Nanoparticles in Genetic Engineering: A New Era of Precision Editing

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Abstract

Nanoparticles are changing genetic engineering by acting as well-defined, effective and safe methods for bringing advanced gene-editing technologies such as CRISPR-Cas9 into cells. Their adjustable physicochemical qualities, these particles can boost how medications are delivered, prevent them from affecting the wrong cells and prevent a strong immune response. Such features suggest that nanoparticles can be a reliable method for targeting genes, useful in treating inherited disease as well as making genetically altered food materials. Focus has also been placed on innovative ways to deliver drugs and on making use of nanoparticles in unusual biological communities such as those of extremophiles, plants and people with rare diseases. The use of nanoparticles improves the potential benefits of gene editing in many new fields of science. Also, ethical questions and clear rules are taking on greater relevance to support responsible use of this technology. Because research advances, this technology should completely reshape medicine, sustain agriculture and biotechnology by giving extremely precise, safe and flexible solutions for genome engineering. The use of nanoparticles in gene editing will soon open the way for precise and organized genetic alterations.

Keywords: Nanoparticles, Gene Editing, CRISPR-Cas9 Delivery, Genetic Engineering, Agriculture, Biotechnology, Genome Engineering

Cite this Article as: Ali A, Alam S, Ehsan M, Ahmad M, Qureshi R, Talib M, Maheen A. Altaf M, Khan MS and Hussain R, 2025. Nanoparticles in genetic engineering: a new era of precision editing. In: Nisa ZU, Altaf S, Zahra A and Saeed K (eds), Nanobiotech in Holistic Health: Innovations for Integrated Well-being. Unique Scientific Publishers, Faisalabad, Pakistan, pp: 72-77. https://doi.org/10.47278/book.HH/2025.417

A Publication of Unique Scientific Publishers

Chapter No: 25-011

Received: 13-Feb-2025
Revised: 15-Apr-2025
Accepted: 13-May-2025

Introduction

Enabled by nanoparticles, genetic engineering can work better, faster and more safely than before. Due to their tiny size, from 1 to 100 nanometers, these materials show properties that make them different from larger-scale samples (Chehelgerdi et al., 2023). Their capacity to interact at the molecular level, together with their adjustable shape and thin size, means nanoparticles are especially suited for biomedical uses such as delivering gene-editing agents. By adding these materials to the latest gene-editing techniques, scientists have introduced better precision into genetic engineering with major effects on medicine, agriculture and biotechnology (Rahimi et al., 2020). Performed with nanoparticles, placing DNA, RNA or CRISPR-Cas9 gene-editing tools into target cells is specific and very little is lost (Sharma et al., 2024). Often, viral vectors, as a classical way to deliver genome-editing, run into problems such as immune reactions, not enough room for the release and integrating randomly around the genome which can result in unexpected effects and health threats (Aljabali et al., 2024). Alternatively, nanoparticles offer an efficient way to protect against these problems, as they offer superior guidance for delivering drugs. Using ligands, antibodies or peptides on the surface of nanoparticles improves their ability to reach target tissues, protecting cells near the treatment area. For instance, lipid nanoparticles are commonly used to deliver mRNA and are found to be highly successful in reaching liver cells which supports new methods in treating specific diseases (Tao et al., 2019). Precise control over nanoparticle characteristics improves the ways they are used in genetic engineering. Nanoparticles produced in the lab can react to changes in pH, temperature or enzymes, permitting the release of genetic material at the proper target site (Janjua et al., 2023). Specifically, this feature is important in in vivo applications since it greatly lowers chances of harmful impacts outside the target area and in other parts of the body. Selective release of CRISPR-Cas9 allows polymeric nanoparticles to target just the cancer cells in tumors, thus harming fewer healthy tissues. These small inventions prove that nanoparticles may help make gene-editing safer and more precise (Goldberg et al., 2007).

Precision is necessary in genetic engineering, because tiny mistakes might produce unwanted changes and unpleasant results. By adding nanoparticles to gene-editing, gene treatment can be done more efficiently and safely. To make new medicines with CRISPR-Cas9, guide RNA and Cas9 proteins must be added with precision to specific cells (Li et al., 2023). When nanoparticles are used, damage to the elements is

avoided and their transfer inside the cell makes genome editing more effective. Gold nanoparticles are commonly used to ensure that the CRISPR-Cas9 cargoes reach the right sites and are not likely to have side effects (Lei et. al., 2024).

