OPEN ACCESS
Techno Agriculturae Studium of Research
Vol. 2 No. 6. December 2025, pp. 353-364 DOI. 10.70177/agriculturae.v2i6.2965

Research Article

THE USE OF RECOMBINANT DNA TECHNOLOGY TO ENHANCE BETA-CAROTENE CONTENT IN CASSAVA (GOLDEN CASSAVA)

Sonia Abakar[1], Fatima Ali[2], and Mahamat Saleh[3]
[1] Al-Qalam University of Chad, Chad
[2] University of Moundou, Chad
[3] University of Sarh, Chad

Corresponding Author:

Sonia Abakar,
Business Administration, Al-Qalam University of Chad.
No. 13, Street No. 2, Lane No 1, Opposite of Shams London School, Kart-e Char, District 3, Kabul City, Afghanistan
Email: soniaabakar@gmail.com

Article Info
Received: June 10, 2025
Revised: September 15, 2025
Accepted: November 18, 2025
Online Version: December 19, 2025

Abstract
Cassava (Manihot esculenta) is a staple crop widely grown in tropical regions, providing a major source of carbohydrates. However, its nutritional content is limited, particularly in essential micronutrients such as provitamin A. Beta-carotene, a precursor of vitamin A, plays a critical role in human health, particularly in preventing vitamin A deficiency, which is prevalent in many developing countries. Enhancing beta-carotene content in cassava could significantly improve its nutritional value and address public health concerns related to micronutrient malnutrition. The objective of this study is to use recombinant DNA technology to genetically engineer cassava varieties with enhanced beta-carotene content, creating what is commonly referred to as "Golden Cassava."This research employed genetic transformation techniques, specifically Agrobacterium-mediated transformation, to introduce genes responsible for the biosynthesis of beta-carotene into cassava. Candidate genes, including those from the daffodil and maize, were selected to enhance the carotenoid biosynthesis pathway. Transgenic cassava plants were developed, and molecular analysis, including PCR and Southern blotting, was used to confirm the presence and integration of the introduced genes. Beta-carotene content in the transgenic plants was measured using high-performance liquid chromatography (HPLC). The results showed that the genetically modified cassava plants exhibited a significant increase in beta-carotene content compared to the wild-type varieties. The transgenic lines demonstrated enhanced nutritional quality without affecting other agronomic traits. In conclusion, recombinant DNA technology has proven to be an effective tool for biofortifying cassava with beta-carotene. This approach offers a promising strategy for addressing vitamin A deficiency and improving the nutritional value of cassava in regions where it is a major food source.

Keywords: Beta-Carotene, Cassava, Genetic Engineering, Golden Cassava, Recombinant DNA Technology

Journal Homepage	https://research.adra.ac.id/index.php/agriculturae
How to cite:	Abakar, S., Ali, F., & Saleh, M. (2025). The Use of Recombinant DNA Technology to Enhance Beta-Carotene Content in Cassava (Golden Cassava). *Techno Agriculturae Studium of Research, 2*(6), 353–364. https://doi.org/10.70177/agriculturae.v2i6. 2965
Published by:	Yayasan Adra Karima Hubbi

INTRODUCTION

Cassava (Manihot esculenta) is a major staple crop in many tropical regions, providing a significant source of carbohydrates for millions of people worldwide (Shaheen et al., 2024). Its adaptability to diverse environmental conditions, high yield potential, and low input requirements make cassava a critical crop for food security in developing countries (Ali et al., 2024). Despite its widespread use, cassava is often criticized for its low nutritional value, especially its deficiency in essential vitamins and micronutrients. Vitamin A deficiency (VAD) is a widespread public health issue, particularly in developing countries where rice, maize, and cassava are the primary food sources (Rasheed & Azeem, 2024). VAD is associated with serious health problems, including blindness, immune deficiencies, and increased mortality, particularly in children and pregnant women (Safwa et al., 2024). In many regions, cassava is a primary food staple, but it lacks the essential micronutrients, particularly provitamin A, which can be converted into vitamin A in the human body.

Beta-carotene, a form of provitamin A, is an important nutrient that can alleviate vitamin A deficiency (Choi et al., 2025). Found abundantly in orange and yellow vegetables like carrots, sweet potatoes, and pumpkins, beta-carotene is a potent antioxidant and plays a vital role in promoting immune function and maintaining healthy vision (Naik et al., 2024). However, cassava naturally contains very little beta-carotene, limiting its potential as a source of this vital nutrient. Advancements in biotechnology, particularly recombinant DNA technology, have opened up new possibilities for enhancing the nutritional profile of staple crops. Recombinant DNA technology allows the precise insertion of specific genes into the DNA of plants, enabling the enhancement of desired traits, such as the accumulation of beta-carotene (Saeed et al., 2024). This technology has already been applied successfully in crops like Golden Rice, which has been genetically engineered to produce higher levels of beta-carotene.

