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# Harnessing Biotechnology for Enhanced Crop Resistance and Dietary Quality

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## ABSTRACT

The progressive effect of biotechnology on crop improvement is tested in this review, boosting nutritional quality and sensory features while strengthening resilience to biotic and abiotic challenges. Despite their effectiveness, conventional breeding methods are often expensive and prolonged. Crop engineering has been transformed by the emergence of modern genetic technologies, mainly CRISPR/Cas9, which allows for specific gene alteration without the creation of transient DNA. Growing disease-tolerant crops and improving traits like drought resistance and nutritional value have shown potential in this era. Transgenic processes for manipulating pests and diseases are also covered in the review, emphasizing how modified organisms can offer environmentally friendly substitutes for chemical insecticides. Moreover, metabolic engineering is investigated to enhance the nutritional value by modifying biosynthetic pathways. Through demonstrating how beneficial bacteria can improve nutrient absorption and strain resilience, the relevance of microbiome manipulation in increasing agricultural output is highlighted. The review additionally discusses the implications of artificial biology in agriculture, which allows the introduction of innovative organic systems to deal with the complicated problems driven by rising food demands and global warming. Through evidence-based decision-making and real-time tracking, the mixing of precision agriculture technology improves resource efficiency. The examination concludes with the help of reflecting on the popularity and commercialization of biotechnology crops, considering both public concerns and the potential benefits for agricultural productivity. This thorough analysis emphasizes how essential biotechnology is in shaping future sustainable farming practices.

**Keywords:** CAS9, CRISPR, Metabolic engineering, Microbiome manipulation, Synthetic biology in agriculture, Transgenic pest control

## Introduction

Crop development has been a point of interest for plant breeders and agronomists, with the need to develop plants that might be resistant to various biotic and abiotic stresses and also enhance their dietary and morphological features. Traditional breeding strategies, though powerful, are time-consuming and complex, as they regularly contain a series of backcrossing and selection to introduce perfect developments into stronger germplasm. However, the utilization of recombinant DNA technology and, more recently, CRISPR/Cas9 have revolutionized crop development by providing cost-effective and precise tools for genetic manipulation.<sup>1</sup>

CRISPR/Cas9, mainly, has proven extraordinary potential in developing disease-tolerant crops. This gene-editing technology can overcome the limitations of conventional breeding with the targeted modification of specific genes related to disease tolerance without creating exogenous DNA. The CRISPR/Cas9 device has been successfully applied to engineer resistance toward diverse plant pathogens, such as viruses, microorganisms, and fungi, through disruption or modification of the expression of host susceptibility genes or by introducing pathogen-derived resistance genes.<sup>2,3</sup> In addition to disease tolerance, CRISPR/Cas9 has additionally been utilized to improve ideal crop characteristics, including drought tolerance, improved nutrient content, and better taste and structure.<sup>4</sup>

The combination of biotechnology in agriculture has revolutionized crop resistance strategies, improving food safety and sustainability. Current improvements highlight the capacity of modern strategies, such as genome editing and RNA interference, which permit precise modifications in plant traits to fight biotic and abiotic stresses. Using those biotechnological methodologies, researchers propose to develop crops that resist pests and diseases more effectively and additionally improve nutritional content. This ongoing evolution in crop biotechnology is vital for adapting to the challenges arising from temperature fluctuation and growing global food demands.

## Methodology

This review followed the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) 2020 statement methodology, which allowed for complete and transparent reporting of systematic review methods. This work has been reported in line with the PRISMA criteria.<sup>5</sup> A comprehensive literature search was performed, focusing on published peer-reviewed literature from 2010 to 2025 among several databases, including PubMed, Scopus, and Google Scholar. We searched for relevant studies using keywords related to metabolic engineering, microbiome manipulation, crop development, precision agriculture, synthetic biology (SynBio), and gene-editing technologies (e.g., CRISPR/Cas9). The articles were screened, selected, and synthesized under the guidance of PRISMA principles to ensure methodological rigor and reproducibility. To assess progress in plant biotechnology methods for crop improvement, data were systematically extracted and assessed. To promote evidence-based judgments and modern research guidelines, this study is presented according to the PRISMA guidelines, which aim to offer a comprehensive and systematic synthesis of modern-day agricultural biotechnology studies.

