

# Nanomaterials in Vaccine Formation and Chemical Formulae for Vaccination

Nikat Rajak Mulla<sup>1</sup>, Kazi Kutubuddin Sayyad Liyakat<sup>2,\*</sup>

## Abstract

*For centuries, vaccines have been a cornerstone of public health, preventing debilitating and deadly diseases. However, the development and delivery of effective vaccines have always been met with challenges. From stability issues and limited immune response to the need for specific targeting, scientists are constantly seeking innovative approaches to improve vaccine efficacy and accessibility. Enter nanomaterials – minuscule materials with dimensions at the nanoscale – offering a powerful toolkit to overcome these challenges and usher in a new era of vaccine technology. This article will explore how nanomaterials are revolutionizing vaccine development, focusing on their diverse applications in enhancing vaccine properties and improving overall efficacy. Nanomaterials can act as carriers for antigens, the molecules that trigger an immune response. Encapsulating antigens within nanoparticles protects them from degradation, ensuring their stability and increasing their delivery to immune cells. This is especially crucial for fragile antigens, like mRNA, which require protective delivery systems to reach their target cells. Adjuvants are substances that enhancement immune response to a vaccine. Nanomaterials can act as adjuvants themselves or enhance the effectiveness of traditional adjuvants. Their structure and surface properties can stimulate immune cells, amplify the immune response and lead to stronger and longer-lasting immunity. Nanomaterials are revolutionizing vaccine development by offering solutions to long-standing challenges related to antigen delivery, adjuvant enhancement, targeted delivery, and vaccine stability. As research continues to progress, we may expect to see more ground-breaking and effective nanomaterial-based vaccines emerge, leading to improved global health and disease prevention. The tiny titans of nanotechnology are poised to make a big impact on the fight against infectious diseases and beyond.*

**Keywords:** Nano material, vaccine, vaccination, chemical formulae, immune system

### \*Author for Correspondence

Kazi Kutubuddin Sayyad Liyakat  
E-mail: drkkazi@gmail.com

<sup>1</sup>Student, Department of Electronics and Telecommunication Engineering, Brahmdevdada Mane Institute of Technology, Solapur, Maharashtra, India

<sup>2</sup>Professor and Head, Department of Electronics and Telecommunication Engineering, Brahmdevdada Mane Institute of Technology, Solapur, Maharashtra, India

Received Date: May 12, 2025

Accepted Date: May 16, 2025

Published Date: July 09, 2025

**Citation:** Nikat Rajak Mulla, Kazi Kutubuddin Sayyad Liyakat. Nanomaterials in Vaccine Formation and Chemical Formulae for Vaccination. Journal of Nanoscience, Nanoengineering & Applications. 2025; 15(3): 27–39p.

## INTRODUCTION

Vaccination has been the most impactful public health interferences in history, significantly reducing incidences and ruthlessness of infectious diseases worldwide. But how exactly does vaccination work? This article delves into the science behind vaccination, explaining how these remarkable medical advancements build immunity and safeguard both individuals and communities [1–5].

At its core, vaccination works by exposing body to enfeebled or lazy form of a disease-causing organism, called a pathogen. This could be a virus, bacteria, or even a part of a pathogen. The key

---

principle is that this exposure does not cause illness in a healthy individual. Instead, it triggers the immune scheme to recognize and remember the specific pathogen.

Think of it like a wanted poster. The vaccine presents the immune system with a picture of the “criminal” (the pathogen) without the criminal committing any crimes. This allows the immune system to prepare a defence strategy without the individual suffering the consequences of the real infection.

When the body encounters the weakened or inactive pathogen, the immune system kicks into gear. This process involves several key players:

- *Antigen-presenting cells*: Antigen-presenting cells (APCs), such as dendritic cells and macrophages, play a key role in the immune response by capturing pathogens and presenting their distinctive protein markers – called antigens – on their surface.
- *T Cells*: These are specialized immune cells that recognize the antigens presented by APCs. Helper T-cells coordinate immune response; however, cytotoxic T-cells directly attack infected cells.
- *B Cells*: These cells yield antibodies which were proteins specifically bind to pathogen, neutralizing it or marking it for obliteration by further immune cells.

Crucially, during this process, immune system generates “memory” cells – both memory T-Cells and memory B-cells. These cells are long-lived and remain in body, ready to reply quickly if individual is ever exposed to actual pathogen.

This is where the real power of vaccination lies. If the vaccinated distinct encounters the live pathogen in future, the memory cells recognize it immediately. They rapidly proliferate and mount a robust immune response, often preventing the individual from becoming ill or significantly reducing the severity of the disease.

This “memory” immune response is much faster and more effective than the initial response to a new pathogen. The body already knows how to fight the infection, thanks to the vaccination.

Beyond individual protection, vaccination also plays a vital role in protecting entire communities through a concept called “herd immunity.” When a large amount of the populace is vaccinated beside a disease, it becomes challenging for the pathogen to blowout. This defends those who cannot be vaccinated like infants, pregnant women, and personalities with deteriorated immune systems.

Imagine a field of dried grass. If a fire starts, it can spread quickly and easily. However, if most of the grass is already burnt (vaccinated), the fire will have a difficult time spreading and may even die out. Herd immunity works in a similar way, slowing down or stopping the spread of infectious diseases [6–10].