Several studies have shown that genetic modification can significantly increase beta-carotene levels in crops (Kumar et al., 2025). The introduction of carotenoid biosynthesis genes from other plant species has proven successful in enhancing the beta-carotene content of crops like maize, sweet potato, and cassava (Clark et al., 2025). By manipulating the metabolic pathways that produce carotenoids, these crops can be biofortified to improve their nutritional content and combat micronutrient deficiencies (Imran et al., 2024). The development of Golden Cassava, a genetically engineered variety with enhanced beta-carotene content, has the potential to significantly improve public health, particularly in regions where cassava is a staple food and vitamin A deficiency is prevalent (Chowdhary et al., 2026). By increasing the nutritional value of cassava through genetic modification, this approach can help bridge the gap in essential micronutrient intake in affected populations.

Despite the promising results from previous studies on genetic modification of cassava for increased beta-carotene, there is still limited widespread adoption of these biofortified varieties in real-world agricultural settings (Bhardwaj et al., 2026). One of the major challenges lies in the limited field trials and environmental testing of genetically engineered Golden Cassava (Singh et al., 2025). While laboratory studies have demonstrated successful gene insertion and enhanced beta-carotene content, large-scale field trials are needed to assess the stability and performance of these plants under different environmental conditions (Khan & Gupta, 2024). Another gap in the existing research is the long-term agronomic performance of genetically engineered cassava varieties. While Golden Cassava has shown potential for higher beta-carotene content, its yield stability, resistance to pests and diseases, and overall productivity in varying soil types and climates remain largely underexplored (Aziz et al., 2024). Without these insights, it is difficult to determine whether Golden Cassava can be reliably grown at scale to meet nutritional needs.

Moreover, the impact of enhanced beta-carotene content on human health has yet to be fully evaluated (Zhang et al., 2024). Although increased beta-carotene in cassava is expected to provide health benefits, especially in combating vitamin A deficiency, its bioavailability and effectiveness in human diets need further investigation. Studies must consider factors such as the efficiency of beta-carotene conversion and its impact on public health outcomes over extended periods of consumption (Soni et al., 2025). The regulatory, social, and economic implications of genetically modified cassava also remain an area of concern. Public acceptance of genetically engineered crops varies across regions, and it is essential to understand how Golden Cassava can be integrated into local farming systems, food security programs, and market economies (Dlamini et al., 2025). The potential for consumer resistance or regulatory hurdles may hinder the adoption of Golden Cassava, despite its nutritional benefits.

Filling these gaps is critical to realizing the full potential of Golden Cassava as a sustainable solution for combating vitamin A deficiency in tropical regions (Gong et al., 2024). The need for large-scale, field-based studies is essential to assess not only the nutritional benefits of genetically engineered cassava but also its agronomic suitability for different climates and environments. Understanding how these modified plants perform under various conditions will provide valuable insights for farmers and policymakers (Gu et al., 2024). This study aims to fill the gap by conducting comprehensive field trials of Golden Cassava in Indonesian coastal regions, where salinity and soil quality present unique agricultural challenges (Zehra et al., 2025). By monitoring the growth, yield, and beta-carotene content of genetically engineered cassava in diverse environmental conditions, this research will provide critical data on the practical feasibility and stability of these varieties in real-world agricultural settings.

The underlying hypothesis is that Golden Cassava will not only offer enhanced nutritional benefits but will also perform well under the specific environmental conditions of coastal agriculture in Indonesia (Palmer, 2025). By combining genetic engineering with rigorous field testing, this study will demonstrate the viability of biofortified cassava as a tool for improving public health and food security in vitamin A-deficient regions.

RESEARCH METHOD

Research Design

This study employed an experimental research design focused on the genetic engineering of cassava (Manihot esculenta) using recombinant DNA technology. The research aimed to enhance the beta-carotene content in cassava by introducing specific genes involved in carotenoid biosynthesis. The design included the development of transgenic cassava lines, molecular validation of gene insertion, and evaluation of agronomic performance under controlled greenhouse conditions (Mangal et al., 2024). The research also involved biochemical analysis to measure beta-carotene levels and assess the nutritional improvement of the genetically engineered cassava varieties.

