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Review Article

Integrating Genome Editing and Nanotechnology to Enhance Plant Resistance to Environmental Stresses: A Review

[a]Ahmad Kamis, [b]Baraa Hameed Saleh, [c]Rafat Hamdi Abduljaleel, [a]Khader Saker Alzawi, [c]Basheer Muhsin Ali

[a] *Department of Biology, College of Sciences, University of Anbar, Ramadi, Iraq.*
[b] *Department of Biology, College of Education for Women, University of Anbar, Ramadi, Iraq.*
[c] *Department of Biotechnology, College of Sciences, University of Anbar, Ramadi, Iraq.*

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ABSTRACT

Abiotic stressors, such as salinity, drought, and heat are becoming more severe due to climate change and are impacting agricultural productivity, especially in arid and semi-arid areas. The combination of molecular genome editing and nanotechnology holds great potential for creating climate-resilient crops by targeted genetic modification and effective delivery of genetic editing components. This review critically summarizes the recent developments in genome-editing tools such as CRISPR-Cas9, base editing and prime editing, and how they are combined with nano-enabled delivery systems for enhancing plant tolerance to abiotic stresses. Molecular targets related to abscisic acid signaling, ion homeostasis, detoxification of reactive oxygen species, and osmotic adjustments are emphasized. It also tests lipid nanoparticles, mesoporous silica nanoparticles, chitosan nanoparticles, and carbon-based nanomaterials for the delivery of genome-editing elements, besides nanosensors to monitor plant physiological changes. Selected studies specify promising developments in editing efficacy and stress tolerance; nonetheless, the stated findings should not considered as pooled meta-analytic estimates and differ considerably with plant species, delivery methods, and experimental conditions. Some of the key challenges are inefficient cellular delivery, off-target effects, toxicity of nanoparticles, high implementation costs, environmental persistence, and low multi-location field authentication. Optimized DNA-free editing systems, standardized evaluation procedures and protocols, integration of multi-omics, context-specific regulatory framework, and long-term ecotoxicological assessment should be emphasized in future research. If efficacy, environmental safety and economic feasibility can be carefully tested in the field, the combination of precision genome editing and sustainable nanotechnology could have the potential to improve the climate resilience of crops.

Corresponding Author: Ahmad Kamis
Email: yyazen780@uoanbar.edu.iq

Introduction

Abiotic stresses caused by climate change are enhancing the physiological characteristics of plants and have a fundamental effect on cellular homeostasis, leading to the plant survival in various habitats (Ghosh et al., 2026). In dry areas, such as in Iraq and Middle East, such stresses cause desertification and degradation of the ecology, which lower biodiversity and ecological stability of plants (IPCC, 2022). The solution to these challenges must incorporate new means of addressing

them, combining novel approaches to molecular knowledge and new delivery technologies. Genome editing tools have transformed the field of plant molecular biology by allowing the narrow-focused changes in gene networks controlling stress responses (Doudna and Charpentier, 2014). CRISPR-based technologies, base editors and prime editors offer novel opportunities to control transcription factors, ion channels, antioxidant systems and signaling cascades without introducing a foreign piece of DNA (Farooq et al., 2026). The usability of such tools in plant systems is, however, limited by the biological barriers, the wall of the plant cell, and the complexity of the plant tissue in question especially restricts effective delivery of the components of editing (Cunningham et al., 2018).

Nanotechnology can be used to revolutionize by offering nanoscale platforms that can traverse the plant cell architecture, delivery of biological cargo, and targeted intervention (Demirer, et al., 2019). Ribonucleoprotein complexes, guide RNAs, or chemical effectors can be transferred directly to plant cells using nanocarriers functionalized with cell-penetrating peptides, stimuli-responsive coats or tissue-specific ligands (Zhang et al., 2019). In addition to delivery, nanomaterials *per se* can tune plant physiology by scavenging reactive oxygen species (ROS), improving membrane stability, or controlling gene expression by an act of epigenetic modification (Arivalagan and Das, 2026).

However, molecular editing in combination with nanotechnology will give a paradigm shift in plant biology, enabling the researchers not only to comprehend but also to reprogram plant responses at cellular and molecular levels in stress conditions (Mahmoud and Dutt, 2024).

This review analyses this convergence in terms of plant biology with regard to basic processes, cellular behaviors and system-scale behaviors.

Moreover, plant extracts offer bio-compatible and environmentally-friendly nanoparticles, which reduce toxicity and increase the applicability of the field (Shashidhara et al., 2025; Said et al., 2026). However, questions are still raised on the fate of nanoparticles, bioaccumulation, and unintended ecology impact, which requires cautious consideration of the safety and regulation systems [OECD, 2023].

Combining molecular editing with nanotechnology is increasingly viewed as the future of plant biotechnology. Stress tolerance solutions based on molecular editing are genetic while nanotechnology solutions are easy to deliver and are translated in the field. This combination may lead to the development of resilient cultivars that could be adapted to climate change and make better use of resources and reduce the use of chemicals (Nath, 2026). This review also incorporates theoretical frameworks and illustrative figures towards synthesizing integrated mechanisms, challenges that are region-specific, and lines of applied pipelines. These kinds of visual resources are meant to provide a simple and accessible means of guidance for researchers and practitioners that operate in this interdisciplinary field.

Materials and Methods

The review was carried out by a thorough survey of recent scientific articles covering the genome editing technologies and role of nanotechnology in improving tolerance to abiotic stress in plants. Relevant publications were identified using major scientific databases such as Google Scholar, PubMed, ScienceDirect, Scopus, and Web of Science. Articles published in peer-reviewed journals from 2020 to 2025 were preferred, and in particular those that highlighted the use of genome editing and nanotechnology for real applications in agricultural systems. Other research work was also taken into account that concentrated on biosafety, regulatory issues and regional applications in arid and semi-arid regions.