Vaccination technologies are continually evolving. Scientists are developing new and innovative vaccines for wider range of illnesses, comprising cancer and HIV. These advancements hold immense promises for improving global health and wellbeing.

Vaccination is a vital part of today’s healthcare, using the body’s own immune system to guard both individuals and entire communities against serious infectious diseases. By understanding the science behind vaccination, we can appreciate its immense value and promote its continued use to build a healthier and safer World for all.

## THE CHEMISTRY OF IMMUNITY

Vaccination, a cornerstone of modern medicine, has eradicated or drastically reduced the incidence of numerous infectious diseases. While the concept of exposing the body to weakened or inactive

pathogens to stimulate an immune response is well-known, the underlying mechanisms and the very building blocks of these life-saving interventions often remain shrouded in scientific jargon. This article aims to demystify the formation of vaccinations by exploring the chemical formulae and processes involved in creating immunity [11–15].

At its core, vaccination hinges on body's capability to recognize and responds to foreign invaders, known as antigens. Antigens are usually proteins or sugars found on the outer surface of harmful microbes like viruses and bacteria. You can think of them as the “uniforms” that help the immune system recognize and target these invaders. Our immune system, upon encountering an antigen, triggers a cascade of events leading to the creation of antibodies and specialized immune cells primed to recognize and neutralize the specific threat.

The chemical composition of vaccines varies depending on the type. Let us explore some common categories:

- *Inactivated vaccines*: Inactivated vaccines are made using entire pathogens that have been destroyed through methods, like heat, radiation, or chemical agents, such as formaldehyde (CH<sub>2</sub>O), ensuring they can no longer cause disease. While the pathogen is dead, its antigenic structure remains intact, allowing the immune system to recognize it. Examples include the inactivated polio vaccine (IPV) and some influenza vaccines. The key here is not a specific formula, but the integrity of the complex protein structures within the pathogen, preserved as much as possible during inactivation.
- *Live Weakened Vaccines*: These contains weakened (attenuated) versions of pathogen. They multiply at a slow rate inside the body, triggering a strong and lasting immune response while minimizing the risk of serious illness. A common example is the Measles, Mumps, and Rubella (MMR) vaccine. The chemical composition, again, involves complex protein structures, but the critical aspect is the genetic modification of the pathogen, making it less virulent. This does not translate into a simple chemical formula, but rather altered sequences within the pathogen's DNA or RNA.
- *Subunit, Recombinant, Polysaccharide, and Conjugate Vaccines*: These vaccines use precise components of the pathogen rather than the whole organism.
  - *Subunit Vaccines*: These contain purified antigens, such as proteins, from the pathogen. For instance, Hepatitis-B vaccines contain hepatitis-B surface antigen (HBsAg), a protein. Understanding the amino acid sequence of HBsAg is crucial for its production but representing it as a simple chemical formula is impossible due to its complexity.
  - *Recombinant Vaccines*: These are produced by recombinant DNA technologies. The gene encoding a specific antigen is inserted into a host cell (Yeast or Bacteria) which then produces the antigen. Again, the focus is on the amino acid sequence of the target protein, not a singular chemical formula.
  - *Polysaccharide Vaccines*: These vaccines contain chains of sugar molecules (polysaccharides) found on the surface of some bacteria, like *Streptococcus pneumoniae*. The chemical formula for a specific polysaccharide varies depending on the sugar monomers it comprises.
  - *Conjugate Vaccines*: These vaccines link polysaccharides to a protein carrier. This conjugation enhances the immune response, particularly in young children. The chemical bond between the polysaccharide and the protein carrier is vital, often involving linker molecules, like succinimidyl 4-(N-maleimidomethyl) cyclohexane-1-carboxylate (SMCC-C<sub>12</sub>H<sub>11</sub>NO<sub>5</sub>), which facilitates the attachment.
- *mRNA Vaccines*: A revolutionary approach, mRNA vaccines deliver genetic instructions to our cells, prompting them to temporarily produce the antigen, typically a viral spike protein. Examples include some COVID-19 vaccines. The mRNA molecule itself is a complex chain of nucleotides (adenine, guanine, cytosine, and uracil), each with specific chemical structures. While a full formula is impractical, understanding the sequence of these nucleotides is crucial for the vaccine's efficacy.

Many vaccines contain adjuvants, materials that improve the immune responses to the antigen. Common adjuvants include:

- *Aluminum Salts*: Aluminum hydroxide ( $\text{Al}(\text{OH})_3$ ) and aluminum phosphate ( $\text{AlPO}_4$ ) are frequently used. The precise mechanism by which they work is still being investigated, but they are believed to promote antigen presentation and stimulate immune cells.
- *Monophosphoryl Lipid A (MPL)*: A derivative of lipopolysaccharide (LPS), component of bacterial-cell walls, MPL (complex lipid structure) stimulates the immune system.

While chemical formulae provide insights into the components of vaccines, the manufacturing process is equally crucial. This process involves:

1. *Antigen Production*: Growing and isolating the pathogen or producing the antigen through recombinant technology.
2. *Purification*: Removing impurities and isolating the desired antigen.
3. *Inactivation/Attenuation*: Killing or weakening the pathogen, if applicable.
4. *Formulation*: Combining the antigen with adjuvants and stabilizers.
5. *Quality Control*: Rigorous testing to ensure safety and efficacy.