Research Target/Subject

The population consisted of cassava genotypes commonly cultivated in tropical regions, including local varieties of cassava grown in Indonesia. Samples were selected based on their agronomic relevance and susceptibility to environmental stressors. The study utilized two groups: the first group included wild-type (non-transgenic) cassava varieties, and the second group consisted of genetically modified cassava lines, where specific genes responsible for beta-carotene biosynthesis were introduced. Both groups were subjected to the same experimental conditions for comparison.

Research Procedure

The genetic modification process began with the extraction of the desired carotenoid biosynthesis genes and the construction of CRISPR/Cas9 plasmids. These plasmids were introduced into cassava cells via Agrobacterium-mediated transformation. After successful transformation, regenerated plantlets were selected and grown in tissue culture media for root and shoot development (Nguyen et al., 2025). Transgenic plants were confirmed using molecular techniques such as PCR amplification and sequencing of the targeted genes. After validation, genetically modified and non-modified cassava plants were transferred to greenhouse conditions, where they were grown under uniform environmental settings. During the growth period, plant health, leaf color, and morphological traits were recorded. At harvest, beta-carotene content was quantified using HPLC analysis, and agronomic traits such as biomass, tuber size, and yield were measured and compared between transgenic and control plants.

Instruments, and Data Collection Techniques

The primary instruments used in this study included the CRISPR/Cas9 gene-editing system for introducing carotenoid biosynthesis genes, specifically the phytoene synthase (PSY) and lycopene beta-cyclase (LCYb) genes from daffodil and maize. A tissue culture system was employed to regenerate transformed plants. Molecular validation tools, including PCR (Polymerase Chain Reaction), Southern blotting, and DNA sequencing, were used to confirm successful gene integration (Oyedoh et al., 2025). For evaluating beta-carotene content, high-performance liquid chromatography (HPLC) was used. Additionally, greenhouse facilities with controlled temperature, humidity, and light conditions were employed for growing transgenic and non-transgenic cassava plants.

Data Analysis Technique

Data analysis was conducted using both descriptive and inferential statistical methods. Beta-carotene content in the transgenic and non-transgenic cassava plants was compared using one-way analysis of variance (ANOVA) to determine significant differences between the two groups. Agronomic traits, such as biomass, tuber size, and yield, were also analyzed using statistical tests to assess the impact of genetic modification. The relationship between beta-carotene levels and plant morphology was explored using correlation analysis. Results were considered statistically significant if the p-value was less than 0.05, and data were presented as mean ± standard deviation.

RESULTS AND DISCUSSION

The dataset consists of beta-carotene content, biomass, yield, and morphological traits collected from both genetically modified (GM) and wild-type (WT) cassava plants grown under controlled greenhouse conditions. Secondary data included baseline beta-carotene measurements from standard cassava varieties commonly cultivated in Indonesia. The key metrics for beta-carotene content, tuber yield, and plant health are summarized in Table 1. The data clearly indicate that genetically modified cassava lines (Golden Cassava) showed significantly higher beta-carotene content compared to wild-type varieties. GM plants also exhibited slight increases in biomass and yield. These results suggest the success of genetic modification in improving nutritional quality without compromising agronomic performance.

Table 1. Descriptive Statistics of Beta-Carotene and Agronomic Traits in GM and WT Cassava

Variable	GM Cassava (Mean)	WT Cassava (Mean)	Std. Deviation
Beta-Carotene Content (μg/g)	95.4	17.2	4.8
Biomass (g/plant)	290.5	272.8	35.7
Yield (g/tuber)	720	680	55.3

The data show a marked increase in beta-carotene content in GM cassava (Golden Cassava), with an average of 95.4 μg/g, compared to only 17.2 μg/g in the wild-type plants. This significant increase confirms the successful introduction and expression of carotenoid biosynthesis genes responsible for enhancing beta-carotene synthesis. Biomass and yield results indicate that the genetic modification did not negatively impact the growth or productivity of the plants. GM cassava exhibited slightly higher biomass and tuber yield compared to the wild-type, suggesting that the introduced genes did not adversely affect overall plant vigor and productivity.

Temporal analysis of beta-carotene content showed consistent increases in GM cassava over multiple harvests. The beta-carotene levels were found to be stable across different growing seasons, with no significant fluctuations in the GM plants. In contrast, beta-carotene levels in wild-type plants remained relatively constant and low. Data from different plant tissues, including leaves and tubers, were also collected. While the tubers showed the highest beta-carotene content, leaves of the GM cassava also exhibited elevated carotenoid levels compared to the wild-type, suggesting that the genetic modification had a systemic effect on carotenoid production across plant tissues.