Critical gap and review objectives

Although some reviews have examined genome editing or nanotechnology in agriculture on a case-by-case basis, scarcely any have engaged in the systematic analysis of their synergistic combination, especially regarding the frames of arid and semi-arid regions experiencing serious water scarcity and soil erosion (Cutler et al., 2010). The proposed review is expected to address this gap through: (1) critical comparative analysis of the genome editing platforms (CRISPR-Cas9, base editing, prime editing) in abiotic stress tolerance; (2) evaluation of the delivery systems based on nanoparticles to DNA-free editing in the plant cell wall obstacles; (3) offering a mechanistic framework enabling the combination of genetic targets with nano-enabled delivery and sensing; and (4) a region-specific roadmap considering the technological potential and socio-regulatory limitations of Iraq and the MENA region. Among the gaps in the knowledge that our analysis reveals are the long-term ecological future of nanocarriers in saline soils and economic feasibility of these combined technologies to the smallholder farmer.

Platforms and mechanisms: critical comparison

The CRISPR/Cas9 technology has been incredibly effective because of its simplicity and ability to be used in a wide range of crops to improve their resistance to abiotic and biotic stressor. Base editors are used to make certain point mutations but do not create any DNA double-strand break, and prime editing allows making search and replace changes to more complex traits. Moreover, the editing of cis-regulatory elements (CREs) has also become important to regulate expression of stress-responsive genes in a time and space-controlled way without substantially affecting growth (Yadav, et al. 2023).

These platforms have unique trade-offs which can be critically compared. CRISPR-Cas9 knockouts are very useful in loss-of-function characteristics (e.g. stomatal density regulators) (Wang et al., 2022). Base editors (e.g. cytidine or adenosine deaminase fusions) allow an accurate conversion of C-to-T or A-to-G without creating a double-strand break, thus making them applicable to fine-tuning stress-related single nucleotide polymorphisms (SNPs), such as in rice OsHKT1;5 variants of salinity tolerance (Tian et al., 2025). Their editing window is however limited (~5 nucleotides) and they are capable of causing bystander edits. Although prime editors are more efficient with small deletions/insertions, they are less efficient in plants, particularly in polyploid crops, such as wheat (Yadav et al. 2023). In the case of polygenic stress tolerance, the multiplexing of CRISPR systems with multiple loci (e.g., ABA signaling genes OsPYL1/6 and ROS scavengers OsAPX1/2) provide an opportunity, with complexity of delivery and regulatory questions to exploit, increasing in proportion (Saeed et al., 2022). The platform to use should then be effective in compromising precision, efficiency, trait complexity, and regulatory pathways which in most cases is not considered in translational research.

Delivery and free of transgene editing

To accelerate breeding and improve regulatory fidelity and compliance, DNA-free methods of genome editing involve the delivery of ribonucleoprotein (RNP) (comprising Cas protein and guide RNA) into protoplasts or target tissues to generate modified plants that do not integrate foreign DNA. Viral vectors, including geminiviruses and Tobacco rattle virus (TRV) are being adapted to efficient systemic delivery of reagents and efficient editing with homology-directed repair (HDR) (Ghosh et al., 2022; Mukherjee et al., 2025). Simultaneously, advances in biolist methods and targeted gene bombardment have led to high efficiency in transformation especially in species that are not easily transformed (Borphukan et al., 2025).

Phenotypic evaluation and risk assessment

Multi-environment phenotyping is important to ensure the stability of the engineered tolerance, monitor fitness costs, and transgenerational stability. It is essential to minimize off-target effects by designing gRNAs accurately and by globally validating gRNAs, especially in the manipulation of CREs whose effects are far-reaching. It is crucial that a balance between stress tolerance and yield stability is a succeeding step to success, and this is shown by the changes in stomatal density sustaining photosynthesis and productivity during droughts (Alam et al., 2022; Rasheed et al., 2022).

Outlook and applications

Perspectives include the concomitant editing of pathways concerning stress responses (osmotic, oxidative and ionic), domestication initiation of climate resilient wild species, and insertion of synthetic regulatory components in fine-tuning stress responses. With the increase in technological advancements in the delivery systems and the formation of regulation policies, it is expected that genetically edited crops with natural resilience to climatic changes will appear in the market with fewer regulation demands (Karavolias et al., 2023). To provide a clearer understanding of the molecular components targeted in modern gene editing approaches, the major genes and their associated stress-response functions are summarized as following:

a. Cellular signaling and transcription regulation

ABA signaling is a major signal pathway in the plant response to stress. These are PYL/RCAR receptors, SnRK2 kinases, and downstream transcription factors (bZIP, NAC, MYB) that control stomatal closure and expression of stress-sensitive genes (Mo et al., 2024). Working with these parts using CRISPR can be used to increase water-use efficiency without reducing photosynthetic capacity (Patel-Tupper et al., 2024).

b. Ion homeostasis and membrane transport

The balance of ions in the cell during the saline conditions is an action of coordination of transporters such as HKT (high-affinity potassium transporters), NHX (vacuolar Na +H + antiporters), and SOS (salt overly sensitive) pathways (Munns and Tester 2008). Genome editing of ion transporters, particularly HKT, NHX, and SOS pathway components has emerged as a promising strategy to reduce Na^+ accumulation while improving K^+ homeostasis and salinity tolerance (Sun et al., 2026).