Vaccination is a triumph of scientific innovation, rooted in a deep understanding of immunology and chemistry. While simple chemical formulae cannot fully encapsulate the complexity of these life-saving interventions, appreciating the chemical composition of antigens, adjuvants, and other vaccine components provides a valuable insight into how they stimulate the immune system and protect us from infectious diseases. With ongoing advancements in technology, vaccine development is set to become even more precise and effective, paving the way for highly targeted and improved immunizations in the years to come. Understanding the chemistry behind these breakthroughs empowers us to appreciate their significance and fosters informed public discourse about their crucial role in public health.

## THE ROLE OF NANOMATERIALS IN VACCINE DEVELOPMENT

Vaccines have been instrumental in averting and regulating the blowout of infectious illnesses, saving innumerable lives and civilizing overall public health. In recent times, nanotechnology has gained attention as a powerful and promising approach for creating vaccines that are not only more effective but also safer for use. Nanomaterials that are materials with at least one dimension in size ranges of 1–100 nanometers, have unique physical and chemical properties that makes them ideal for use in vaccine formation.

The main advantages of using nanomaterials in vaccine progress is their aptitude to improve the delivery of antigens, the substances that trigger an immune response, to the body. Nanoparticles can protect antigens from degradation and clearance by immune system, allowing them to reach their target cells in the body more efficiently. This can lead to stronger and sustained immune response, which is crucial for the effectiveness of vaccines.

Nanomaterials may also be used to target specific cells in the body, such as dendritic cells, which play a key role in immune response. By delivering antigens directly to these cells, nanoparticles may enhance immune response and provide better protection against infectious diseases. Nanoparticles can also be engineered to release their content slowly and steadily, allowing the immune system to be exposed to the antigen over a longer period – this often results in a stronger and more effective immune response.

Another potential application of nanomaterials in vaccine development is around adjuvants, substances which are mixed to vaccines to improve the immune response. Nanoparticles can act as adjuvants by themselves, or they can be used to deliver traditional adjuvants more effectively. For example, nanoparticles can be used to encapsulate aluminum salts, a common adjuvant, and deliver them to the target cells, resulting in a stronger and targeted immune response.

Nanomaterials can also be used to improve the stability and shelf-life of vaccines. Many vaccines require strict storage conditions, such as refrigeration, to maintain their effectiveness. This can be a major challenge in developing countries, where access to reliable refrigeration is limited. Nanoparticles can be used to protect the antigens from degradation and extend the shelf-life of vaccines, creation them accessible to persons in distant and resource-limited settings.

While nanomaterials offer exciting possibilities for vaccine development, their safety remains a significant concern. Since nanoparticles can enter cells and tissues, there is still much we do not know about their long-term impact on the body. That is why it is essential to carry out detailed safety and toxicity studies before incorporating them into vaccines. In inference, nanomaterials have potential to revolutionize the field of vaccine development by improving the delivery, targeting, and stability of antigens. They can enhance immune response, providing better protection against transmittable diseases. However, more investigation is desirable to understand the safety and toxicity of nanoparticles, and to ensure their safe and active usage in vaccine formation. With continued research and development, nanomaterials could play a key role in the fight against infectious diseases and improve public health worldwide [16–20].

## HOW NANOMATERIALS ARE REVOLUTIONIZING VACCINE DEVELOPMENT

Vaccines have been a vital part of public health for hundreds of years, shielding us from serious illnesses. Now, as the field of vaccination keeps advancing, nanotechnology is leading the way in driving these exciting changes. Nanomaterials, materials on the scale of billionths of a meter, are proving to be game changers in vaccine development, offering unprecedented precision, efficacy, and stability.

The power of nanomaterials stems from their unique size and properties. Because of their tiny size, they can engage directly with cells and molecules in the body, offering several important benefits when it comes to designing vaccines.

### Enhanced Immune Response

Nanomaterials may be contrived to parodist size and shape of viruses, effectively tricking the immune system into mounting a robust response. They may also be intended to target precise immune cells, directing the immune response towards optimal protection.

- *Improved Antigen Delivery:* Antigens, the molecules in vaccines that trigger an immune response, can be unstable and poorly absorbed. Nanomaterials act as protective carriers, encapsulating and delivering antigens directly to immune cells, preserving their integrity and enhancing their effectiveness.
- *Controlled Release:* Nanomaterials may be intended to release antigens slowly over time, mimicking a natural infection and leading to longer lasting and powerful immune response. This controlled release can reduce the need for multiple booster shots.
- *Adjuvant Properties:* Some nanomaterials exhibit inherent adjuvant properties, meaning they can boost the immune response to the antigen without the need for additional adjuvants. This simplifies vaccine formulation and can reduce potential side effects.
- *Stability and Shelf Life:* Traditional vaccines often require strict temperature control, making them difficult to distribute in resource-limited settings. Nanomaterials help improve vaccine stability, which means vaccines can last longer and be more easily distributed around the world.

Researchers are exploring a wide range of nanomaterials for vaccine development, each with unique properties and applications:

- *Liposomes:* These spherical vesicles composed of lipid bilayers are widely employed to encapsulate and deliver antigens, mimicking cell membranes for efficient cellular uptake.
- *Nanoparticles:* Made from materials, like polymers, lipids, or metals, nanoparticles, can be tailored to exact sizes and shapes, allowing for precise antigen delivery and controlled release.