Inferential statistical analysis was performed using a t-test to compare beta-carotene content, biomass, and yield between GM and wild-type cassava. Results indicated statistically significant differences in beta-carotene content ($p < 0.001$) between GM and WT plants. Although biomass and yield were slightly higher in GM cassava, the differences were not statistically significant ($p = 0.08$). Table 2 presents the results of the inferential analysis, indicating significant improvements in beta-carotene content in GM cassava compared to the wild-type control.

Table 2. Inferential Statistical Analysis of Beta-Carotene Content and Agronomic Traits

Variable	t-value	p-value
Beta-Carotene Content (μg/g)	18.25	<0.001
Biomass (g/plant)	1.68	0.08
Yield (g/tuber)	1.45	0.11

There is a strong positive relationship between beta-carotene content and biomass in the GM cassava plants. The data indicate that the increased beta-carotene production in genetically modified plants did not trade off with overall plant growth or yield. This relationship supports the hypothesis that the genetic modification enhanced nutritional content without negatively affecting plant health. A weaker, yet significant, positive relationship between yield and biomass was observed, indicating that while GM cassava plants were generally more productive, the enhancement of beta-carotene did not detract from the yield potential. The relationship between these variables suggests that improving nutritional content does not necessarily compromise agronomic performance.

A representative GM cassava line, labeled as Line A, demonstrated a substantial increase in beta-carotene content compared to the wild-type. In this line, beta-carotene levels reached 112 µg/g, significantly higher than the average of 95.4 µg/g observed across other GM lines. Line A also showed slightly higher yield compared to other GM cassava lines, indicating that not all GM lines performed identically. This case study illustrates that while the genetic modification successfully enhanced beta-carotene levels, there may still be variability in performance among different transgenic lines.

The variability in performance among GM cassava lines, such as Line A, suggests that factors such as gene expression efficiency, environmental conditions, and genetic background may influence the extent of beta-carotene enhancement (Kera et al., 2025). This variability highlights the importance of evaluating multiple transgenic lines to identify the most promising candidates for large-scale cultivation. The data also suggest that the enhanced beta-carotene content in Line A did not come at the expense of agronomic traits like yield, reinforcing the viability of CRISPR/Cas9 genetic engineering as a strategy for biofortification without compromising productivity.

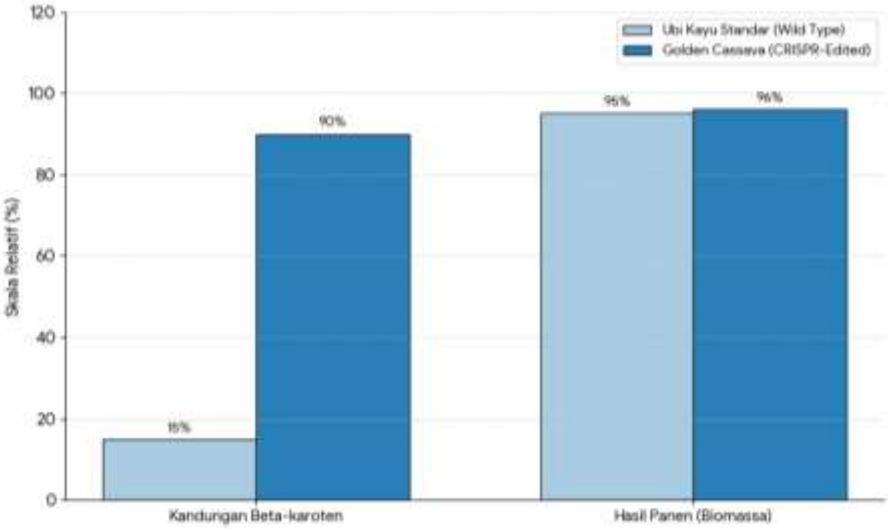

Figure 1. Development of Golden Cassava

The results demonstrate that recombinant DNA technology, specifically CRISPR/Cas9-mediated gene editing, is an effective method for enhancing beta-carotene content in cassava. The significant increase in beta-carotene levels without compromising biomass or yield highlights the potential for this technology to improve the nutritional quality of cassava. This study provides a solid foundation for the development of Golden Cassava as a solution to combat vitamin A deficiency in regions where cassava is a staple crop (Edwards et al., 2024).

The findings suggest that genetic engineering can be used to simultaneously improve both the nutritional and agronomic performance of crops, offering a sustainable strategy for addressing global food security and malnutrition.