It is also valuable in these fields to treat people who have various conditions. Using nanoparticles to deliver genome-editing tools in plants alters their genes to produce bigger harvests, increase illness resistance and improve their reactions to their environment. Using silica nanoparticles, the CRISPR-Cas9 system has been applied to plant cells, resulting in precise gene changes required for increased crop productivity. This technology helps sustainable agriculture and provides a valuable solution to worldwide hunger (Hamdana & Tana, 2024).

New biological systems for synthetic biology can be accurately created with the help of nanoparticles. Because nanoparticles accurately end up DNA elements, they are needed to create bio factories that make biofuels, pharmaceuticals and industrial enzymes. Ensuring synthetic biological processes are both reliable and can be repeated many times helps to make them useful in various areas (Burgos-Morales et al., 2021).

Nanoparticles could be useful in genetic engineering, but they also lead to certain problems. Researchers are putting great effort into discovering the possible risks of nanoparticles, as we do not know how they may harm humans and the environment in the future (Xuan et al., 2023). Scaling up nanoparticle-based delivery is often expensive and challenging, mainly in places that are short of resources. Solving these difficulties will be possible if people from diverse areas team up and make tough regulations for using nanotechnology in genetic engineering, as suggested by PJ et al. (2021).

2. Nanoparticles as Delivery Vehicles for Gene Editing Tools

These new technologies in gene editing have radically changed molecular biology by supplying precise ways to alter an organism's genome. How well these tools function mainly depends on safe and efficient systems. Nanoparticles, rather than viral vectors, now present a better way to deal with challenges in gene-editing methods. Such surfaces, adjustability and overall compatibility mean that using these particles with CRISPR-Cas9 and similar tools is safer (Liu et al., 2021).

3. Role of Nanoparticles in Delivering CRISPR-Cas9 and Other Gene-Editing Tools

Nanoparticles are made by humans to aid in transporting biomaterials into living cells. They have been adjusted to perform the task of inserting essential elements from CRISPR-Cas9, guide RNA (gRNA) and Cas9 protein, into the chosen cells. Genome editing requires these molecules to be sent accurately to the nucleus, so they do not become inactive or break down (Smith et al., 2020). Nanoparticles allow delicate proteins to be protected from unwanted activity by enzymes and recognition by the immune system (Hejabi et al., 2022). RNPs of CRISPR-Cas9 are delivered by nanoparticles, offering an important advantage. Because plasmid-based delivery needs the cell to produce messenger RNA, it may be time-consuming, while RNP delivery does not, so editing the genome works quickly and precisely. To introduce the CRISPR-Cas9 RNPs into some mammalian cells, they are frequently coated in lipid nanoparticles. Once the nanoparticles link to cell walls, their content is moved into the cytoplasm inside the cell, making editing possible (Givens et al., 2018). Figure 3 shows the schematic illustration of the use of smart nanoparticles (NPs) with stimulus-responsive properties for the efficient delivery of CRISPR/Cas9 systems. These nanoparticles are designed to respond to specific stimuli, such as pH changes, temperature variations, redox conditions, or enzyme activity, enabling controlled release of the CRISPR/Cas9 components at the target site. Upon encountering the appropriate stimulus within the cellular microenvironment, the nanoparticles undergo structural or compositional transformations, releasing the Cas9 protein and guiding RNA complex into the cytoplasm. The complex then translocates to the nucleus to facilitate precise gene editing with minimal off-target effects. This approach improves the stability, specificity, and therapeutic efficacy of CRISPR/Cas9 in gene editing applications.

CRISPR-Cas9 can be successfully delivered using AuNPs. DNA- or RNA-labeled AuNPs improve the access of CRISPR components to the nuclear region of cells. Gene editing experiments have found that AuNP systems are highly effective in both test tubes and in the body, so they are a perfect option for using this technology. In addition, nanoparticles made with poly (lactic-co-glycolic acid) (PLGA) are applied to deliver Cas9 mRNA and gRNA, increasing the time of treatment and yielding better effects (Ferreira et al. 2020). Delivering genes using magnetic nanoparticles is now an option. The introduction of magnetic fields to the system gives these particles greater accuracy as they are delivered. Once inside the cell, the nanoparticles transfer their cargo, making genome editing much simpler. It concludes that selective antibodies can be used for cancer treatment as well as for other types of diseases (Rarokar et al., 2024).

4. Advantages over Traditional Delivery Methods (e.g., Viral Vectors)

Viral vectors are efficient and make it easy to introduce genetic data into a cell; they do well for gene editing. Yet, these approaches present a few big issues: immunogenicity, few cells they can carry and the risk of accidental genomic insertion. As they are non-viral, nanoparticles help meet all these requirements and offer strong efficiency, high flexibility and safety too (El Karoui et al., 2019).