### Transgenic Approaches to Pest and Disease Control

Managing pests and diseases is a crucial challenge in agriculture and environmental management. Conventional techniques have often relied on chemical pesticides, which can have negative impacts on the surroundings and human health.<sup>6</sup> Furthermore, the repetitive use of insecticides has caused the development of resistance in many pest populations but lowered their effectiveness over time.<sup>7</sup>

Recently, there has been growing interest in developing alternative, increasingly sustainable pest management strategies. One such approach is transgenic organisms, which may be engineered to resist or repel pests and pathogens. Transgenic procedures offer the potential for increased targeted and environmentally friendly pest manipulation, with the capacity to precisely target unique pest species or intermediate hosts.<sup>7,8</sup>

One promising application of the transgenic era is the utilization of the entomopathogenic fungi *Metarhizium anisopliae* as a microbial control agent. These fungi are engineered for targeted pathogenicity, presenting a powerful and environmentally friendly alternative to chemical insecticides. Similarly, the usage of genetic modification approaches, which could spread genetic modifications through pest populations, has additionally been explored for controlling insect pests and disease carriers.<sup>7</sup>

### Targeted Gene Editing in Crop Plants

Targeted gene editing in crop plants has gained traction in recent years, in most cases due to improvements in genome editing technology, such as CRISPR/Cas9. Figure 1 shows that this system allows for precise modifications to plant genomes, facilitating the improvement of crops with better traits, including improved yield, immunity against disease, and enhanced nutritional content. CRISPR/Cas9 has been recognized for its precision, efficiency, and versatility compared to traditional breeding methods and genome-enhancing strategies like zinc finger nucleases and transcription activator-like effector nucleases.<sup>9–11</sup>

These improvements not only exhibit the potential of CRISPR/Cas9 for creating genetically modified organisms but also emphasize its role in accelerating

the breeding process. Several studies have proven the successful applications of this technology to improve traits, including flowering time in soybeans and pathogen resistance in tomatoes and wheat.<sup>12</sup>

One tremendous advantage of CRISPR/Cas9 technology is its ability to bring particular genetic modifications without incorporating foreign DNA. This feature has addressed public concerns, particularly genetically modified organisms, and resulted in the development of nontransgenic varieties with improved traits. To combat food deficits in developing countries, researchers have, for instance, used CRISPR/Cas9 to improve beta-carotene production in corn, greatly increasing its levels in specific genotypes. Cas enzyme variations like Cas12a (formerly known as Cpf1) are being investigated by researchers because they might provide higher specificity and enhanced activity.<sup>12,13</sup>

Additionally, though CRISPR/Cas9 has shown high specificity in targeted genes, off-target effects can still occur, necessitating further refinement of the technology to ensure accuracy.<sup>14,15</sup>

### Metabolic Engineering for Enhanced Nutritional Quality

Metabolic engineering has emerged as a powerful tool for enhancing the nutritional content and safety of crops. Plants and algae exhibit various metabolic pathways that may be harnessed to produce an extensive range of valuable compounds, which include vitamins, other nutrients, and specialized metabolites. Advances in genetic engineering and genome editing technologies have enabled researchers to rewire plant metabolism for enhanced bioproduction. For example, modifying the biosynthetic pathways for primary metabolites can enhance the nutritional value of crops, whereas the optimization of secondary metabolic pathways can lead to the overproduction of specialized compounds with medicinal or industrial programs.<sup>16</sup>

One example is the metabolic engineering of hairy root cultures to enhance the production of valuable secondary metabolites.<sup>17</sup> Alteration of the expression of key regulatory genes enables researchers to improve the deposition of energy-rich compounds, such as tropane alkaloids and ginsenosides in engineered hairy roots.<sup>18</sup> Furthermore, creating heterologous biosynthetic pathways in microalgae has enabled the production of valuable lipids, pigments, and antioxidants.<sup>16,19</sup>

### Nutritional and Palatability Improvements Through Biotechnology

Biotechnology has focused on numerous methods to biofortify staple plants with essential vitamins and enhance their sensory attributes. High-oil corn, for example, is being developed by incorporating high-protein genes and increasing essential amino acid content material in grains. This molecular breeding method aims to fortify cereals with essential amino acids like lysine, methionine, threonine, and tryptophan, potentially lowering the need for exogenous amino acid supplementation in feed rations. Biofortification efforts amplify past cereals to encompass different crops, consisting of wheat, soybeans, and canola. These projects address dietary deficiencies in developing countries

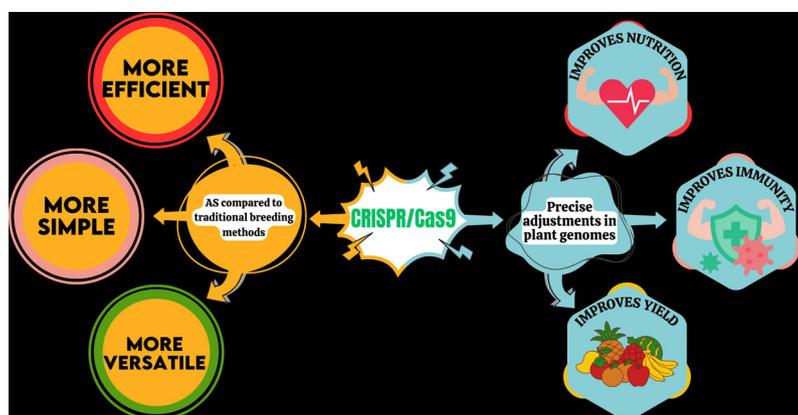


Fig 1 | CRISPR/Cas9

and also cater to the evolving dietary needs of emerging economies through the production of novel nutrients in grains. As our knowledge of the human genome and biochemical methods associated with fitness and disorder progression deepens, biotechnology enables the elimination of antinutrients and the enhancement of beneficial vitamins in our food.<sup>20</sup>