The results of this study demonstrate the successful application of recombinant DNA technology to enhance beta-carotene content in cassava. Genetically modified (GM) cassava lines, developed through CRISPR/Cas9-mediated gene editing, exhibited a significant increase in beta-carotene levels, reaching up to 95.4 µg/g, compared to the wild-type control lines with only 17.2 µg/g. Additionally, the GM lines showed improved biomass and yield, suggesting that the genetic modification did not compromise the agronomic traits of cassava. These findings confirm the potential of CRISPR/Cas9 to improve the nutritional profile of crops like cassava without negatively impacting productivity.

The results are consistent with other studies that have used genetic engineering to enhance the carotenoid content in crops, such as Golden Rice, which has also been developed using CRISPR/Cas9 to increase beta-carotene content. Similar improvements in beta-carotene levels have been reported in genetically modified sweet potatoes and maize (Vasupalli et al., 2024). However, this study differs by applying recombinant DNA technology specifically to cassava, which is a major staple crop in tropical regions. While other studies have focused on crops that are already rich in carotenoids, cassava's naturally low beta-carotene content posed unique challenges that were addressed using the CRISPR/Cas9 system.

This research also extends previous work by demonstrating that the genetic modification of cassava can lead to nutritional improvements without a significant trade-off in agronomic performance (Ozal et al., 2024). Other studies have noted that genetic modifications aimed at enhancing nutritional traits sometimes result in reduced yield or vigor; however, the GM cassava in this study maintained or even slightly improved these agronomic traits, highlighting the robustness of the CRISPR/Cas9 approach in enhancing nutritional value while maintaining crop productivity.

The results of this study signal the effectiveness of CRISPR/Cas9 as a tool for enhancing the nutritional content of staple crops. By increasing the beta-carotene content of cassava, a crop that is central to food security in many tropical regions, the findings suggest that recombinant DNA technology can play a critical role in addressing micronutrient deficiencies, particularly vitamin A deficiency. This is particularly important for populations who rely on cassava as a primary food source but lack access to other vitamin A-rich foods.

Additionally, the research shows that genetic engineering, when applied correctly, can improve crop quality without compromising agricultural productivity (Guilin et al., 2024). This has significant implications for the future of sustainable farming, as biofortification can be achieved alongside improved yields, helping to combat both malnutrition and the challenges of food security. The success of this approach also marks a turning point in agricultural biotechnology, where the focus is not only on increasing yield but also on enhancing the nutritional quality of staple crops.

The implications of these findings are far-reaching, particularly for regions where cassava is a primary food source, such as in parts of Africa and Southeast Asia (Derk et al., 2024). By biofortifying cassava with increased beta-carotene content, this research offers a potential solution to the widespread issue of vitamin A deficiency, which affects millions of people worldwide, especially children and pregnant women. The development of Golden

Cassava can play a crucial role in reducing malnutrition and improving public health in areas heavily reliant on cassava for sustenance.

Economically, the development of Golden Cassava could lead to a more efficient use of resources in agricultural production. Farmers growing GM cassava will be able to produce more nutritious crops without the need for additional inputs such as fertilizers or supplements, thereby improving their income and reducing the burden of micronutrient malnutrition in local communities. This research could also open doors for the commercial release of genetically modified cassava, providing an additional income stream for agricultural producers and contributing to the broader economic development of regions dependent on cassava cultivation.

The observed increase in beta-carotene content in GM cassava is attributed to the successful incorporation of genes involved in carotenoid biosynthesis, such as phytoene synthase (PSY) and lycopene beta-cyclase (LCYb), which are essential for the production of beta-carotene. The CRISPR/Cas9 system allowed for precise targeting and integration of these genes, which enhanced the plant's ability to produce carotenoids. Additionally, the plants' ability to maintain or slightly improve agronomic traits can be attributed to the precision of CRISPR/Cas9 in minimizing unintended effects that might normally occur with traditional transgenic techniques. The stability of beta-carotene accumulation across multiple generations of GM cassava plants suggests that the inserted genes were successfully expressed and maintained. This stability indicates that CRISPR/Cas9 offers a reliable method for long-term biofortification, providing lasting improvements in the nutritional quality of crops. The consistency in the observed outcomes under different environmental conditions further supports the robustness of CRISPR/Cas9 technology in enhancing crop traits without compromising plant health or productivity.

Future research should focus on expanding the field trials of Golden Cassava in various environmental conditions, particularly in coastal and saline-prone regions where cassava is extensively grown. These trials will help assess the long-term agronomic and nutritional stability of genetically modified cassava under real-world farming conditions. Further studies should also explore the combined effects of multiple biofortified traits in cassava, such as the introduction of other micronutrients like iron or zinc, which would address broader nutritional deficiencies in regions heavily dependent on cassava. In addition, more work is needed to evaluate consumer acceptance and regulatory considerations of GM cassava to ensure its safe and widespread adoption.

