jan/16/medicine-is-going-personalised-modernas-uk-boss-on-the-coming-vaccine-revolution
19 Gote V, Bolla PK, Kommineni N, Butreddy A, Nukala PK, Palakurthi SS, et al. A comprehensive review of mRNA vaccines. Int J Mol Sci. 2023;24(3):2700. https://doi.org/10.3390/ijms24032700
20 Al Jazeera. Infographic: the COVID-19 vaccine divide; 2021. Available from: https://www.aljazeera.com/amp/news/2021/6/23/infographic-covid19-vaccine-divide
21 Iqbal SM, Rosen AM, Edwards D, Bolio A, Larson HJ, Servin M, et al. Opportunities and challenges to implementing mRNA-based vaccines and medicines: lessons from COVID-19. Front Public Health. 2024;12:1429265. https://doi.org/10.3389/fpubh.2024.1429265
22 World Health Organization. Potential benefits and limitations of mRNA technology for vaccine research and development for infectious diseases and virus-induced cancers: report of the WHO Science Council. Geneva: WHO; 2023. Available from: https://iris.who.int/bitstream/handle/10665/375031/9789240084551-eng.pdf [Accessed 25 May 2025].
23 Wong BK, Mabbott NA. Systematic review and meta-analysis of COVID-19 mRNA vaccine effectiveness against hospitalizations in adults. Immunother Adv. 2024;4(1):ltae011. Available from: https://academic.oup.com/immunotherapyadv/article-abstract/4/1/ltae011/7909242 [Accessed 25 May 2025].
24 Jamal A. Vaccines: advancements, impact, and the road ahead in medicine. BULLET J Multidisiplin Ilmu. 2023;2(5):1047–55. Available from: https://www.researchgate.net/profile/Ahmad-Jamal-16/publication/379927658_Vaccines_Advancements_Impact_and_the_Road_Ahead_in_Medicine/links/6622302e66ba7e2359e8ecb7/Vaccines-Advancements-Impact-and-the-Road-Ahead-in-Medicine.pdf
25 Troncoso-Bravo T, Ramírez MA, Loaiza RA, Román-Cárdenas C, Papazisis G, Garrido D, et al. Advancement in the development of mRNA-based vaccines for respiratory viruses. Immunology. 2024;173(3):481–96. https://doi.org/10.1111/imm.13844
26 Karam M, Daoud G. mRNA vaccines: past, present, future. Asian J Pharm Sci. 2022;17(4):491–522. https://doi.org/10.1016/j.ajps.2022.05.003
27 Leite GS, Albuquerque AB, Pinheiro PR. Applications of technological solutions in primary ways of preventing transmission of respiratory infectious diseases—a systematic literature review. Int J Environ Res Public Health. 2021;18(20):10765. https://doi.org/10.3390/ijerph182010765
28 Li S, Zheng L, Zhong J, Gao X. Advancing mRNA vaccines for infectious diseases: key components, innovations, and clinical progress. Essays Biochem. 2025;69(2):EBC20253009. https://doi.org/10.1042/EBC20253009
29 Lu RM, Hsu HE, Perez SJ, Kumari M, Chen GH, Hong MH, et al. The current landscape of mRNA technologies and delivery systems for new modality therapeutics. J Biomed Sci. 2024;31(1):89. https://doi.org/10.1186/s12929-024-01080-z
30 Pardi N, Krammer F. mRNA vaccines for infectious diseases—advances, challenges and opportunities. Nat Rev Drug Discov. 2024;23(11):838–61. https://doi.org/10.1038/s41573-024-01042-y
31 Tian Y, Deng Z, Yang P. mRNA vaccines: a novel weapon to control infectious diseases. Front Microbiol. 2022;13:1008684. https://doi.org/10.3389/fmicb.2022.1008684
32 Zhang G, Tang T, Chen Y, Huang X, Liang T. mRNA vaccines in disease prevention and treatment. Signal Transduct Target Ther. 2023;8(1):365. Available from: https://www.nature.com/articles/s41392-023-01579-1 [Accessed 25 May 2025].
33 Sylvanus B, Adebanjo EA, Fatai LO, Muojekwu EE, Bakare KM, Oseni VE, et al. New developments in messenger ribonucleic acids (mRNA) vaccine technology: future applications in cancer oncology. In: Cancer diagnosis, treatment and care: reflections for the education of survivors and healthcare providers. Hershey, PA: IGI Global Scientific Publishing; 2025. p. 125–44. https://doi.org/10.4018/979-8-3693-5400-1.ch008
34 Li L, Liu X, Bai Y, Yao B, Luo H, Tu T. High-throughput screening techniques for the selection of thermostable enzymes. J Agric Food Chem. 2024;72(8):3833–45. https://doi.org/10.1021/acs.jafc.3c07554
35 Xu R, Pan Q, Zhu G, Ye Y, Xin M, Wang Z, et al. Thermo L ink: bridging disulfide bonds and enzyme thermostability through database construction and machine learning prediction. Protein Sci. 2024;33(9):e5097. https://doi.org/10.1002/pro.5097
36 Alejo T, Toro-Córdova A, Fernández L, Rivero A, Stoian AM, Pérez L, et al. Comprehensive optimization of a freeze-drying process achieving enhanced long-term stability and in vivo performance of lyophilized mRNA-LNPs. Int J Mol Sci. 2024;25(19):10603. https://doi.org/10.3390/ijms251910603
37 Wei Z, Zhang S, Wang X, Xue Y, Dang S, Zhai J. Technological breakthroughs and advancements in the application of mRNA vaccines: a comprehensive exploration and prospects. Front Immunol. 2025;16:1524317. Available from: https://www.frontiersin.org/journals/immunology/articles/10.3389/fimmu.2025.1524317/full [Accessed 25 May 2025].
38 Ye Z, Harmon J, Ni W, Li Y, Wich D, Xu Q. The mRNA vaccine revolution: COVID-19 has launched the future of vaccinology. ACS Nano. 2023;17(16):15231–53. Available from: https://pubs.acs.org/doi/abs/10.1021/acsnano.2c12584 [Accessed 25 May 2025].
39 Saxena S, Mandurah V, Tariq W, Das P, Sambhav K, Devi SH, et al. The future of mRNA vaccines: potential beyond COVID-19. Cureus. 2025;17(5):e84529. https://doi.org/10.7759/cureus.84529
40 Wang SC, Rai CI, Chen YC. Challenges and recent advancements in COVID-19 vaccines. Microorganisms. 2023;11(3):787. https://doi.org/10.3390/microorganisms11030787