Traditional plant breeding, molecular breeding, and agronomic practices are employed to develop nutrient-rich plants. The HarvestPlus biofortification program, a collaborative effort involving international research, aims to improve vitamin A, iron, and zinc content in various crops, including beans, pearl millet, maize, cassava, potato, wheat, and rice. This initiative's goal is to combat micronutrient malnutrition in developing countries by delivering nutrient-rich crops.<sup>21</sup>

Biotechnology is also applied to improve the palatability and storage qualities of plants. For instance, research on tomatoes has explored mutations in genes like *alcalycophyllous* (*alc*) that can extend storage life while retaining fruit color and aroma. Moreover, research has investigated the role of cell-wall-degrading enzymes in fruit texture, with RNA interference of the pectate lyase gene resulting in fruit phenotypes and extended shelf life without compromising organoleptic and nutritional qualities.<sup>22</sup>

#### Microbiome Manipulation for Crop Productivity

Manipulating the plant microbiome, the diverse community of microorganisms that live inside and on the plant is one promising technique to enhance crop productivity. Researchers have found that those microbial groups play a crucial role in plant growth, nutrient acquisition, and strain tolerance. By gaining insights into the mechanisms of plant-microbe interactions and factors involved in microbial network assembly, researchers aim to harness the potential of these

microorganisms as biofertilizers and biopesticides, decreasing the reliance on synthetic chemical inputs.<sup>23,24</sup>

Analysis of the recent literature highlights the rising traits in microbial application for crop productivity.<sup>23</sup> One key focus is the role of microbial phytohormones in promoting stress tolerance in crops. Microorganisms can produce a healthy range of phytohormones, including auxins, cytokinins, and gibberellins, that may modulate plant morphophysiological traits and enhance stress resilience.<sup>25</sup> Researchers are particularly interested in identifying effective microbes that can improve plant development and health under adverse environmental fluctuations. Another area of interest is the synergistic effects of nanomaterials and plant probiotics, enhancing the effectiveness of microbial inoculants. Nanomaterials have been proven to modify the survival, colonization, and activity of beneficial microbes, leading to improved crop yield and stress tolerance.<sup>26</sup>

The review additionally highlights the significance of the complex interactions in the mycorrhizosphere, the soil area shaped by the symbiotic relationship between plant roots and mycorrhizal fungi. Mycorrhizal fungi can form symbiotic relationships with plant probiotics, such as bacteria, leading to additive and synergistic effects on plant development and health, such as improved nutrient uptake and pathogen resistance.<sup>25–28</sup> Figure 2 illustrates the effect of microbiome manipulation on crops.

#### SynBio in Agricultural Systems

Current advancements in SynBio significantly influence agricultural structures, imparting innovative solutions to enhance crop productivity and resilience. Conventional breeding strategies have traditionally been important for developing agronomically important traits; however, they are increasingly seen as insufficient in addressing the complicated and demanding situations posed as a result of global warming and biotic stresses. SynBio gives a transformative technique by establishing novel biological components and systems, which could introduce multiple genes at a locus or create novel genomes from standardized genetic components. This functionality permits enhanced trait development, together with improved resistance to diseases, pests, and environmental stressors like drought and high temperature, ultimately aiming to preserve and increase crop yields in an era of escalating agricultural demands.<sup>29</sup>

The use of SynBio in agriculture drives fundamental advancements. For example, it permits the rational reprogramming of plant development and growth, leading to large breakthroughs comparable to a green Revolution. By systematically manipulating biological structures, researchers can explore fundamental questions about plant biology and simultaneously address practical challenges in sustainable agriculture. The integration of SynBio principles can facilitate the engineering of crops for enhanced nutritional value and reduce harmful compounds, contributing to a sustainable bioeconomy.<sup>30</sup>