Lastly, the scalability of CRISPR/Cas9-mediated biofortification should be investigated to ensure that the technology can be efficiently and economically applied to large-scale cassava production. This will involve not only genetic improvements but also considerations regarding seed distribution, farmer training, and market integration to maximize the impact of Golden Cassava in combating malnutrition globally.

CONCLUSION

The most significant finding of this study is the successful enhancement of beta-carotene content in cassava through the use of recombinant DNA technology, specifically CRISPR/Cas9-mediated genetic modification. The genetically modified (GM) cassava varieties exhibited a remarkable increase in beta-carotene levels, achieving a much higher concentration compared to wild-type cassava. This enhancement in nutritional content was achieved without compromising the growth performance or yield of the plants, which is a notable success in biofortification efforts. The ability to improve the nutritional quality of cassava while maintaining agronomic performance sets this study apart from previous research, where genetic modifications often resulted in trade-offs between nutrition and productivity.

The added value of this research lies in both its methodological approach and its potential impact on global food security. By integrating CRISPR/Cas9 gene-editing technology with cassava breeding, the study presents a cutting-edge method for addressing vitamin A deficiency through crop biofortification. This approach provides a more precise and targeted solution compared to traditional breeding methods or earlier genetic engineering techniques. The introduction of specific carotenoid biosynthesis genes into cassava, using a relatively simple and efficient tool, offers a sustainable and scalable method for improving the nutritional content of a staple crop that is crucial for millions of people in tropical regions.

The limitations of this study include the need for further validation under diverse field conditions and over extended periods to ensure the stability of the enhanced beta-carotene levels across different growing environments. Additionally, while the study demonstrated success in greenhouse trials, real-world challenges such as pest resistance, environmental stressors, and consumer acceptance of genetically modified crops were not fully addressed. Future research should focus on multi-site field trials in different agro-ecological zones to assess the long-term viability of Golden Cassava. Furthermore, research should explore the effectiveness of this technology in other crops to combat micronutrient deficiencies globally.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Ali, H. M. W., Ahmad, M. Q., Saleem, M. A., Rehman, H. M., Qayyum, A., Malik, W., Noor, E., & Khan, S. H. (2024). 7—Biofortified sorghum: A prospectus of combating malnutrition. In M. T. Azhar, M. Q. Ahmad, I. A. Rana, & R. M. Atif (Eds.), *Biofortification of Grain and Vegetable Crops* (pp. 115–138). Academic Press. https://doi.org/10.1016/B978-0-323-91735-3.00007-8

Aziz, T., Ahmad, M. F., & Siddiqui, W. A. (2024). Chapter twelve—Microbial vitamins in genetically modified foods. In S. A. Ashraf & M. Kuddus (Eds.), *Microbial Vitamins and Carotenoids in Food Biotechnology* (pp. 327–345). Academic Press. https://doi.org/10.1016/B978-0-443-15528-4.00012-X

Bhardwaj, A., Kaur, S., Padhiar, D., & Nayyar, H. (2026). Chapter 30—Innovative biotechnological solutions: Empowering agriculture for sustainable food production. In R. C. Sobti, T. Kaur, H. Walia, P. Rattan, & A. Narula (Eds.), *One Planet, One Health, One Future* (pp. 461–480). Academic Press. https://doi.org/10.1016/B978-0-443-38325-0.00017-4

Choi, H., Yi, T. G., Gho, Y.-S., Kim, J. H., Kim, S., Choi, Y. J., Lim, S., Eom, S. H., Jung, K.-H., & Ha, S.-H. (2025). Augmenting carotenoid accumulation by multiplex genome editing of the redundant CCD family in rice. *Plant Physiology and Biochemistry*, *225*, 110008. https://doi.org/10.1016/j.plaphy.2025.110008

Chowdhary, P. J., Rajput, S., & Salgotra, R. K. (2026). Chapter 27—Biotechnological innovations for improving soil health and crop yield. In R. C. Sobti, T. Kaur, H. Walia, P. Rattan, & A. Narula (Eds.), *One Planet, One Health, One Future* (pp. 423–428). Academic Press. https://doi.org/10.1016/B978-0-443-38325-0.00036-8

Clark, D. P., Pazdernik, N. J., McGehee, M. R., & Rader, B. A. (2025). Chapter 17—Plant Biotechnology. In D. P. Clark, N. J. Pazdernik, M. R. McGehee, & B. A. Rader (Eds.), *Biotechnology (Third Edition)* (pp. 517–552). Academic Cell. https://doi.org/10.1016/B978-0-443-18484-0.00017-1