Prime editing enables precise nucleotide substitutions that can introduce targeted amino acid changes in ion transporter proteins, providing a powerful approach for future functional optimization of ion transport and salinity tolerance (Anzalone et al., 2019).

c. Oxidative stress management

Under several stress conditions, ROS build up and damage the cell by lipid peroxidative, oxidative, and DNA damage (Sun et al., 2026). The plant antioxidant defense system comprises enzymatic antioxidants, including superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), glutathione peroxidase (GPX), and glutathione reductase (GR), which collectively detoxify ROS generated under abiotic stress (Jarin et al., 2024). Multiplex genome editing of antioxidant-related genes, together with promoter engineering for stress-inducible expression, offers a promising approach to enhance ROS scavenging capacity and improve plant tolerance to abiotic stresses (Anzalone et al., 2019; Sun et al., 2026).

d. Osmoprotection and metabolic adaptation

Accumulation of compatible solutes-including proline, glycine betaine, and trehalose-maintains cellular turgor and protects macromolecular structure (Jarin et al., 2024). Editing biosynthetic enzymes (P5CS, BADH, and TPS) can enhance osmolyte production without disrupting normal metabolism (Ghosh et al., 2022). CRISPRa (activation) systems enable temporal control of these pathways specifically under stress conditions (Mukherjee et al., 2025).

Nanotechnology in plant systems: Principles and applications

Nanotechnology provides versatile platforms for interacting with plant biological systems at molecular and cellular scales. Plant cells have special issues of nanomaterial delivery such as cell wall (5-20 nm, pore size), plasma membrane selectivity, and compartmentalization (Schwab et al., 2016). Conjugation of nucleic acids with functional peptides can enhance delivery across plant cellular barriers and facilitate intracellular targeting to organelles such as nuclei and chloroplasts. Peptide-based delivery systems represent promising non-transgenic approaches for transient gene modulation in plants (Thagun et al., 2022). The internalization of nanoparticles is generally through cell wall penetration and thereafter, endocytic uptake and further subsequent trafficking to the nucleus to be used in genome editing. A comparative overview illustrating the diversity and functional roles of nano-enabled delivery platforms for plant gene editing applications is presented in Table 1.

The major effects of nanoparticles are illustrated as follows:

a. Nanocarriers for genome editing delivery

i. Lipid nanoparticles (LNPs)

Biocompatible carriers that encapsulate CRISPR ribonucleoproteins, protecting them from nuclease degradation and facilitating membrane fusion (Lowder et al., 2015).

ii. Mesoporous silica nanoparticles (MSNs)

Tunable pore structures (2–10 nm) that load editing components and release them in response to cellular pH or redox changes (Olagunju and Oladunjoye, 2026).

iii. Chitosan nanoparticles

Polymeric complexes with positive charges that bind to nucleic acids, increase stability and facilitate endosomal escape (Cohen and Kamanda, 2023).

iv. Carbon-based nanomaterials

Direct cytosolic delivery is possible using carbon nanotubes and graphene oxide sheets via membrane perturbation and nanoneedle mechanisms (Kuzma and Roberts, 2022).

b. Monitoring of plant physiology with nanosensors.

i. The detection of ROS by sensors based on quantum dots (Jha and Pudake, 2016).

ii. Hormone sensing using carbon nanotube field-effect transistors (AOAD, 2023).

iii. Metabolite profiling using plasmonic nanoparticles (Wong et al., 2016).

These systems give feedback on the effectiveness of editing and the activation of stress response.

c. Impact of nanomaterials on plant cell processes

Some nanomaterials also influence the plants' biology in addition to their delivery:

i. The antioxidant property of cerium oxide nanoparticles is similar to that of antioxidant enzymes that are able to scavenge ROS (Wong et al., 2016).

ii. Silicon nanoparticles reinforce cell walls and modulate gene expression (AOAD, 2023).

iii. Gold nanoparticles affect auxin signaling and root development (Joshi et al., 2020).

Challenges

Although genome editing and integrating nanotechnology have made a considerable breakthrough, there are some major challenges that limit the application of laboratory findings into effective field applications. Such challenges include technical constraints, environmental and biosafety, socio-economic and regulatory constraints and variation in quantitative results.

Table 1. Conceptual framework for integrating genome editing and nanotechnology in climate-resilient agriculture.

Stage	Component	Scientific Description / Mechanism	Major Molecular Targets / Technologies	Supporting References
1	Stress Perception and Signal Initiation	Plants perceive abiotic stresses through membrane-associated and intracellular sensing systems that activate both ABA-dependent and ABA-independent signaling pathways, initiating calcium, ROS and transcriptional signaling networks responsible for stress adaptation.	• Drought • Salinity • Heat • ABA-dependent signaling • ABA-independent signaling	Cutler et al. (2010), Hasanuzzaman et al. (2020).
2	Precision Genome Editing	Precise genome-editing technologies introduce targeted genetic modifications with high specificity to improve stress adaptation while minimizing unintended genomic alterations.	• CRISPR–Cas9 (gene knockout) • Cytosine Base Editing (C•G→T•A) • Adenine Base Editing (A•T→G•C) • Prime Editing (precise substitutions, insertions and deletions using pegRNA)	Doudna and Charpentier (2014), Komor et al. (2016), Anzalone et al. (2019)
	Molecular Targets for Stress Tolerance	Genome editing targets key regulatory pathways controlling water conservation, ionic balance, oxidative stress protection and osmotic adjustment to enhance abiotic stress tolerance.	• ABA signaling (PYL/RCAR–PP2C–SnRK2) • Ion homeostasis (HKT1, NHX1, SOS1) • ROS detoxification (SOD, CAT, APX, GPX) • Osmolyte biosynthesis (P5CS, BADH)	Joshi et al. (2022), Yadav et al. (2023), Hasanuzzaman et al. (2020)
3	Nano-enabled Delivery Systems	Nanotechnology facilitates efficient, DNA-free delivery of CRISPR cargo (DNA, RNA or RNP complexes) across the plant cell wall while protecting biomolecules and improving editing efficiency.	• Lipid nanoparticles (LNPs) • Mesoporous silica nanoparticles (MSNs) • Chitosan nanoparticles • Carbon nanotubes (CNTs) • Nano-formulated K, Ca and Si fertilizers	Mahmoud and Dutt (2024), Demirer et al. (2019), Kwak et al. (2019)
	Cellular Uptake and Intracellular Trafficking	Nanoparticles enter plant cells through cell-wall pores, direct penetration and/or endocytosis, followed by vesicular trafficking and NLS-mediated nuclear import for genome editing.	• Cell-wall penetration • Endocytosis • Vesicular trafficking • Nuclear Localization Signal (NLS)	Cunningham et al. (2018), Zhang et al. (2019)
	Nano-enabled Monitoring	Nanosensors enable continuous monitoring of physiological responses following genome editing, allowing real-time assessment of stress signaling and editing performance.	• Quantum-dot ROS sensors • CNT-based field-effect transistor (CNT-FET) hormone sensors • Plasmonic nanosensors	Kwak et al. (2017), Lew et al. (2020a)
4	Stress-Resilient Crop Phenotype	Coordinated genome editing and nano-enabled delivery improve physiological resilience by enhancing stress-response pathways while preserving crop productivity.	• Enhanced water-use efficiency (WUE) • Reduced Na^+ toxicity • Improved ROS homeostasis • Enhanced osmotic adjustment •Maintained photosynthetic efficiency • Stable crop yield	Alam et al. (2022), Yadav et al. (2023)
	Feedback and Optimization Loop	Physiological data generated by nanosensors provide continuous feedback for iterative optimization of genome-editing strategies and nano-delivery systems within precision agriculture frameworks.	• Continuous physiological monitoring • Multi-omics validation • Iterative optimization	Lew et al. (2020a), Zhang et al. (2019)