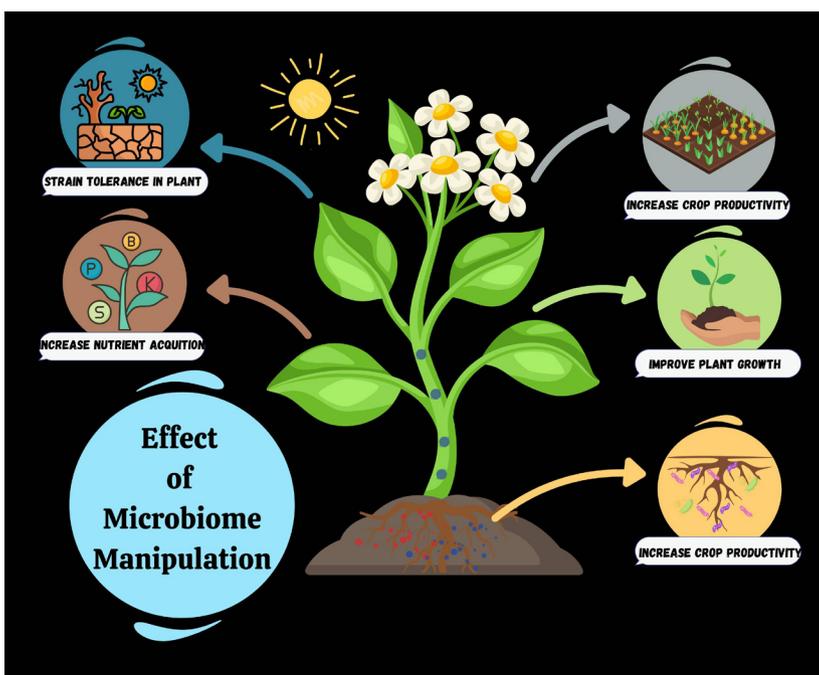


Fig 2 | Effects of microbiome manipulation

However, the complexity of plant structures remains a substantial obstacle, necessitating precise information on their molecular and cell interactions to fully leverage SynBio technology.<sup>31</sup> Furthermore, current agricultural practices face mounting pressure to enhance food production by about 70% by 2050 to satisfy global needs. SynBio is an essential tool in this endeavor, using engineering ideas to improve plant morphology and structure. Innovative approaches, such as synthetic carbon-recycling pathways enhance crop yields, optimize nutrient utilization, and decrease fertilizer dependency. For instance, engineering nitrogen fixation into plants and growing synthetic plant-microbiota structures are promising approaches that could improve agricultural sustainability.<sup>32</sup>

### Precision Agriculture and Sensor Technologies

Smart sensors play a pivotal function in precision farming by providing practical insights into improving soil profile, climate ranges, and crop health. These sensors include soil moisture, temperature, and nutrient level sensors, enabling precise irrigation and fertilization strategies, resulting in resource efficiency and better crop yields.<sup>33,34</sup>

The evolution of Internet of Things technology has revolutionized precision agriculture. For example, cloud-based platforms permit seamless information collection and analysis from many sensor types, allowing farmers to monitor environmental factors remotely. This integration optimizes greenhouse control and also supports decision-making processes through predictive modeling.<sup>33</sup>

On-farm experimentation practices have gained popularity as a means of validating the effectiveness of technology in real-global settings. Recent research emphasizes the importance of farmer-centric methods in generating credible scientific knowledge while addressing localized agricultural challenges. This shift toward participatory research enhances the relevance

of precision agriculture techniques by incorporating various farmer experiences and insights into technology deployment.<sup>35</sup>

### Commercialization and Adoption of Biotech Crops

The commercialization and adoption of biotechnological crops are presently a subject of growing interest. The dramatic increase in the GM crop industry has caused significant changes in both the extent of adoption and the overall effect of these technologies.<sup>36</sup> The creation of genetically modified crops has been a debatable subject globally, with stakeholders advocating for their adoption to enhance food safety and reduce poverty. In contrast, others express concerns regarding their health, environmental impacts, and moral issues. The global area of biotechnological crops has increased substantially in recent years, accomplishing 191.7 million hectares in 2020, with America, Brazil, and Argentina leading their cultivation.<sup>37</sup>

Conversely, the commercialization of genetically modified plants has been challenged by several regulations throughout the European Union, Australia, and beyond based on social concerns about potential risks.<sup>38</sup> Regardless of a few consumer concerns, the global distribution and adoption of GM crops have accelerated rapidly over the last decade.<sup>39</sup>

### Biotechnology for Climate-Smart Agriculture (CSA)

In the face of the developing issues of global warming, the application of biotechnology in agriculture has become increasingly vital. Figure 3 illustrates that drought, temperature, salinity tolerance, improved nutrient use efficiency, and disease tolerance are some important traits that may be engineered through superior biotechnological tools to develop climate-resilient plants.<sup>4,40,41</sup>

A systematic review of CSA practices shows that integrating advanced technologies can significantly enhance farm productivity and economic viability. For example, the adoption of precision agriculture tools, which include sensors and drones, allows for better tracking of environmental conditions, optimizing irrigation and crop management, and improving resource use efficiency. Such technologies help in increasing crop yields and also in reducing greenhouse gas emissions from agricultural activities, which are responsible for a sizable portion of worldwide emissions.<sup>42,43</sup>

In sub-Saharan Africa, there is a developing emphasis on adopting CSA technology customized to regional contexts. It includes advanced plant breeding and genomics, which offer insights into how crops can tolerate climate stresses. The combination of artificial intelligence and robotics in farming practices is gaining traction, permitting farmers to make data-driven decisions that enhance productivity and minimize environmental impacts.<sup>44</sup>

Moreover, practices consisting of agroforestry and soil carbon sequestration are being promoted as powerful techniques to sequester carbon dioxide and mitigate global warming effects. These techniques not only maintain soil health but also contribute