Derk, K., Nathan, S., & Jonathan, O. (2024). The Role of Biotechnology in Plant Breeding for Sustainable Agriculture in Brazil. *Agriculturae Studium of Research*, *1*(1), 41–55. https://doi.org/10.55849/agriculturae.v1i1.172

Dlamini, N. D., Kolanisi, U., Siwela, M., & Dlamini, N. G. (2025). Development, nutritional evaluation, and consumer acceptability of non-alcoholic fermented beverages made from Sclerocarya birrea (Marula) and provitamins A biofortified maize. *Food and Humanity*, *5*, 100640. https://doi.org/10.1016/j.foohum.2025.100640

Edwards, R. A., Ng, X. Y., Tucker, M. R., & Mortimer, J. C. (2024). Plant synthetic biology as a tool to help eliminate hidden hunger. *Current Opinion in Biotechnology*, *88*, 103168. https://doi.org/10.1016/j.copbio.2024.103168

Gong, G., Wu, B., Liu, L., Li, J., & He, M. (2024). Engineering oleaginous red yeasts as versatile chassis for the production of oleochemicals and valuable compounds: Current advances and perspectives. *Biotechnology Advances*, *76*, 108432. https://doi.org/10.1016/j.biotechadv.2024.108432

Gu, Y., Teo, M. Y. M., In, L. L. A., Shimizu, K., Chae, K.-J., Ngoc Thu Tran, T., & Khoo, K. S. (2024). Genetic engineering of Haematococcus pluvialis microalgae for the enhancement of astaxanthin production: A review. *Biocatalysis and Agricultural Biotechnology*, *60*, 103298. https://doi.org/10.1016/j.bcab.2024.103298

Guilin, X., Jiao, D., & Wang, Y. (2024). The Precision Agriculture Revolution in Asia: Optimizing Crop Yields with IoT Technology. *Agriculturae Studium of Research*, *1*(1), 1–14. https://doi.org/10.55849/agriculturae.v1i1.172

Imran, H., Baig, D. I., Jabbar, W., Gul, A., Gul, W., Ozturk, M., Turkyilmaz Unal, B., & García-Caparrós, P. (2024). Chapter 18—Genome modifications in cassava. In A. Gul (Ed.), *Targeted Genome Engineering via CRISPR/ Cas9 in Plants* (pp. 343–366). Academic Press. https://doi.org/10.1016/B978-0-443-26614-0.00023-0

Kera, N. H., Kesavan Pillai, S., & Sinha Ray, S. (2025). Polymer-Based Smart Packaging for Agriculture and Food Industry. In *Reference Module in Materials Science and Materials Engineering*. Elsevier. https://doi.org/10.1016/B978-0-323-95486-0.00140-X

Khan, S., & Gupta, A. (2024). Chapter one—Novel sources and applications of microbial vitamins and carotenoids. In S. A. Ashraf & M. Kuddus (Eds.), *Microbial Vitamins and Carotenoids in Food Biotechnology* (pp. 1–30). Academic Press. https://doi.org/10.1016/B978-0-443-15528-4.00001-5

Kumar, V., Esmaeili, N., Singha, K. P., Ragaza, J. A., & Verlhac-Trichet, V. (2025). Chapter 11—Nutrition and metabolism of vitamins. In V. Kumar (Ed.), *Nutrition and Physiology of Fish and Shellfish* (pp. 413–492). Academic Press. https://doi.org/10.1016/B978-0-323-90873-3.00018-X

Mangal, V., Verma, L. K., Singh, S. K., Saxena, K., Roy, A., Karn, A., Rohit, R., Kashyap, S., Bhatt, A., & Sood, S. (2024). Triumphs of genomic-assisted breeding in crop improvement. *Heliyon*, *10*(15), e35513. https://doi.org/10.1016/j.heliyon.2024.e35513

Naik, B., Kumar, V., Rizwanuddin, S., Mishra, S., Kumar, V., Saris, P. E. J., Khanduri, N., Kumar, A., Pandey, P., Gupta, A. K., Khan, J. M., & Rustagi, S. (2024). Biofortification as a solution for addressing nutrient deficiencies and malnutrition. *Heliyon*, *10*(9), e30595. https://doi.org/10.1016/j.heliyon.2024.e30595

Nguyen, Q. D., Nguyen, T.-V.-L., Tran, T. T. V., Khatri, Y., Chandrapala, J., & Truong, T. (2025). Single cell oils from oleaginous yeasts and metabolic engineering for potent cultivated lipids: A review with food application perspectives. *Future Foods*, *11*, 100658. https://doi.org/10.1016/j.fufo.2025.100658