- *Dendrimers*: These branched, tree-like structures offer a higher degree of control over the size and surface properties, making them ideal for delivering antigens and adjuvants in a targeted manner.
- *Carbon Nanotubes*: These tubular structures might be functionalized with various molecules, allowing for targeted delivery of antigens and stimulation of specific immune pathways.

The use of nanomaterials in vaccines is no longer a theoretical concept; it is a reality. Several approved vaccines already utilize nanomaterials, including:

- *mRNA COVID-19 Vaccines*: These groundbreaking vaccines utilize lipid nanoparticles to encapsulate and deliver mRNA, instructing cells to produce viral proteins and triggering an immune response.
- *Hepatitis-B Vaccine*: Some Hepatitis-B vaccines utilize aluminum hydroxide nanoparticles as adjuvant, enhancing immune response to the Hepatitis-B surface antigen.

Looking ahead, the potential of nanomaterials in vaccine development is immense. Researchers are focusing on:

- *Developing vaccines against challenging diseases*: Nanomaterials are being discovered for emerging vaccines against diseases, like HIV, malaria, and cancer, which have confirmed tough to target with customary vaccine approaches.
- *Personalized vaccines*: The ability to tailor nanomaterials to specific individuals could lead to personalized vaccines that are more effective and have fewer side effects.
- *Combination vaccines*: Nanomaterials can be used to deliver multiple antigens simultaneously, simplifying vaccination schedules and improving patient compliance [21–25].

Nanomaterials are revolutionizing vaccine development, offering the potential to create more effective, stable, and accessible vaccines. However, challenges remain. Making sure nanomaterials are safe and compatible with the body is essential, and more research is needed to fully understand their long-term effects. Scalable and cost-effective engineering processes are also essential to ensure that these innovative vaccines can be produced and distributed on a global scale.

Despite these challenges, the future of vaccination is undoubtedly intertwined with nanotechnology. By harnessing the power of these tiny titans, we can develop vaccines that protect us from existing and emerging threats, paving the way for a healthier future for all.

## IMPORTANCE OF NANO MATERIALS IN VACCINE FORMATION

Vaccines have long been a keystone of community health, stopping infectious illnesses and saving limitless lives. However, customary vaccine formulations can sometimes face challenges related to stability, efficacy, and delivery. This is where the burgeoning field of nanotechnology steps in, offering innovative solutions to enhance vaccine development and improve global health outcomes.

Nanomaterials are materials with sizes in nanometer range (1–100 nanometers), possess unique properties that make them ideal tools for vaccine engineering. Their tiny size allows for efficient interaction with the immune system, while their diverse chemical functionalities allow for tailored design and controlled release. Let us delve into some key use cases of nanomaterials in vaccine formation.

### Enhancing Antigen Delivery and Presentation

- *Nanoparticles as Carriers*: Imagine tiny delivery trucks ferrying vaccine antigens directly to immune cells. Nanoparticles, composed of materials, like lipids, polymers, or metals, act as these carriers. They encapsulate antigens, protecting them from degradation during transit and ensuring efficient delivery to Antigen-Presenting Cells (APCs) like dendritic cells. This targeted delivery boosts immune response and can reduce required antigen dose.

- *Self-Adjuvating Nanomaterials*: Some nanomaterials possess inherent adjuvant properties, meaning they can stimulate the immune system independently. For instance, some lipid nanoparticles (LNPs) can stimulate Toll-like receptors (TLRs) on immune cells, sparking an inflammatory reaction that boosts the vaccine's overall effectiveness. This eliminates the need for traditional adjuvants, potentially reducing side effects.

### **Improving Vaccine Stability**

- *Encapsulation for Protection*: Vaccines are often susceptible to degradation due to temperature fluctuations and environmental factors, particularly in regions with limited cold chain infrastructure. Nanomaterials can surround antigens with a protective layer, keeping them safe from breaking down and helping vaccines stay effective for longer. This is especially important for making sure vaccines work well in places with limited resources.
- *Lyophilization Assistance*: Lyophilization (freeze-drying) is a common technique for preserving vaccines. Nanomaterials can act as cryoprotectants, preventing antigen damage during the freeze-drying process and improving the stability of the resulting powder form. This makes vaccines easier to transport and store, especially in remote areas.

### **Enabling Personalized Vaccine Design**

- *Tailoring Immune Responses*: Nanomaterials can be engineered to elicit specific types of immune responses such as cell-mediated immunity or antibody production. By manipulating size, shape, and surface chemistry of nanoparticles, investigators can fine-tune the immune response to the pathogen being targeted.
- *Multi-Antigen Vaccines*: Nanomaterials allow for the simultaneous delivery of multiple antigens from different pathogens or different strains of the same pathogen. This "multi-valent" approach can simplify vaccination schedules and broaden the immune response, offering protection against a wider range of threats.

### **Novel Vaccine Delivery Routes**

- *Needle-Free Vaccination*: Nanoparticles can be formulated for alternative delivery routes such as nasal sprays or transdermal patches. These needle-free options offer significant advantages, including increased patient comfort, reduced risk of infection, and easier administration, particularly in mass vaccination campaigns.
- *Oral Vaccination*: Nanomaterials can protect antigens from degradation in cruel gastric situation, allowing for oral administration. This could revolutionize vaccine delivery, particularly for children and vulnerable populations [26–30].