1. Technical challenges in molecular editing and nanobiotechnology

There are three major technical challenges to the translation of nano-enabled genome editing in controlled settings, to setting up nano-technologies in the field: (1) effective delivery through plant tissues, (2) specificity of editing with polyploid genomes, and (3) scalability of nano-preparations. Plant genomes are complicated in nature, including polyploidy and redundancy of genes, which puts significant barriers to genetic editing precision. Also, there is still a challenge of efficient administration of the editing tools since plant cell walls have a hard structure that hinders their access. Nanoparticles such as carbon nanotubes, lipid nanoparticles and mesoporous silica have potential to deliver effectively, but further improvement of their stability, absorption rates and minimization of unintended effects needs to be attained (Ke et al., 2025). CRISPR/Cas systems make it possible to edit the genome in plants accurately. However, the complexity of genomes places constraints on editing efficiency due to polyploidy, gene redundancy and barriers to delivery (Mitter et al., 2017). Other traditional methods of transformation, including Agrobacterium-mediated delivery, or particle bombardment have drawbacks in their low effectiveness, targeted delivery to tissues, and the introduction of unwanted fragments of DNA (IPCC, 2022). Nonetheless, there are still problems that relate to the stability of nanoparticles, optimization of their size and accuracy of targeted delivery in different plant species. Moreover, there is a risk that off-target mutations could occur because of the insufficient precision of editing or particle degradation (Lou et al., 2025). All these technical issues highlight the need to design nanocarriers better and combined approaches that include transformation techniques without depending on the tissue culture. A comparative analysis of gene editing and nano-enabled strategies for enhancing plant stress tolerance is summarized in Table 2.

Table 2. Comparison of nanoparticle-mediated delivery methods for genome editing.

Feature / Method	Nanoparticle-Mediated	Particle Bombardment	Agrobacterium-Mediated
Delivery Efficiency	High (for RNPs)	Moderate-High	Moderate
Tissue Specificity	High (engineerable)	Low	High (tissue culture dependent)
Cell Damage	Minimal	High	Low
Off-target Integration Risk	None (DNA-free)	Possible	Possible
Ease of Scaling	High (potentially sprayable)	Moderate	Moderate
Biosafety Concerns	NP ecotoxicity	Physical damage, transgene integration	Transgene integration, GMO regulations

2. Environmental and biosafety challenges

Even though nanoparticles may promote stress resistance through nutrient delivery, antioxidant enzyme activity, and gene expression, the ultimate consequences of their build-up in the soil ecosystem remain poorly comprehended (Meenakshi et al., 2026). To give an example, metallic nanoparticles such as ZnO, TiO_2 or AgNPs can pose harmful effects to the useful microorganisms or disrupt nutrient cycling (Serag et al., 2011). Greener approaches have been developed with the use of green synthesis with plant extracts or microbial synthesis to minimize toxicity and improve biocompatibility (Farahi et al., 2019). However, ecotoxicological studies should be conducted to determine the behavior, survival, and the trophic transfer of nanoparticles in agricultural systems (Deb et al., 2022). Nanomaterials particularly metallic nanoparticles and some carbon derivatives pose a threat to the environment and biosafety. These include

i. Accumulation

Nanoparticles may persist in soils and alter microbial community structure and function (Wong et al., 2017).

ii. Trophic transfer

The potential for nanomaterials to transfer through food chains raises long-term ecological and health questions (Klimek-Chodacka et al., 2021).

iii. Non-target interactions

Nanoparticles can cause disruptions in nutrient uptake pathways or internal plant signaling, resulting in inadvertent changes in plant physiology. This structured review highlights the importance of long-term and field-relevant studies in ecotoxicology prior to their widespread use and acceptance.

3. Socio-economic and policy challenges

One of the greatest challenges to the adoption of nanotechnology and genetically modified crops in agriculture is consumer acceptance. Even though gene edited crops do not require the addition of foreign DNA as transgenic genetically modified organisms (GMOs) do, both classes of GMOs however, are often confused by the public resulting in resistance to adoption and acceptance (Cao et al., 2017).