1. Reduced Immunogenicity and Toxicity

Viral vectors, for example, adenoviruses and lentiviruses, frequently cause a negative immune reaction and can even be dangerous when being used for treatments. On the other hand, nanoparticle-based drugs are made to be friendly to cells and immune systems, making many adverse side effects much less likely. In fact, lipid nanoparticles were tested in human clinical trials and worked effectively and safely for delivering RNA-based drugs (Shirley et al., 2020).

2. Higher Payload Capacity

The restriction on large gene-editing components with viral vectors is caused by their small capsid size. By comparison, multiple payloads can be fitted into nanoparticles, for example RNP complexes, mRNA and other functional molecules. As a result, editing tools and the needed donor DNA can be co-delivered using this approach (Asmamaw Mengstie, 2022).

3. Targeted Delivery and Cellular Uptake

Targeting abilities with nanoparticles are better than those possible with viral vectors. Tissue-targeting precision can be achieved by modifying the surface of NPs with molecules that recognize the target cell receptors. As an example, nanoparticles with folate receptors can accurately deliver CRISPR-Cas9 to cancerous cells, reducing the errors and boosting its usefulness (Figueroa et al., 2021).

4. Avoidance of Genomic Integration

There is a big risk with viral vectors because they might drop their DNA at a random place in the genome, raising the chances of causing insertional mutagenesis and oncogenesis (Jones et al., 2019). With nanoparticles, the CRISPR-Cas9 materials are removed from the cell as soon as their task is done, minimizing the chance of unintended changes. As a result of this short expression, off-target effects and future problems become less likely (Butt et al., 2022).

5. Scalability and Versatility

The creation of viral vectors is both complicated, lengthy and costly, so they are not easily scaled up leading to limited use (Y. Zhang et al., 2024). In fact, nanoparticles are typically produced using easy chemical and physical approaches which means they are both less expensive and easier to use for clinical or industrial purposes. These nanoparticles are also adjustable depending on the desired route, including into veins, into muscles and on the skin (Gutiérrez-Granados et al., 2018).

6. Environmental and Regulatory Considerations

Nanoparticles are accepted as safer for the environment and regulators, because they are unable to replicate and are synthetic in nature. Viral vectors, unlike lentivirus vectors, must go through tough regulatory tests because they raise concerns about safety and their environment effects. Due to their synthetic construction, nanoparticles can be approved efficiently and added to therapeutic pipelines (Wang et al., 2022). Applying nanoparticles to deliver CRISPR-Cas9 and similar editing tools has already seen helpful results in therapeutics, agriculture and synthetic biology. Using nanoparticles as carriers, researchers are trying gene therapies for genetic diseases, including Duchenne muscular dystrophy and sickle cell anemia, where correcting the genome can bring back the missing or mutated genes. Scientists use nanoparticles in the agricultural industry to help crops gain better qualities such as being resistant to drought and nutritious (Li et al., 2023).

Integrating nanoparticles with the latest technologies, for example, artificial intelligence and machine learning will likely produce important results going forward. These algorithms can help improve nanoparticles by foreseeing their effects on the body which makes them safer and easier to use. Improves in nanorobotics may open the way for smart nanoparticles to find their own routes in difficult biological locations, possibly expanding where they can be used. Although they are helpful, many are still hesitant about using nanoparticle-based delivery systems because of safety, how well they work on a large scale and their cost. To handle these problems, we will need help from experts in various fields and will need to keep funding research and development. Conquering these obstacles could allow nanoparticles to influence gene editing by improving its accessibility, accuracy and overall safety in many uses (Nandipati et al., 2024).

5. Applications in Therapeutics and Agriculture

Nanoparticle-assisted genetic editing is making an important difference in medicine and agriculture because it provides improved precision and efficiency. Researchers are using the various properties of nanoparticles to advance how genetic disorders are treated and how robust crops are grown. These advancements are set to improve medicine and agriculture, solving tough problems and allowing for new ways to support the environment and improve human health (Wu et al., 2023).

6. Treating Genetic Disorders Using Nanoparticle-Facilitated Editing

Much progress has been made in treating genetic disorders using gene editing by adding nanoparticles to deliver the CRISPR-Cas9 tool. Genetic disorders usually result from changes in genes that interrupt their functions. Because nanoparticles are precise and able to protect payloads, they can take delivery components to the proper cells in different tissues and help with correcting these mutations (Kolanu, 2024). When compared to viruses, nanoparticles give us a safe way to transfer DNA that avoids the issues of responses by the immune system and genetic changes in cells. LNPs such as lipid nanoparticles, are now considered the top way to deliver CRISPR-Cas9 materials. By allowing RNP complexes to be carried in their structure, AAVs can support the delivery and function of the editing tools needed for in vivo editing (Taghdiri & Mussolino, 2024). LNPs are used in experiments with animals to treat alterations that cause Duchenne muscular dystrophy, allowing affected proteins to work and strengthen muscles (Ibba et al., 2021).