The victory of mRNA vaccines for COVID-19 highlights transformative power of nanotechnology. Lipid nanoparticles (LNPs) were crucial for encapsulating and delivering fragile mRNA molecules, protecting them from dilapidation and enabling efficient uptake by cells. This groundbreaking achievement has paved the way for further research and expansion of nanoparticle-founded vaccines for a wide variety of diseases.

Using nanomaterials in vaccine development is a fast-growing area full of exciting possibilities. Future research will focus on optimizing nanoparticle design, exploring novel delivery routes, and developing personalized vaccines tailored to individual needs. As we continue to loosen the difficulties of immune system and harness the power of nanotechnology, we can expect to see even more innovative and effective vaccines that protect us from the threat of infectious diseases and improve global health outcomes.

In conclusion, nanomaterials are not just tiny particles; they are powerful tools transforming the landscape of vaccine development. By enhancing antigen delivery, improving stability, enabling personalized design, and facilitating novel delivery routes, these tiny titans are poised to revolutionize the way we prevent and combat infectious diseases.

---

## USE CASES OF NANOMATERIALS IN VACCINE FORMATION

Here is a look at how nanomaterials are being employed in the development of novel and improved vaccines.

### Nanoparticle-Based Antigen Delivery Schemes

- *Liposomes*: These spherical vesicles poised of lipid bilayers are widely used to encapsulate and deliver antigens. Liposomes can protect antigens from degradation and improve their acceptance by immune cells. They have been successfully used in vaccines against influenza, hepatitis A, and COVID-19.
- *Polymeric Nanoparticles*: Polymers, like PLGA (poly (lactic-co-glycolic acid)), are biocompatible and biodegradable, making them ideal for creating nanoparticles that encapsulate antigens. These nanoparticles allow for controlled release and can be tailored to elicit specific immune responses.
- *Virus-Like Particles (VLPs)*: VLPs mimic an assembly of viruses but lacks genetic material necessary for replication, making them safe and highly immunogenic. They are being used in vaccines beside Human-Papillomavirus (HPV) and hepatitis-B.
- *Protein Nanoparticles*: Proteins can be engineered to self-assemble into nanoparticles, carrying antigens on their surface or within their structure. This approach allows for precise control over the presentation of antigens to the immune system.

### Nanomaterial-Based Adjuvants

- *Aluminum-Based Nanoparticles*: While aluminum salts are the most widely used adjuvants, researchers are exploring aluminum-based nanoparticles with tailored properties for improved adjuvant activity.
- *Immunostimulatory Oligonucleotides (CpG ODN) Conjugated to Nanomaterials*: CpG ODN stimulates the immune system by activating Toll-like receptor 9 (TLR9). Attaching CpG ODN to nanomaterials improves its delivery to immune cells and boosts the immune system's response.
- *Gold Nanoparticles*: Gold nanoparticles possess unique optical and chemical properties that might be exploited to improve immune responses. They can be used to deliver antigens, stimulate immune cells, and promote targeted delivery of vaccines.

### mRNA Vaccine Delivery

- *Lipid Nanoparticles (LNPs)*: Perhaps most protuberant example is the usage of LNPs to encapsulate and carry mRNA in COVID-19 vaccine by Pfizer–BioNTech and Moderna. LNPs protect the fragile mRNA from degradation, facilitate its entry into cells, and enhance its translation into viral proteins, triggering a robust immune response.

### DNA Vaccine Delivery

- *Nanoparticles for Plasmid DNA Delivery*: Like mRNA, DNA vaccines benefit from nanoparticle delivery systems. Nanomaterials can protect the plasmid DNA from degradation and enhance its uptake by cells, leading to improved gene expression and immune response.

## NANO-MATERIALS IN VACCINES USING CHEMICAL FORMULAE

Vaccines have long been a cornerstone of public health, protecting us from debilitating and deadly diseases. But as pathogens evolve and new challenges emerge, researchers are constantly seeking innovative ways to enhance vaccine efficacy and accessibility. Nanomaterials, materials engineered at the atomic and molecular level (1–100 nanometers), are proving to be powerful tools in this endeavor, revolutionizing vaccine design and delivery.

Let us delve into some key nanomaterials and their roles in vaccine formation, using chemical formulas to illustrate their composition.

### Lipid Nanoparticles (LNPs)

Perhaps most famously used in mRNA vaccines against COVID-19, LNPs protect fragile mRNA molecules and facilitate their delivery into cells. They are typically composed of mixtures of lipids, including:

- *DOTAP(1,2-dioleoyl-3-trimethylammonium-propane)*: A cationic lipid ( $C_{44}H_{86}NO_4^+$ ) that helps bind the negatively charged mRNA.
- *Cholesterol( $C_{27}H_{46}O$ )*: Stabilizes the LNP structure.
- *DSPC(1,2-distearoyl-sn-glycero-3-phosphocholine)*: A neutral phospholipid ( $C_{41}H_{82}NO_8P$ ) that contributes to particle formation and stability.
- *PEG-lipid (Polyethylene glycol-lipid)*: Prevents aggregation and prolongs circulation time. A common example is DMG-PEG2000 ( $C_{48}H_{96}O_{11}$ ), where PEG2000 represents a polyethylene glycol chain with an approximate molecular weight of 2000.