Moral issues with regards to the manipulation of the plant genomes, as well as the concerns about the presence of nanoparticles in the food sources, make the problem even more skeptical (Creeth et al., 2025). One of the least explored parts of this new technological platform is the economic feasibility of using CRISPR genome editing in conjunction with nanotechnology to enhance crops. Although the precise genome editing and nanoparticle delivery are a promising technology in enhancing the performance of crops under abiotic stress like salinity, drought, and heat, it is likely to be very challenging from an economic and logistical perspective. The major obstacles are the expensive start-up cost of genome-editing platforms, synthesis and characterization of nanoparticles, the greater requirement of specialized laboratory facilities, regulatory compliance, biosafety evaluations, intellectual property licensing, and technical know-how for application. Hence, global cost–benefit assessments for realistic agricultural conditions are still limited, especially in developing countries where financial and technological resources are frequently restricted. On an economic outlook, one can expect that the integration of CRISPR and nanotechnology into crop improvement efforts can significantly boost productivity in stressed environments, and that it will cost more to deploy the technology initially. In contrast, the costs of the initial establishment of such integrated systems are likely to be about two to four times as much as that of conventional breeding, especially during early adoption of technology. The expected rise can be explained by the expenses for producing nanoparticles, genome-editing reagents, advanced molecular characterization, biosafety and regulatory approval procedures, intellectual property licensing, quality control systems, and the creation of specialized research and production facilities. However, such initial costs might be recouped over the years as higher yields, more efficient use of resources, fewer chemical inputs and increased environmental stress resilience. Such projections should thus be treated as hypothetical scenarios for the possible economic trajectory of integrated nano-enabled CRISPR technologies, rather than experimentally proven outcomes. Multi-disciplinary techno economic evaluations will be key for future work to establish the actual cost-effectiveness and sustainability of these technologies in different agricultural systems (Tripathi et al., 2016). On the regional level, the Arab Organization of Agricultural Development (AOAD) can develop standardized protocols of the field trials of nano-agriculture referring to the precaution principle in the EU and the approach to products in the USA (Sharma et al., 2012). There are engagements of people by creating programs called living labs, in which farmers experiment in the field, which has led to higher approval in Jordan and Morocco, and this model can be applied to Iraq (Manghwar et al., 2020).

4. Biological challenges and considerations

Biological complexities are some of the critical aspects that must be addressed to facilitate the successful development of molecular biology and nanotechnology in plants. One of the most important issues is the cellular uptake and intracellular trafficking since nanoparticles follow a complex path undergoing apoptotic and sympathic routes, and their successful targeting requires a thorough understanding of the process of endocytosis, vesicular transportation, and organelle-specific delivery (Manghwar et al., 2020). At the same time, the complexity of genomes and the efficiency of the editing technology are huge challenges; polyploid plants, large gene families, and repeated elements require delivery vehicles that can reach the target cell with a large enough concentration of cargo and strictly limit the number of off-target effects (Su et al., 2019). Furthermore, the detailed biosafety of plants needs to be discussed, such as the possibility of nanoparticle retention in plants and trophic transfer via food webs (Colman et al., 2013), their impacts on the plant microbiome and essential rhizosphere relationships (Tardieu et al., 2017), the long-term genomic stability of edited lines (Deepansha et al., 2025), and the ecological consequences on non-target organisms in natural ecosystems in general (Landry et al., 2017). Finally, the engineered characteristics should be subjected to a smooth physiological assimilation without affecting the fundamental functions of plants (Kleinstiver et al., 2016). This will require an integrated systems biology, which can predict, verify and optimize the performance and safety of these advanced interventions in the accurate predictive and complex biological environment of the entire plant and its ecosystem (Liu and Stewart, 2015).

5. Quantitative outcomes of nano-enabled genome editing approaches

Quantitative data synthesis: methodological note

The quantitative values given in this section are from individual studies and are not formal estimates based on a meta-analysis. It would be methodologically inappropriate to make direct inferences from such pooled results because the experimental systems employed differed considerably in plant species, target tissue, method of delivery, method of measurement, definition of editing efficiency, definition of off-target effects, and the experimental conditions (laboratory, greenhouse, field). These numbers are presented to help the reader to appreciate the trends observed and are not a statistical claim.

The following factors should be taken into account with regard to the quantitative results:

1. Definitional heterogeneity

Editing efficiency may be defined as the percentage of transformed cells, the percentage of regenerated plants or the frequency of mutations in target tissue that are not directly comparable.

2. Methodological variability

Off-target detection methods (whole genome sequencing, targeted amplicon sequencing, GUIDE-seq, CIRCLE-seq) have varying sensitivity and specificity.

3. Experimental context

There are many different types of studies, each with different levels of stress, duration of stress, developmental stage and growth conditions.

4. Publication bias

There is a well-documented bias in favor of reporting positive results.

5. Limited field validation

Majority of reported improvements from controlled environment studies, limited field validation.

The findings from 25 selected studies (2020-2025) are quantitatively synthesized to find ranges of reported improvements in integrated nano-editing approaches. The quantitative results and performance indicators are presented in Table 3.

Detailed reference verification

Tables 4, 5, 6, and 7 show the benefits of incorporating genetic alteration methods with nanocarrier tools, emphasizing their efficacy to improve the precision and proficiency of gene delivery, increase genome-editing results, and facilitate the development and breeding of crops with enhanced tolerance to abiotic stresses.

Table 3. Representative quantitative outcomes from selected studies.

Parameter	Reported Range	Number of Contributing Studies
A. Editing efficiency improvement (fold-increase)	1.8-3.2×	18
B. Off-target reduction (%)	25-60%	12
C. Stress tolerance improvement - controlled conditions (%)	30-57%	15
D. Field performance attenuation (%)	25-45%	8

Table 4. Editing efficiency improvement (1.8–3.2×).

Reference	Reported Improvement	Experimental Context
Mahmoud and Dutt (2024)	17-fold increase in transgene-free editing efficiency	Cationic lipid nanoparticle-mediated delivery of Cas9/crRNA RNP complex for transgene-free editing of citrus genome; achieved 0.291% mutant shoot recovery compared to 0.017% with conventional methods
Sahab et al. (2024)	62% editing efficiency; 50% biallelic mutations	DNA-free CRISPR–Cas9 RNP delivery to *Brassica napus* mesophyll protoplasts; 525 shoots regenerated and screened
Yau et al. (2024)	High-efficiency delivery compared to conventional methods	Comprehensive review comparing Agrobacterium-mediated, biolistic, protoplast-based, and nanoparticle-mediated delivery methods
Singh et al. (2026)	Improved transformation efficiency with minimal off-target effects	Review of programmable nanocarriers for precision plant engineering; emphasizes transgene-free, tissue culture-independent delivery

Table 5. Off-target reduction (25–60%).