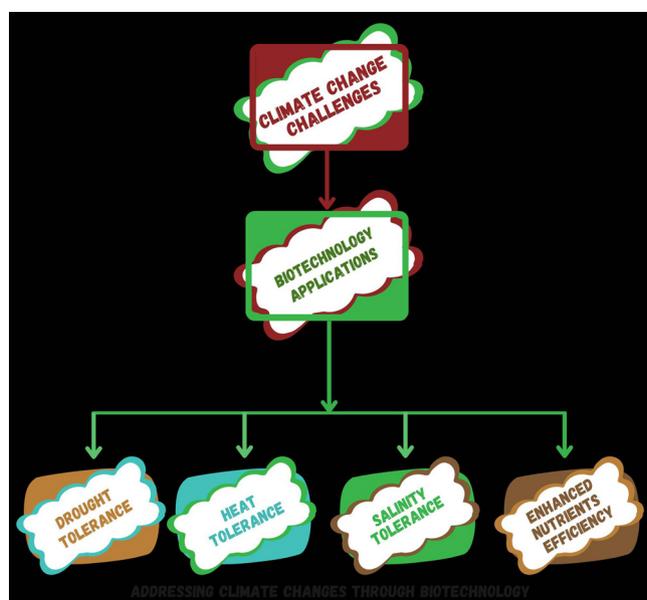


Fig 3 | Addressing climate change through biotechnology

to biodiversity conservation and enhanced soil water-holding capacity.<sup>43</sup>

### Integrated Pest Management with Biotech Approaches

Integrated pest management has been a subject of extensive debate and interpretation historically. The word “integrated control” was coined to describe the potential for integrating chemical and organic control tactics to manage pests. As global health challenges regarding pesticide presence in food and the environment have grown, there has been an increased plant stress tolerance to lessen chemical pesticide use and explore environmentally safe alternatives.<sup>45</sup>

Another technique is agroecological crop safety, which takes a holistic view of farming systems and emphasizes promoting biodiversity. The agroecological approach to pest management has been successful in a few contexts, including in Réunion, where it has been proven to contribute to sustainable pest management.<sup>46</sup>

In the context of incorporated pest management, combining various management processes, such as chemical, biological, cultural, and host plant resistance, is desired to mitigate the harmful effects of pest control and attain more sustainable crop manufacturing. The success of biological control applications often relies on the compatibility of the natural enemies with different management practices, including chemical control. Increasing concerns about the destructive effects of insecticides have brought about the development of rationally designed insecticidal molecules and the expansion of environmentally safe production systems, including organic farming, where the synthetic component is constrained. However, even organic insecticides have been documented to have deadly and sublethal effects on beneficial insects, consisting of parasitoids of stinkbug eggs.<sup>45–48</sup>

### Gaps in Current Research and Future Directions

Despite the fact that gene editing has been revolutionized by CRISPR/Cas9, problems with off-target effects and transportation efficiency in different crop genotypes still exist, and better variants of Cas enzyme (including Cas12a) with increased selectivity need to be developed. Since metabolic flux manipulation is not fully understood, especially in secondary metabolite pathways, metabolic engineering attempts often lack scalability and necessitate novel strategies to optimize biosynthetic networks. Future research is required to create artificial microbial consortia that cooperatively improve nutrient absorption and stress tolerance without disturbing soil ecosystems, as microbiome manipulation techniques are not yet fully understood in terms of their long-term ecological impacts.

Regulatory and socioeconomic barriers to the adoption of biotechnologically modified crops are frequently overlooked, particularly in developing countries where access is impeded by proprietary information and public skepticism. Because fragmented data limits predictive analytics, precision agriculture faces data integration issues. This gap can be filled by integrating these datasets using AI-driven systems. Furthermore,

specialized research on individual stressors (such as drought) ignores eventualities of compounded stress that are exacerbated by climate change and require multifactorial resilience engineering. Ultimately, international governance frameworks for SynBio projects and the ethical issues surrounding genetic engineering necessitate immediate interdisciplinary cooperation to align innovation with global sustainability goals.

### Conclusion

This review provides a comprehensive evaluation of the modern function that biotechnology plays in enhancing crop resilience and promoting nutritional value. It highlights the drawbacks of conventional breeding techniques and underlines the advantages of genetic technologies, especially CRISPR/Cas9, which permit specific gene modification without using foreign DNA. This method has confirmed its ability to develop genotypes that can be more nutritious and resilient against environmental stressors and disease. The study examines several biotechnology techniques, which include metabolic engineering for dietary development, microbiome modification to increase crop output, and transgenic strategies for pest management. These methods tackle essential problems like food safety and adapting to climate change by providing sustainable alternatives to traditional farming techniques. Incorporating precision agriculture technology is also emphasized as a way to enhance farming and maximize resource utilization. To sum up, biotechnology is at the vanguard of modern-day agriculture, supplying creative ways to improve the dietary cost and resilience of crops. They improve food security, and the potential benefits of these technologies also support sustainable farming strategies. For biotechnology plants to be successfully implemented, commercialization and public acceptance are still vital. Navigating these boundaries and attaining the full potential of biotechnology in agriculture would require ongoing studies and discussion.