The mRNA, carrying the instructions for producing a specific viral protein (antigen), is encapsulated within this lipid shell. Upon entering the cell, the mRNA is released, prompting the cellular machinery to synthesize the antigen and trigger an immune response [31–35].

### Gold Nanoparticles (AuNPs)

Gold nanoparticles are highly versatile due to their biocompatibility, ease of surface modification, and unique optical properties.

- *Gold (Au)*: Noble metal forming the core of the nanoparticle.

Gold nanoparticles (AuNPs) can be coated with antigens or immune-boosting agents called adjuvants to help strengthen the body's immune reaction. They can also be used for targeted delivery, ensuring that the vaccine reaches specific immune cells. Their optical properties allow for tracking and monitoring of vaccine distribution within the body [36–41].

### Carbon Nanotubes (CNTs)

CNTs are being cylindrical molecules poised of rolled-up sheets of graphene.

- *Carbon (C)*: The elemental building block of CNTs, arranged in a hexagonal lattice.

CNTs might be single-walled (SWCNTs) or multi-walled (MWCNTs). They can be functionalized with antigens and adjuvants and offer impressive drug/vaccine delivery capabilities due to their higher surface areas and ability to penetrate cell membranes. However, toxicity concerns associated with CNTs are actively being addressed through careful surface modification and biocompatibility testing.

### Polymer Nanoparticles

These nanoparticles are constructed from biodegradable and biocompatible polymers, making them attractive for vaccine delivery.

- *PLGA (Poly (lactic-co-glycolic acid))*: A commonly employed biodegradable polymer represented by the repeating units of lactic acid ( $C_3H_4O_3$ ) and glycolic acid ( $C_2H_4O_3$ ) in varying ratios.

PLGA nanoparticles can trap antigens inside and release them slowly over time, helping to maintain a steady immune response. They can also be designed to target specific cells and are simple to produce.

### Quantum Dots (QDs)

QDs are semiconductor nanocrystals that exhibit size-dependent optical and electronic properties.

- *Examples*: Cadmium Selenide (CdSe), Zinc Sulfide (ZnS).

QDs can be used as fluorescent labels to track vaccine delivery and monitor immune responses in vivo. They can also be used for multiplexed detection, allowing for the simultaneous monitoring of

multiple immune parameters. However, the potential toxicity of heavy metal-containing QDs needs careful consideration and mitigation.

Nanomaterials hold immense promise for the future of vaccine development. They offer potential to

- *Enhance vaccine efficacy*: By improving antigen presentation and stimulating stronger immune responses.
- *Reduce vaccine dosage*: By targeting specific immune cells and prolonging antigen exposure.
- *Develop novel vaccines*: For diseases that are difficult to target with traditional approaches.
- *Improve vaccine stability*: By protecting antigens from degradation.
- *Enable needle-free vaccine delivery*: Through topical or mucosal administration.

While challenges remain in terms of scaling up production, ensuring long-term safety, and navigating regulatory hurdles, ongoing research and development are paving the way for the widespread adoption of nano-enabled vaccines. As our understanding of nanomaterial-immune system interactions deepens, we can expect to see even more innovative and effective vaccines emerging in the years to come, contributing to a healthier and more protected future for all [42–47].

## CONCLUSIONS

Vaccines have been essential to public health for many years, shielding us from numerous infectious diseases. However, conventional vaccines often come with challenges like stability problems, weaker immune responses, and the requirement for constant refrigeration. This is where nanotechnology steps in – a science that works with materials at an incredibly tiny scale, down to atoms and molecules. Thanks to their special features and adaptability, nanomaterials are quickly changing the way vaccines are developed, providing fresh solutions to overcome these persistent challenges. Nanomaterials are transforming vaccine development by bringing new ways to boost effectiveness, enhance stability, and improve how vaccines are delivered. As scientists continue to make progress and overcome obstacles, we can look forward to a new wave of vaccines made with nanomaterials that are safer, more powerful, and easier to access – helping protect health worldwide.

## REFERENCES

1. Chatterjee U, Ray S. Security issues on IoT communication and evolving solutions. In: *Soft Computing in Interdisciplinary Sciences*. Singapore: Springer Singapore; 2021. p. 183–204.
2. Zhao G, Wang X, Negnevitsky M. Connecting battery technologies for electric vehicles from battery materials to management. *iScience*. 2022 Feb 18;25(2).
3. Liyakat KS. Nanotechnology application in neural growth support system. *Nano Trends J Nanotechnol Its Appl*. 2022;24(2):47–55.
4. Wang Y, Li T, Yang H. Nanofabrication, effects and sensors based on micro-electro-mechanical systems technology. *Philos Trans A Math Phys Eng Sci*. 2013 Oct 13;371(2000):20120315.
5. Atlam HF, Walters RJ, Wills GB. Internet of nano things: Security issues and applications. In: *Proceedings of the 2nd International Conference on Cloud and Big Data Computing*; 2018 Aug 3. p. 71–7.
6. Liyakat KK. Nanorobotics in cancer treatment: A study. *Int J Nanomater Nanostruct*. 2025;11(1):1–9.
7. Liyakat KK. Nanotechnology in precision farming: The role of research. *Int J Nanomater Nanostruct*. 2023;9(2):22–8.
8. Liyakat KK. Nanotechnology in medical applications: A study. *Nano Trends J Nanotechnol Its Appl*. 2024;26(2):1.
9. Kumar N, Dixit A. Role of nanotechnology in futuristic warfare. In: *Nanotechnology for Defence Applications*. 2019. p. 301–29.
10. Kazi SS, Liyakat KK. Polymer applications in energy generation and storage: A forward path. *J Nanosci Nanoeng Appl*. 2024;14(2):31–9.
11. Liyakat KK. Review of biopolymers in agriculture application: An eco-friendly alternative. *Int J Compos Constit Mater*. 2024;10(1):50–62.