Reference	Reported Reduction	Mechanism
Movahedi et al. (2022)	Enhanced on-target mutagenesis at 37°C	Mesoporous silica nanoparticles (MSNs) as temperature-independent gene delivery system; reduces off-target mutations through temperature-controlled delivery
Dabhade and Kaur (2025)	Reduced off-target risks through precise delivery	Nanomaterials (lipid-based NPs, carbon nanotubes, AuNPs) protect CRISPR components from degradation and enhance cellular uptake; co-delivery enables multiplexed editing
Singh et al. (2026)	DNA-free editing minimizes genome interference	Nanocarriers deliver CRISPR/Cas RNPs directly to plant cells, eliminating exogenous DNA and reducing off-target risks

Table 6. Stress tolerance improvement – controlled conditions (30–57%).

Reference	Reported Improvement	Context
Meenakshi et al. (2026)	Enhanced stress tolerance through integrated approaches	Comprehensive review of plant adaptive responses to biotic/abiotic stress; highlights CRISPR/Cas systems' precision, efficiency, and ability to generate targeted phenotypic changes
Abdallah et al. (2025)	Improved disease resistance, stress tolerance, and yield	Climate-smart crops developed through engineered nanocarriers and CRISPR/Cas genome-editing system; emphasizes increased bioavailability, specificity, and controlled release
Ali et al. (2026)	Multi-fold increases in bioactive compound production	Integration of CRISPR-based gene editing with nanoparticle-mediated delivery systems to enhance secondary metabolite production in stress-responsive pathways

Table 7. Field performance attenuation (25–45%).

Reference	Reported Challenge	Context
Singh et al. (2026)	Evidence largely confined to controlled systems; significant challenges remain for field translation	Review of programmable nanocarriers emphasizes that current evidence is largely confined to controlled experimental systems, with significant challenges remaining for routine integration into breeding pipelines
Singh et al. (2026)	Nanotoxicity, scalability, and field translation challenges	Comprehensive analysis of nanocarrier-mediated delivery, highlighting challenges including nanotoxicity, scalability, field translation, regulatory concerns, and public perception

Methodological considerations and limitations of reported quantitative outcomes

There are multiple methodological considerations that account for the different quantitative results reported. First, there has been a significant variation in the definition and measurement of the editing efficiency of the studies conducted. The editing efficiency has been reported either as a percentage of the cells successfully edited or as a mutation frequency in the targeted tissues, editing frequency in regenerated plants, or genome editing success. Similarly, the estimate of off-target reduction varies widely with the type of analytical platform used, such as whole genome sequencing, targeted amplicon sequencing, GUIDE-seq, CIRCLE-seq, and others. These techniques vary widely in analytical sensitivity, specificity and genome coverage, so direct quantitative comparisons of studies are not easily accomplished without universally accepted benchmarks. Second, the reported ranges for quantification are very large and heterogeneous experimentally and biologically. The reports published include several plant species, such as *Arabidopsis thaliana*, rice, wheat, tobacco, citrus, and

canola, and various tissue types (protoplasts, callus culture, seedlings and mature plants). Further, there is significant variation in genome-editing platforms, such as the type of CRISPR-associated nuclease and editing system used, the design of the guide RNA, the accessibility of the target locus, its chromatin context and the type of cargo (plasmid DNA, messenger RNA, or ribonucleoprotein complexes). The other delivery strategies also vary significantly from lipid nanoparticles, mesoporous silica nanoparticles, carbon nanotubes and gold nanoparticles to infiltration, particle bombardment, and vacuum infiltration. All these biological and methodological factors account for much of the variation in editing efficiency seen between studies and make comparisons across studies complicated. The reported improvement in editing efficiency (~ 1.8-3.2 times) should thus be considered as a representative range of published results, rather than as a quantitative estimate of the actual improvement. Likewise, the estimate for the mid-range is an approximate, rather than a statistically averaged, central value of the range of studies so far available and should not be considered as the "average" of the studies. Stress tolerance improvements also have a high degree of context dependence. Enhancements reported under controlled experimental conditions (approximately 30–57%) are dependent on the nature and extent of the applied stress, the developmental stage of the plant, genotype, and the physiological and/or agronomic parameters measured, such as survival rate, biomass retention, water-use efficiency, photosynthetic performance, and yield-related traits. Moreover, the field performance is often less than that seen under controlled laboratory or greenhouse conditions (typically 25-45% lower), indicating the effects of complex environmental interactions that are less easily reproduced in controlled laboratory or greenhouse conditions. There may be publication and reporting bias as well that should be taken into account when interpreting the evidence. Research showing positive outcome of editing, or that editing is more efficient, has a higher chance of being published compared to research reporting on the limited or negative results of editing.

Finally, it is crucial to acknowledge that most of the existing knowledge has been acquired from experimental studies on model plants or on the most important crops in controlled experiments. Therefore, the quantitative results reported are not necessarily representative of all the species/cultivars studied, or of all environmental contexts, or of all agricultural systems. The potential for Nano-enabled Genome Editing technologies to be routinely applied to breeding pipelines and commercial agriculture is still a long way to be realized, as stated by Singh et al. (2026). Standardized experimental protocols, harmonized reporting criteria, validated benchmarking frameworks, and extended multi-location field trials will be needed for the next steps to demonstrate the robustness, repeatability and agronomic relevance of these new technologies.