Gold nanoparticles (AuNPs) represent another successful technology in therapeutic gene editing. When DNA or RNA is bound to them, nanoparticles can remove genetic errors precisely at a certain location. AuNPs have been found to help treat monogenic diseases like sickle cell anemia by delivering important gene editing materials to hematopoietic stem cells (Mitchell et al., 2020). Because of this method, therapies are less likely to harm the wrong cells or cause immune problems (Kanu et al., 2022). Now, using nanoparticles, it is also possible to edit genes in hard-to-access tissues. Medicines can rarely cross into the brain from the blood, so treatment for Huntington's and Alzheimer's diseases is challenging. When engineering nanoparticles, researchers are able to transfer gene-editing equipment directly into neurons in the brain. The availability of this technique creates space for addressing conditions we currently lack treatments for (Ereej et al., 2024). Besides studying monogenic diseases, nanoparticles are currently used to look into polygenic diseases and cancer. The use of nanoparticles can help change the genes that control tumor development and drug responsiveness in oncology. With this strategy, scientists have been able to take CRISPR-Cas9 into cancer cells to try to control how cancer spreads (Shchaslyvyi et al., 2023).

7. Enhancing Crop Traits and Resilience through Targeted Genetic Modifications

Nanoparticles improve how genetic editing is done in agriculture, providing options for better crops and meeting problems regarding food and climate. Frequently, genetic and breeding methods are slow and can run into problems with regulations. People agree that nanoparticle delivery is an effective and accurate method for changing genes in plants (Ahmar et al., 2021). Delivering the CRISPR-Cas9 system to plant cells using nanoparticles has become much simpler than with older ways. To illustrate, scientists are using silica nanoparticles to help maize and wheat cell. Relying on this strategy means researchers avoid using Agrobacterium or biolistic delivery and this makes the whole process simpler and less risky (Babaeianjelodar et al., 2025).

Nanoparticles improve a plant's resistance to both living and non-living pressures. Researchers have successfully placed CRISPR-Cas9 into rice using nanoparticles which protected the rice from bacterial blight. Scientists have now updated soybean genes using nanoparticles, so they can resist drought and boost water usage and crop yields in hard conditions (Naik et al., 2022). Precision in farm work is improved by letting growers fine-tune the traits of crops with nanoparticles. If genes controlling when fruits ripen or their nutrients are changed, crops can be produced with a larger shelf life and healthier nutrients. By using nanoparticles to modify ripening genes, tomato growers now enjoy more time to store their produce before it spoils and less waste (Jiang et al., 2021). As well as altering individual crop features, nanoparticles make it possible to change several genes at once. The ability to explain these traits by considering pathways is especially important since they use several genes. In one study, using silica nanoparticles in a multiplexed system increased how wheat utilized nitrogen and cut back on the need for synthetic fertilizers (Ahmad, 2023).

Gene editing presents special problems for plant scientists and nanoparticles offer ways to deliver editing tools into difficult-to-edit plant species. Optimized size, charge and number of surface proteins on nanoparticles have allowed researchers to penetrate plant cell membranes and reach the nucleus with DNA editing tools. By making gene editing possible in more crops such innovations help enable these technologies to support different agriculture sectors (Demirer et al., 2021).

7. Ethical and Regulatory Considerations in Nanoparticle-Enabled Genetic Engineering

Adding nanoparticles to genetic engineering has triggered major developments in medicine, agriculture and biotechnology. Using these tiny vehicles helps to improve delivery of CRISPR-Cas9, increasing accuracy, minimizing effects on unintended cells and reducing immune responses. Even though nanoparticles hold great promise for genetic technologies, several challenging ethical and regulatory issues should be taken care of to make sure these technologies are safe, fair and acceptable for society (Iavicoli et al., 2017).

A main issue is ensuring that nanoparticles used in genetic applications do not pose biosafety and risk problems. People often view nanoparticles as safer than viral vectors, but there are concerns that they could gather in organs and interact strangely with living tissue. It's especially worrying that germline editing can cause genetic changes to be passed on to future generations. These uses are separated by ethics because enriching human traits may bring about social inequality and possible discrimination (Hayenhjelm & Nordlund, 2025).