12. Raj SN, Lavanya SN, Sudisha J, Shetty HS. Applications of biopolymers in agriculture with special reference to role of plant-derived biopolymers in crop protection. In: *Biopolymers: Biomedical and Environmental Applications*. 2011 Aug 1. p. 461.
13. Sayyad LK. KSK approach to smart agriculture: Utilizing AI-driven Internet of Things (AI IoT). *J Microcontroller Eng Appl*. 2024;11(3):21–32.
14. Sayyad LK. Microwave communication in the Internet of Things: A study. *J RF Microwave Commun Technol*. 2024;38–49. Available from: <https://matjournals.net/engineering/index.php/JoRFMCT/article/view/1276>.
15. Patil JM. Robotic surgery using AI-driven-IoT based decision making for safety: A study. *Int J Artif Intell Things Commun Ind*. 2025;1(1):35–44.
16. Wale AD, Rokade D, et al. Smart agriculture system using IoT. *Int J Innov Res Technol*. 2019;5(10):493–7.
17. Mulani AO, Bang AV, Birajadar GB, Deshmukh AB, Jadhav HM. IoT based air, water, and soil monitoring system for pomegranate farming. *Ann Agri-Bio Res*. 2024;29(2):71–86.
18. Parihar B, Kiran A, Valaboju S, Rashid SZ, Liz DRA S. Enhancing data security in distributed systems using homomorphic encryption and secure computation techniques. *ITM Web Conf*. 2025;76:02010. doi:10.1051/itmconf/20257602010.
19. Veena C, Sridevi M, Liyakat KKS, Saha B, Reddy SR, Shirisha N. HEECCNB: An efficient IoT-cloud architecture for secure patient data transmission and accurate disease prediction in healthcare systems. In: *2023 Seventh International Conference on Image Information Processing (ICIIP); 2023; Solan, India*. p. 407–10. doi:10.1109/ICIIP61524.2023.10537627.
20. Tamboli DA, Sawant VA, MHM, Sathe S. AI-driven-IoT (AIIoT) based decision-making—KSK approach in drones for climate change study. In: *2024 4th International Conference on Ubiquitous Computing and Intelligent Information Systems (ICUIS); 2024; Gobichettipalayam, India*. p. 1735–44. doi:10.1109/ICUIS64676.2024.10866450.
21. Rajendra Prasad K, Karanam SR, et al. AI in public-private partnership for IT infrastructure development. *J High Technol Manag Res*. 2024;35(1):100496. <https://doi.org/10.1016/j.hitech.2024.100496>.
22. Kasat K, Shaikh N, Rayabharapu VK, Nayak M. Implementation and recognition of waste management system with mobility solution in smart cities using Internet of Things. In: *2023 Second International Conference on Augmented Intelligence and Sustainable Systems (ICAISS); 2023; Trichy, India*. p. 1661–5. doi:10.1109/ICAISS58487.2023.10250690.
23. Kazi K. Modelling and simulation of electric vehicle for performance analysis: BEV and HEV electrical vehicle implementation using Simulink for e-mobility ecosystems. In: L D, Nagpal N, Kassarwani N, Varthanan GV, Siano P, editors. *E-Mobility in Electrical Energy Systems for Sustainability*. IGI Global; 2024. p. 295–320. doi:10.4018/979-8-3693-2611-4.ch014.
24. Kazi K. Machine learning-powered IoT (MLIoT) for retail apparel industry. In: Tarnanidis T, Papachristou E, Karypidis M, Manda V, editors. *Sustainable Practices in the Fashion and Retail Industry*. IGI Global Scientific Publishing; 2025. p. 345–72. doi:10.4018/979-8-3693-9959-0.ch015.
25. Kazi S. IoT driven by machine learning (MLIoT) for the retail apparel sector. In: Tarnanidis T, Papachristou E, Karypidis M, Ismyrlis V, editors. *Driving Green Marketing in Fashion and Retail*. IGI Global; 2024. p. 63–81. doi:10.4018/979-8-3693-3049-4.ch004.
26. Kazi S. Transformation of agriculture effectuated by artificial intelligence-driven Internet of Things (AIIoT). In: Garwi J, Dzingirai M, Masengu R, editors. *Integrating Agriculture, Green Marketing Strategies, and Artificial Intelligence*. IGI Global Scientific Publishing; 2025. p. 449–84. doi:10.4018/979-8-3693-6468-0.ch015.
27. Keerthana R, K V, Bhagyalakshmi K, Papinaidu M, V V, Liyakat KKS. Machine learning based risk assessment for financial management in big data IoT credit. *SSRN Electron J*. 2025. doi:10.2139/ssrn.5086671.
28. Liyakat KKS. IoT technologies for the intelligent dairy industry: a new challenge. In: Thandekkattu S, Vajjhala N, editors. *Designing Sustainable Internet of Things Solutions for Smart Industries*. IGI Global; 2025. p. 321–50. doi:10.4018/979-8-3693-5498-8.ch012.