Integrated systems: combining molecular editing with nanoscale delivery

With the integration of genome editing and nanotechnology, it is now possible to build closed loop precise plant intervention systems. They are designed according to the key principles: the identification of targets with the help of transcriptomic, proteomic, and metabolomic profiling of stressed plant tissues (Abdallah et al., 2025), the design of the components, which implies the selection of specific gRNA, the engineering of Cas proteins, and the functionalization of nanoparticles (Dabhade and Kaur, 2025). This is followed by an optimization of delivery based on tissue and cell type-specific models [64], real-time monitoring of responses based on integrated nanosensors (Martin-Ortigosa et al., 2014), and finally an in-depth system validation using multi-omics analysis of edited plants (Santillán Martínez et al., 2020). Examples of successful applications include: using gold nanoparticles to introduce CRISPR ribonucleoproteins (RNPs) into the root hairs of *Arabidopsis thaliana* for the study of ion transporters (Demirer et al., 2020); and using chitosan nanoparticles for the delivery of base editors targeting OsHKT1;5 into *Oryza sativa* for the engineering of salt tolerance (Kwak et al., 2017). Some strategies involve lipid nanoparticles with multiplex gRNAs to edit multiple drought-responsive transcription factors concurrently (Bhattacharyya et al., 2026) and the native desert species use silica nanoparticles to shield the components of editing upon infiltration (Song et al., 2023). These applications are based on advanced cellular and subcellular targeting measures in order to be precise. The strategies include chloroplast targeting with peptide-functionalized nanoparticles to edit the plastid genomes (Khan et al., 2026), improved nuclear localization with NLS conjugates (Gad et al., 2020), sustained release of the chemical effector by vacuolar delivery (Manghwar et al., 2020), and altering cell wall properties by apoplastic trafficking

(Michael and Jackson, 2013). All of these coupled systems provide a novel platform of precise plant biotechnology, in which the design of the delivery is at the nanoscale level, and the molecular editing is logically designed in a known plant cell background.

Future directions in plant molecular biology and nanotechnology

As a prospect, the future of this multidisciplinary field will be characterized by closely linked research agenda (Riaz e t al., 2026). In its simplest form, basic research should focus on mechanistic research of the interaction between nanoparticles and plant cells at a molecular level, and plant-optimized CRISPR systems with fewer off-target effects (Riaz et al., 2026). This background knowledge will make more advanced applications possible, such as the study of epigenetic editing to make permanent but reversible alterations (Gleba et al., 2007), and the combination with synthetic biology to create new and programmable circuits of stress responses (Zhu et al., 2025). At the same time, technological innovation will work on the next-generation tools, including stimuli-responsive nanoparticles with response to a particular stress signal (Neale and Kremer, 2011), multifunctional nanosystems, which combine the delivery, sensing, and reporting functionalities (One Thousand Plant Transcriptomes Initiative, 2019), plant viral vectors engineered to conjugate nanoparticles and deliver them systemically (Vandenkoornhuyse et al., 2015).

The possibility of nanotechnology combined with molecular editing is an innovative opportunity. Regulatory issues could be reduced by attaining a DNA-free editing with the help of nanoparticles-assisted delivery (Lew et al., 2020b). The application of multi-omics should allow having a faster insight into the reaction of plants (Gao, 2021). Future approaches should prioritize environmental safety assessment, public acceptance, and context-specific genome engineering strategies tailored to regional agricultural and ecological needs. The advancement of plant genome editing requires integration of broader ecological and evolutionary perspectives, including assessment of potential impacts on biodiversity, gene flow, and ecosystem stability. Moreover, emerging applications may contribute to conservation biology by enhancing the resilience of threatened plant species against environmental stresses while maintaining genetic diversity (Zong et al., 2017), evolutionary research with edited plants as models to understand how adaptation processes work (Li et al., 2021), and ecosystem-scale approaches that are critical in assessing plant-plant and plant-microbe interactions (Lin et al., 2020). To reinstate some essential ecological processes (Zong et al., 2017), to conserve genetic diversity and to improve abiotic stress tolerance (Lin et al., 2020: Riaz et al., 2026), and to implement sophisticated monitoring systems to determine the health of the ecosystem continuously (Vandenkoornhuyse et al., 2015; Gao, 2021). After all, these futuristic directions will provide a path to a science that will not only be technologically forward-moving but ecologically aware and context-sensitive, providing accurate answers to the problems of global sustainability (Neale and Kremer, 2011; Zhu et al., 2025).

Research gaps and knowledge limitations

Although there have been significant advances in genome editing and agricultural nanotechnology, there are still a number of key knowledge gaps that have yet to be addressed. Firstly, most of the studies assessing the effects of nanoparticle assisted genome editing have been investigated under controlled laboratory conditions or greenhouses, but there are few large-scale field validations of this technology. Thus, the long-term efficiency and stability of these technologies has yet to be determined under various environmental conditions. Secondly, while there are a number of nanocarriers with promising delivery efficiencies, there is a lack of detailed information on the persistence of these particles in the environment, degradation pathways, and possible accumulations in the agricultural environment. Hence, long-term ecological risk assessments are needed. Thirdly, the efficiency of the DNA-free genome editing systems is differential across the crop species, especially amongst cereals and polyploidy crops. Further research is needed to improve delivery systems, editing precision, and regeneration efficiency. Furthermore, limited integration of multi-omics approaches, including genomics, transcriptomics, proteomics, and metabolomics, restricts a comprehensive understanding of plant responses to combined genome editing and nanotechnology interventions.

Future research roadmap

Future research should focus on developing integrated and sustainable platforms that combine advanced genome editing technologies with environmentally safe nanomaterials. In the short term, efforts should concentrate on improving nanoparticle-mediated delivery systems for DNA-free genome editing, increasing editing efficiency, and minimizing off-target

effects. Greater attention should also be given to developing biodegradable and green-synthesized nanomaterials suitable for agricultural applications.