### References

- Bhatta BP, Malla S. Improving horticultural crops via CRISPR/Cas9: current successes and prospects. *Plants (Basel)*. 2020;9(10):1360. doi: 10.3390/plants9101360
- Ahmad S, Wei X, Sheng Z, Hu P, Tang S. CRISPR/Cas9 for development of disease resistance in plants: recent progress, limitations and future prospects. *Brief Funct Genomics*. 2020;19(1):26–39. doi: 10.1093/bfpg/elz041
- Eş I, Gavahian M, Marti-Quijal FJ, Lorenzo JM, Mousavi Khaneghah A, Tsatsanis C, et al. The application of the CRISPR-Cas9 genome editing machinery in food and agricultural science: current status, future perspectives, and associated challenges. *Biotechnol Adv*. 2019;37(3):410–21. doi: 10.1016/j.biotechadv.2019.02.006
- Tang Q, Wang X, Jin X, Peng J, Zhang H, Wang Y. CRISPR/Cas technology revolutionizes crop breeding. *Plants (Basel)*. 2023;12(17):3119. doi: 10.3390/plants12173119
- Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *Int J Surg*. 2021;88:105906. doi: 10.1016/j.ijsu.2021.105906
- Lubeck I, Arruda W, Souza BK, Stanisçuaski F, Carlini CR, Schrank A, et al. Evaluation of *Metarhizium anisopliae* strains as potential biocontrol agents of the tick *Rhipicephalus (Boophilus) microplus* and the cotton stainer *Dysdercus peruvianus*. *Fungal Ecol*. 2008;1(2–3):78–88. doi: 10.1016/j.funeco.2008.09.002
- Legros M, Marshall JM, Macfadyen S, Hayes KR, Sheppard A, Barrett LG. Gene drive strategies of pest control in agricultural systems:

- challenges and opportunities. *Evol Appl.* 2021;14(9):2162–78. doi: 10.1111/eva.13285
- 8 Slade G, Morrison N. Developing GM insects for sustainable pest control in agriculture and human health. *BMC Proc.* 2014;8(S4):O43. doi: 10.1186/1753-6561-8-S4-O43
  - 9 Belhaj K, Chaparro-Garcia A, Kamoun S, Nekrasov V. Plant genome editing made easy: targeted mutagenesis in model and crop plants using the CRISPR/Cas system. *Plant Methods.* 2013;9(1):39. doi: 10.1186/1746-4811-9-39
  - 10 Mao Y, Botella JR, Liu Y, Zhu JK. Gene editing in plants: progress and challenges. *Natl Sci Rev.* 2019;6(3):421–37. doi: 10.1093/nsr/nwz005
  - 11 Ercolano MR, Wang K. Editorial: targeted genome editing for crop improvement. *Front Plant Sci.* 2023;14:1106996. doi: 10.3389/fpls.2023.1106996
  - 12 Movahedi A, Aghaei-Dargiri S, Li H, Zhuge Q, Sun W. CRISPR variants for gene editing in plants: biosafety risks and future directions. *Int J Mol Sci.* 2023;24(22):16241. doi: 10.3390/ijms242216241
  - 13 Abdallah NA, Hamwieh A, Radwan K, Fouad N, Prakash C. Genome editing techniques in plants: a comprehensive review and future prospects toward zero hunger. *GM Crops Food.* 2021;12(2):601–15. doi: 10.1080/21645698.2021.2021724
  - 14 Rasheed A, Gill RA, Hassan MU, Mahmood A, Qari S, Zaman QU, et al. A critical review: recent advancements in the use of CRISPR/Cas9 technology to enhance crops and alleviate global food crises. *Curr Issues Mol Biol.* 2021;43(3):1950–76. doi: 10.3390/cimb43030135
  - 15 Hüdig M, Laibach N, Hein AC. Genome editing in crop plant research—alignment of expectations and current developments. *Plants.* 2022;11(2):212. doi: 10.3390/plants11020212
  - 16 O'Neill EC, Kelly S. Engineering biosynthesis of high-value compounds in photosynthetic organisms. *Crit Rev Biotechnol.* 2017;37(6):779–802. doi: 10.1080/07388551.2016.1237467
  - 17 Ludwig-Müller J, Jahn L, Lippert A, Püschel J, Walter A. Improvement of hairy root cultures and plants by changing biosynthetic pathways leading to pharmaceutical metabolites: strategies and applications. *Biotechnol Adv.* 2014;32(6):1168–79. doi: 10.1016/j.biotechadv.2014.03.007
  - 18 Selma S, Ntelkis N, Nguyen TH, Goossens A. Engineering the plant metabolic system by exploiting metabolic regulation. *Plant J.* 2023;114(5):1149–63. doi: 10.1111/tpj.16157
  - 19 Rosenberg JN, Oyler GA, Wilkinson L, Betenbaugh MJ. A green light for engineered algae: redirecting metabolism to fuel a biotechnology revolution. *Curr Opin Biotechnol.* 2008;19(5):430–6. doi: 10.1016/j.copbio.2008.07.008
  - 20 Kishore GM, Shewmaker C. Biotechnology: enhancing human nutrition in developing and developed worlds. *Proc Natl Acad Sci U S A.* 1999;96(11):5968–72. doi: 10.1073/pnas.96.11.5968
  - 21 Gaikwad KB, Rani S, Kumar M, Gupta V, Babu PH, Bainsla NK, et al. Enhancing the nutritional quality of major food crops through conventional and genomics-assisted breeding. *Front Nutr.* 2020;7:533453. doi: 10.3389/fnut.2020.533453
  - 22 Liu Q, Yang F, Zhang J, Liu H, Rahman S, Islam S, et al. Application of CRISPR/Cas9 in crop quality improvement. *Int J Mol Sci.* 2021;22(8):4206. doi: 10.3390/ijms22084206
  - 23 Compant S, Samad A, Faist H, Sessitsch A. A review on the plant microbiome: ecology, functions, and emerging trends in microbial application. *J Adv Res.* 2019;19:29–37. doi: 10.1016/j.jare.2019.03.004
  - 24 Pandiyan K, Kushwaha P, Kashyap PL, Bagul SY, Karthikeyan N, Saxena AK. Phyllosphere microbiome: modern prospectus and application. In: *Microbiomes and plant health.* London: Charlotte Cockle; 2021. p. 345–66. doi: 10.1016/B978-0-12-819715-8.00012-4
  - 25 Egamberdieva D, Wirth SJ, Alqarawi AA, Abd Allah EF, Hashem A. Phytohormones and beneficial microbes: essential components for plants to balance stress and fitness. *Front Microbiol.* 2017;8:2104. doi: 10.3389/fmicb.2017.02104
  - 26 Upadhayay VK, Chitara MK, Mishra D, Jha MN, Jaiswal A, Kumari G, et al. Synergistic impact of nanomaterials and plant probiotics in agriculture: a tale of two-way strategy for long-term sustainability. *Front Microbiol.* 2023;14:1133968. doi: 10.3389/fmicb.2023.1133968
  - 27 Bargaz A, Lyamlouli K, Chtouki M, Zeroual Y, Dhiba D. Soil microbial resources for improving fertilizers efficiency in an integrated plant nutrient management system. *Front Microbiol.* 2018;9:1606. doi: 10.3389/fmicb.2018.01606
  - 28 Santoyo G, Gamalero E, Glick BR. Mycorrhizal-bacterial amelioration of plant abiotic and biotic stress. *Front Sustain Food Syst.* 2021;5. doi: 10.3389/fsufs.2021.672881
  - 29 Sargent D, Conaty WC, Tissue DT, Sharwood RE. Synthetic biology and opportunities within agricultural crops. *J Sustain Agric Environ.* 2022;1(2):89–107. doi: 10.1002/sae2.12014
  - 30 Yang JS, Reyna-Llorens I. Plant synthetic biology: exploring the frontiers of sustainable agriculture and fundamental plant biology. *J Exp Bot.* 2023;74(13):3787–90. doi: 10.1093/jxb/erad220
  - 31 Roell MS, Zurbruggen MD. The impact of synthetic biology for future agriculture and nutrition. *Curr Opin Biotechnol.* 2020;61:102–9. doi: 10.1016/j.copbio.2019.10.004
  - 32 Gooldd HD, Wright P, Hailstones D. Emerging opportunities for synthetic biology in agriculture. *Genes (Basel).* 2018;9(7):341. doi: 10.3390/genes9070341
  - 33 Soussi A, Zero E, Sacile R, Trincherio D, Fossa M. Smart sensors and smart data for precision agriculture: a review. *Sensors (Basel).* 2024;24(8):2647. doi: 10.3390/s24082647
  - 34 Monteiro A, Santos S, Gonçalves P. Precision agriculture for crop and livestock farming—brief review. *Animals.* 2021;11(8):2345. doi: 10.3390/ani11082345
  - 35 Toffolini Q, Jeuffroy MH. On-farm experimentation practices and associated farmer-researcher relationships: a systematic literature review. *Agron Sustain Dev.* 2022;42(6):114. doi: 10.1007/s13593-022-00845-w
  - 36 Brookes G, Barfoot P. Economic impact of GM crops. *GM Crops Food.* 2014;5(1):65–75. doi: 10.4161/gmcr.28098
  - 37 Kamau JN, Karitu PM. Consumer perceptions on the introduction of genetically modified food products in Kenya: a qualitative study in Nyeri and Meru counties. *J Agri Horti Res.* 2023;6(2):282–7.
  - 38 Trump B, Cummings C, Klasa K, Galaitis S, Linkov I. Governing biotechnology to provide safety and security and address ethical, legal, and social implications. *Front Genet.* 2023;13:1052371. doi: 10.3389/fgene.2022.1052371
  - 39 Wan Talaat WIA, Mohd Tahir N, Husain ML. Liability and redress of trans-boundary movement of genetically modified organisms and the biosafety law in Malaysia. *J Sustain Dev.* 2011;4(4). doi: 10.5539/jsd.v4n4p110
  - 40 Vemireddy LR. Food and nutrition security: biotechnology intervention. *Springer Sci Rev.* 2014;2(1–2):35–49. doi: 10.1007/s40362-014-0018-y
  - 41 Yang Y, Li J, Chen L. Editorial: advances in crop breeding for abiotic stress tolerance. *Front Genet.* 2024;15:1521062. doi: 10.3389/fgene.2024.1521062
  - 42 Ma W, Rahut DB. Climate-smart agriculture: adoption, impacts, and implications for sustainable development. *Mitig Adapt Strateg Glob Chang.* 2024;29(5):44. doi: 10.1007/s11027-024-10139-z
  - 43 Zhao J, Liu D, Huang R. A review of climate-smart agriculture: recent advancements, challenges, and future directions. *Sustainability.* 2023;15(4):3404. doi: 10.3390/su15043404
  - 44 Kombat R, Sarfatti P, Fatunbi OA. A review of climate-smart agriculture technology adoption by farming households in Sub-Saharan Africa. *Sustainability.* 2021;13(21):12130. doi: 10.3390/su132112130
  - 45 Rebek EJ, Frank SD, Royer TA, Bográn CE. Alternatives to chemical control of insect pests. In: *Insecticides - basic and other applications.* London: InTech; 2012. doi: 10.5772/29887
  - 46 Deguine JP, Rousse P, Atiama-Nurbel T. Agroecological crop protection: concepts and a case study from reunion. In: *Integrated pest management and pest control - current and future tactics.* London: InTech; 2012. doi: 10.5772/32266
  - 47 Way M, van EH. Integrated pest management in practice — pathways towards successful application. *Crop Protection.* 2000;19(2):81–103. doi: 10.1016/S0261-2194(99)00098-8
  - 48 Ribeiro AV, Holle SG, Hutchison WD, Koch RL. Lethal and sublethal effects of conventional and organic insecticides on the parasitoid *trissolcus japonicus*, a biological control agent for *Halyomorpha halys*. *Front Insect Sci.* 2021;1. doi: 10.3389/finsc.2021.685755