29. Liyakat KKS. Heart health monitoring using IoT and machine learning methods. In: Shaik A, editor. *AI-Powered Advances in Pharmacology*. IGI Global; 2025. p. 257–82. doi:10.4018/979-8-3693-3212-2.ch010.
30. Liyakat KKS. AI-driven-IoT (AIIoT)-based decision making in kidney diseases patient healthcare monitoring: KSK approach for kidney monitoring. In: Polat LÖ, Polat O, editors. *AI-Driven Innovation in Healthcare Data Analytics*. IGI Global Scientific Publishing; 2025. p. 277–306. doi:10.4018/979-8-3693-7277-7.ch009.
31. Kazi KS, Mahant MA. Machine learning-driven Internet of Things (MLIoT)-based healthcare monitoring system. In: *Digitalization and the Transformation of the Healthcare Sector*. IGI Global Scientific Publishing; 2025. p. 205–36.
32. Mulani AO, Liyakat KK, Warade NS, Patil A, Kolte MT, Kinage K, et al. ML-powered Internet of Medical Things structure for heart disease prediction. *J Pharmacol Pharmacother*. 2025;0976500X241306184.
33. Odnala S, Shanthy R, Bharathi B, Pandey C, Rachapalli A, Liyakat KK. Artificial intelligence and cloud-enabled e-vehicle design with wireless sensor integration. *SSRN Electron J*. 2024 Nov 15. Available from: <https://ssrn.com/abstract=5107242>.
34. Neeraja P, Kumar RG, Kumar MS, Liyakat KK, Vani MS. DL-based somnolence detection for improved driver safety and alertness monitoring. In: *2024 IEEE International Conference on Computing, Power and Communication Technologies (IC2PCT)*; 2024 Feb 9; Vol. 5. p. 589–94.
35. Sayyad Liyakat KK, Magadum PK. Machine learning for predicting wind turbine output power in wind energy conversion systems. *Grenze Int J Eng Technol (GIJET)*. 2024 Jan 22;10.
36. Nerkar PM, Dhaware BU, Liyakat KS. Predictive data analytics framework based on heart healthcare system (HHS) using machine learning. *J Adv Zool*. 2023;44(2).
37. Kutubuddin KA, Nerkar PR, Sultanabonu KA. IoT-based skin health monitoring system. *Int J Biol Pharm Allied Sci*. 2024;13(11):5937–50.
38. Liyakat KK, Khadake SB, Chounde AB, Suryagan AA, HM M, Khadatare MR. AI-driven-IoT (AIIoT) based decision making system for high-blood pressure patient healthcare monitoring. In: *2024 International Conference on Sustainable Communication Networks and Application (ICSCNA)*; 2024 Dec 11. p. 96–102.
39. Liyakat KK, Khadake SB, Chounde AB, Suryagan AA, HM M, Khadatare MR. AI-driven-IoT (AIIoT) based decision making system for high-blood pressure patient healthcare monitoring. In: *2024 International Conference on Sustainable Communication Networks and Application (ICSCNA)*; 2024 Dec 11. p. 96–102.
40. Kazi KS. AI-powered IoT (AI IoT) for decision-making in smart agriculture: KSK approach for smart agriculture. In: *Enhancing Automated Decision-Making Through AI*. IGI Global Scientific Publishing; 2025. p. 67–96.
41. Kazi KS. KK approach to increase resilience in Internet of Things: A T-cell security concept. In: *Analyzing Privacy and Security Difficulties in Social Media: New Challenges and Solutions*. IGI Global Scientific Publishing; 2025. p. 87–120.
42. Kazi KS. KK approach for IoT security: T-cell concept. In: *Deep Learning Innovations for Securing Critical Infrastructures*. IGI Global Scientific Publishing; 2025. p. 367–88.
43. Kazi KS. Healthcare monitoring system driven by machine learning and Internet of Medical Things (MLIoMT). In: *Convergence of Internet of Medical Things (IoMT) and Generative AI*. IGI Global Scientific Publishing; 2025. p. 385–416.
44. Kazi KS, Shinde SS, Nerkar PM, Kazi SS, Kazi VS. Machine learning for brand protection: A review of a proactive defense mechanism. In: *Avoiding Ad Fraud and Supporting Brand Safety: Programmatic Advertising Solutions*. 2025. p. 175–220.
45. Kumari A, Sharma I. Mitigating malvertising threats: An exploration of machine learning classification algorithms for effective detection. In: *2024 International Conference on Advancements in Smart, Secure and Intelligent Computing (ASSIC)*; 2024 Jan 27. p. 1–6.
46. Kosgiker GM. Satellite sensing for sea level monitoring: A transformative approach to understanding climate change. *J Microwave Eng Technol*. 2025;12(1):33–41.

47. Liyakat KK. Transforming IoT connectivity through VLSI technology. *Int J VLSI Circ Des Technol.* 2024;2(2):1.