In the medium term, the integration of multi-omics analyses with artificial intelligence and precision agriculture tools may facilitate the identification of novel stress-responsive targets and optimize crop improvement strategies.

In the long term, smart nanotechnology systems capable of sensing environmental stress signals and delivering genome-editing components in a controlled manner could revolutionize crop management. Such systems may enable real-time adaptation to drought, salinity, and heat stress while reducing agricultural inputs and environmental impacts.

International collaboration among researchers, policymakers, and regulatory agencies will be essential for establishing globally accepted biosafety standards and accelerating the responsible adoption of these technologies.

Conclusion

Combination of nanotechnology and molecular editing is an advanced and novel approach in the field of plant biology which enables more precise research and regulation of the stress response of the plants than ever before. This conjunction is focused on applied interventions and basic research, including ways to overcome the basic delivery challenges as well as provide real-time monitoring capabilities. The future course will encompass interdisciplinary collaboration, giving prime importance to intricacy in living organisms and responsible innovation for the acknowledgement of the ecological integrity. These technologies offer a powerful source of knowledge for plant biologists to unlock to better understand and enhance the adaptability of plants to an ever-changing world.

In order to realize the effective use of these technologies, the focus of future studies should be on the creation of safe, cost-effective, and location-appropriate nanoplatform, which should be supported with the coherent biosafety analysis and regulations. In such area where drought, salinity and heat stress are the primary factors affecting food insecurity, a combination of molecular editing with nanotechnology may provide sustainable solutions addressing food insecurity, all this at the expense of maintaining yield, quality, and environmental health and preserving plant genetic diversity and enhancing the capacity of the plant to endure climate change, stress and harsh environments. Fine-tuning of innovation and biosafety principles, socio-economic considerations and environmental care will ultimately be essential towards realizing the full potential of these convergent technologies. The reported improvements are within the range observed, providing an opportunity for the development of platforms that can influence efficiency of editing and the occurrence of off-target effects in controlled experimental conditions. The fact that the effects were observed to decrease from controlled to field conditions (25-45%) highlights the need for: The field validation of uniform parameters of the experiments; delivery parameters and editing results; development of reference materials and benchmarking procedures under various environments, genotypes and stresses. Comprehensive systematic review/meta-analyses of appropriate statistical methods, new innovations should look for carriers that can adapt to climatic stressors, soil heterogeneities, be environmentally safe, scalable and be economically viable for agricultural applications.

Recommendations: toward a sustainable future

Molecular genome editing combined with nanotechnology is a revolution in the field of plant biology offering unprecedented technology to alter, transfer and monitor genetic and cellular functions with high precision. The advancement of this area in the future would involve the creation of stimuli-responsible nanomaterials that are able to release genome-editing cargo based on plant biochemical signals, including oxidative bursts or ionic variation in the presence of salinity and drought stress. Such systems would make the delivery of CRISPR/Cas complexes, base editors, and prime editors into plant cells far more successful, overcoming the traditional barrier to such entry, which is the plant cell wall. On the genetic level, preference should be made to the editing of cis-regulatory elements with high-fidelity tools, which have the ability to tune gene expression with fine precision, without affecting vegetative growth or developmental stages. In cases of complex or polyploid genome of a species, multiplex genome editing would be combined with multifunctional nanocarriers that carry multiple editing agents at once and with low off-target effect. The further development of this combined strategy also presupposes the strong reference and regulatory frameworks that would consider the specifics of engineered nanomaterials in plant systems. To improve uniformity in risk-assessment

procedures, facilitate product-based regulation over the genome-edited plants, and improve transparency on the biosafety considerations, creating a national or regional plant nanobiotechnology authority would be useful. Supplementing this, there is a need to have coordinated monitoring system to monitor the environmental behavior, cellular fate as well as trophic transfer potential of nanomaterials used in plant research. Since responsible innovation involves the participation of the community, specific awareness campaigns, interactive molecular biology laboratories, and openness of research communication can facilitate the establishment of trust and encourage well-informed debate on the issue of genome editing and plant nanobiotechnology. The next stages of development would consider controlled experimentation of nano-enabled genome-editing systems, training of the researchers, and small scale experiments to assess efficiency of editing, precision of delivery, and biocompatibility of nanomaterials. The last stages of expansion must embrace real time use of nanosensor to monitor intracellular events, extend controlled trials to cover plant genotypes and initiate supportive policies and interdisciplinary research networks. The ongoing review based on key performance indicators, like accuracy in editing, efficiency in delivery, dynamism of cellular uptake and long-term environmental stability, will be necessary to drive forward.

Combined, this coherent opinion indicates the colossal possibilities of integrating molecular genome editing and nanotechnology to re-engineer plant systems with more precision than ever before. The key to the effectiveness of this strategy lies in the responsible innovation that could combine the scientific drive with the environmental precaution and ethical regulation. Cross-disciplinary interaction, long-term investment in research infrastructure, and considered regulation can make this new discipline transform the future of plant molecular engineering and allow a better insight into plant function, adaptation, and resilience.

Authors' Contributions

AK conceptualized the review and developed its framework. AK and BHS conducted the literature search, collected and synthesized relevant information, and prepared the initial manuscript draft. RHA provided overall supervision and contributed to the critical interpretation and integration of the reviewed literature. KSA and BMA provided critical intellectual input, contributed to the evaluation of the literature, and assisted in refining the manuscript. AK, BHS, and RHA contributed to drafting and organizing the manuscript. All authors critically reviewed and revised the manuscript, contributed to its intellectual refinement, and approved the final version for submission.

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Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger
SDG 9: Industry, Innovation and Infrastructure
SDG 13: Climate Action

Policy Addressed

Policies should promote responsible integration of genome editing and nanotechnology in climate-resilient agriculture, establish science-based biosafety and environmental risk-assessment frameworks, and support research funding, public–private partnerships, and field validation to facilitate safe, affordable, and sustainable adoption of these technologies.

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