## Appendix 1.

Section	Item #	Checklist Item	Location in Document	
Title	1	Identify the report as a systematic review, meta-analysis, or both.	Title of the document indicates a review (Pg. No. 1)	
Abstract	2	Report the review's main objective(s).	Described in the Introduction (Pg. No. 1)	
		State the eligibility criteria.	Mentioned in the Methodology. (Pg. Nos. 1–2)	
		Indicate the main information sources.	PubMed, Scopus, and Google Scholar are mentioned in the Methodology. (Pg. Nos. 1–2)	
		Present key results.	Present in the Abstract and in the Conclusion (Pg. No. 5)	
Introduction	3	Provide the main conclusions.	Pg. No. 5	
		Describe the rationale for the review in the context of existing knowledge.	The Introduction provides background on crop improvement and the need for biotechnology. (Pg. No. 1)	
Methods	4	State specific objectives for the review, including the research question.	Objectives are outlined in the Introduction and Methodology, focusing on engineered crops, optimized processes, etc. (Pg. Nos. 1–2)	
	5	Specify the study characteristics (e.g., PICO).	Engineered crops (Pg. No. 1–2)	
	6	Indicate the eligibility criteria.	Eligibility criteria are mentioned in the Methodology. (Pg. No. 1–2)	
	7	Describe all information sources (databases, registers, websites, organizations, reference lists).	PubMed, Scopus, and Google Scholar are specified in the Methodology. (Pg. No. 1–2)	
	8	Present the search strategies used.	Keyword searches are mentioned in the Methodology. (Pg. No. 1–2)	
	9	Describe the selection process.	The Methodology mentions the assimilation, scrutinization, and synthesis of publications. (Pg. Nos. 1–2)	
	10	Describe the data collection process.	Data was collected from peer-reviewed publications (Methodology). (Pg. No. 2)	
	11	Describe the data synthesis methods.	Data synthesis is described in the Methodology. (Pg. No. 2)	
	Results	12	For each study, present the characteristics.	Characteristics of included studies are generally discussed in the context of each topic (e.g., transgenic approaches, gene editing). (Pg. Nos. 2, 3, and 4)
		13	Present the main results of the review.	Main results are presented throughout the document, discussing advancements in each area.
		14	Present assessments of risk of bias.	N/A
15		Present the results of any synthesis performed.	Synthesis is presented in the discussion of each topic. (Pg. Nos. 2–5)	
Discussion	16	Discuss the main limitations of the review process.	Limitation is mentioned in the discussion of each topic.	
	17	Provide a general interpretation of the results.	The entire Conclusion interprets the results in the context of crop improvement. (Pg. No. 5)	
Other	18	Report the review protocol registration number.	Not applicable	
	19	Indicate sources of funding and other support.	Not applicable	