There is also a concern about how nanoparticles affect the environment in genetically modified agriculture. Gene flow from genetically changed crops to wild plants may cause invasive weeds or upset existing natural plant communities. The main goal of regulatory frameworks should be to do environmental risk assessments and implement measures to stop accidents where they are needed. Usually, just to be sure, the precautionary principle is brought up; requiring regulatory bodies to hold off on approval until the possible consequences are better understood (Labrighli et al., 2025).

Trust from the public and getting permission should both be prioritized. Before joining tests, patients must be fully aware of the risks, whether they are identified or not, linked with gene editing. Although they show improved accuracy, nanoparticles remain concerned about their spread throughout the body, their ability to break down and what impact they might have in the long run. The process of getting informed consent should always change when new information is discovered and the situation evolves (Delhove et al., 2020). Similarly, these technologies are approved by society when public views are positively influenced by cultural and ethical beliefs. According to studies, most concerns among the public about nanotechnology and genetic engineering revolve around "playing God," unusual interventions and the chance of wrongful uses (Benjamin & Familusi, 2020).

Work is being done to resolve these issues. Both the World Health Organization (WHO) and the Organization for Economic Co-operation and Development (OECD) see that a global framework is needed to manage nanotechnology. Any frameworks used should cover safety standards, correct labeling, designs for long-term monitoring and observing what happens after the products reach the market. Furthermore, making sure ethical advisory boards and stakeholders are part of policy creation helps a committee to be properly accountable and recognized (Khatoon & Velidandi, 2025).

9. Advancing Non-Invasive Gene Editing Techniques

The field of genetic editing aims to create methods that minimize problems, help patients recover better and make treatments more accessible. Injections and surgeries, traditional delivery methods, sometimes cause infection, inflammation and pain to the patient. Using modern technology and safe ways, scientists now try to fix these issues without affecting the patient too much (Huang et al., 2022). Non-invasive gene editing is advanced largely through the use of nanotechnology. Nanoparticles meant for inhalation, ingestion or applied directly to the skin may replace unpleasant invasive options. Researchers are investigating the use of lipid nanoparticles (LNPs) for the pulmonary delivery of CRISPR-Cas9 goods which avoids the need for injections in lung tissue. Therapies designed this way could be promising for cystic fibrosis and pulmonary arterial hypertension, as they do not cause much discomfort to those being treated (Lei et al., 2024).

Using nanoparticles made from hydrogels is an additional way to achieve non-invasive gene editing. Such materials may be put on top of the skin or into mucous membranes to control the local delivery of gene-editing agents. Because of these systems, doctors can deliver corrective gene therapies straight to areas affected by genetic skin disorders such as epidermolysis bullosa. Continued progress in hydrogel development is believed to improve how effective they are and increase their usefulness (Su et al., 2024). These nanoparticles provide new non-invasive possibilities for gene editing. Both magnetic and ultrasound-responsive nanoparticles can target tissues by guiding themselves

with external technologies and only releasing their content at the desired sites. It demonstrates that physics methods can join forces with molecular biology to produce innovative non-invasive ways (Qian et al., 2020).

Many forms of extracellular vehicles (EVs) are now being employed as safe and effective carriers for gene-editing reagents. Because EVs are not recognized by our bodies, they can clear the blood-brain barrier. Using CRISPR-Cas9 components, we are able to introduce gene-editing medicines to specific tissues by means of engineered EVs which target the brain and the central nervous system. Alzheimer's disease and Huntington's disease may respond well to treatment since scientist struggle to find suitable treatments for these conditions (Payandeh et al., 2024).

Conclusion

Genetic engineering now benefits from safer, more powerful and precisely focused tools made possible by adding nanoparticles. They give cell-friendly alternatives to viral carriers for carrying CRISPR-Cas9, so off-target events and cell toxicity are markedly reduced. Because nanoparticles can be modified in size, charge and function, they find use in areas such as treating genetic diseases, increasing crop resistance to diseases and learning about complex biological systems. What's more, new types of intelligent nanoparticles and improved non-invasive methods are helping researchers use gene editing in places that were previously not possible. Although there is a lot of hope, important obstacles stand in the way, including biosafety, immunogenicity, controversies over ethics and well-defined regulations. Yet, new developments in nanoparticle delivery are ready to transform genetic engineering through increased precision, safety and accuracy. As technology develops, it could bring new changes to personalized medicine, eco-friendly farming and make biotechnological innovation more successful, allowing for sweeping genetic interventions worldwide.

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