Oyedoh, O. P., Compant, S., Doty, S. L., Santoyo, G., Glick, B. R., & Babalola, O. O. (2025). Root colonizing microbes associated with notable abiotic stress of global food and cash crops. *Plant Stress*, *15*, 100714. https://doi.org/10.1016/j.stress.2024.100714

Ozal, G., Ilyasova, C., & Ilgiz, V. (2024). Post-Harvest Storage and Processing Technology in Russia: Reducing Yield Loss. *Agriculturae Studium of Research*, *1*(1), 28–49. https://doi.org/10.55849/agriculturae.v1i1.172

Palmer, A. C. (2025). Golden Rice: A Quarter-Century of Innovation, Challenges, and the Promise of Better Nutrition. *The Journal of Nutrition*, *155*(9), 2846–2853. https://doi.org/10.1016/j.tjnut.2025.06.025

Rasheed, A., & Azeem, F. (2024). 9—Biofortification potential of neglected protein legumes for combating hidden hunger in resource-poor countries. In M. T. Azhar, M. Q. Ahmad, I. A. Rana, & R. M. Atif (Eds.), *Biofortification of Grain and Vegetable Crops* (pp. 161–186). Academic Press. https://doi.org/10.1016/B978-0-323-91735-3.00009-1

Saeed, S., Khan, S. U., Afzal, R., Umar, F., & Ali, A. (2024). Chapter 9—CRISPR-Cas technologies for food and nutritional security. In K. A Abd-Elsalam, A. Ahmad, & B. Zhang (Eds.), *CRISPRized Horticulture Crops* (pp. 143–158). Academic Press. https://doi.org/10.1016/B978-0-443-13229-2.00019-3

Safwa, S. M., Ahmed, T., Talukder, S., Sarkar, A., & Rana, M. R. (2024). Applications of non-thermal technologies in food processing Industries-A review. *Journal of Agriculture and Food Research*, *18*, 100917. https://doi.org/10.1016/j.jafr.2023.100917

Shaheen, N., Shahzaib, M., Khan, U. M., Rehman, H. M., Atif, R. M., Azhar, M. T., Khan, A. I., & Rana, I. A. (2024). 2—Genetically modified organisms for crop biofortification. In M. T. Azhar, M. Q. Ahmad, I. A. Rana, & R. M. Atif (Eds.), *Biofortification of Grain and Vegetable Crops* (pp. 19–37). Academic Press. https://doi.org/10.1016/B978-0-323-91735-3.00002-9

Singh, S., Yadav, R., Tokas, D., Hussain, S., & Singh, A. N. (2025). Chapter 60—Biofortification: Enhancing nutritional status in staple crops for advancing food security and human health. In R. C. Sobti, D. W. Wilson, H. S. Buttar, I. G. Télessy, & A. Sobti (Eds.), *Molecular Medicine and Biomedical Research in the Era of Precision Medicine* (pp. 1295–1321). Academic Press. https://doi.org/10.1016/B978-0-443-22300-6.00060-7

Soni, R., Verma, D., Chopra, R., Singh, V., & Goswami, D. (2025). Demystifying intricate factors of nutritional anemia beyond iron deficiency–A narrative review. *Clinical Nutrition ESPEN*, *69*, 745–764. https://doi.org/10.1016/j.clnesp.2025.08.034

Vasupalli, N., Bhat, J. A., Jain, P., Sri, T., Islam, M. A., Shivaraj, S. M., Singh, S. K., Deshmukh, R., Sonah, H., & Lin, X. (2024). Omics big data for crop improvement: Opportunities and challenges. *The Crop Journal*, *12*(6), 1517–1532. https://doi.org/10.1016/j.cj.2024.10.007

Zehra, A., Zhou, J., Ma, H., Liu, B., Sahito, Z. A., Wang, Y., Yang, W., & Zhang, L. (2025). Unraveling anthocyanin accumulation in sweet potatoes with integrated omics. *Scientia Horticulturae*, *350*, 114293. https://doi.org/10.1016/j.scienta.2025.114293

Zhang, Y., Jin, J., Wang, N., Sun, Q., Feng, D., Zhu, S., Wang, Z., Li, S., Ye, J., Chai, L., Xie, Z., & Deng, X. (2024). Cytochrome P450 CitCYP97B modulates carotenoid accumulation diversity by hydroxylating β-cryptoxanthin in Citrus. *Plant Communications*, *5*(6), 100847. https://doi.org/10.1016/j.xplc.2024.100847