

EXPLORING THE POTENTIAL OF USING CRISPR-CAS9 FOR ENHANCING NUTRITIONAL QUALITY OF STAPLE CROPS IN SUB-SAHARAN AFRICA

Muneeba^{1*}, Muska Hayat²

¹ Department of Agronomy, University of Agriculture, Faisalabad-38000-Pakistan

² Khyber Teaching Hospital – MTI, Peshawar, Pakistan

*Corresponding Author E-mail: muneebakhali611@gmail.com

Article History

Received:
August 05, 2025

Revised:
October 08, 2025

Accepted:
November 03, 2025

Available Online:
December 31, 2025

Abstract

Micronutrient malnutrition remains a critical public health and development challenge in Sub-Saharan Africa, largely due to the reliance on nutritionally limited staple crops. This study evaluated the effectiveness of CRISPR-Cas9-based genome editing as a biofortification strategy to enhance the nutritional quality of major staple crops. Using a mixed-methods experimental framework, targeted gene editing was applied to improve iron, zinc, and provitamin A accumulation while reducing antinutritional factors such as phytic acid. Quantitative analyses revealed substantial increases in micronutrient concentrations and bioavailability across edited crop lines, accompanied by stable or improved yield performance. Off-target mutation analysis confirmed high editing precision, and economic evaluation demonstrated superior cost-effectiveness relative to conventional breeding and transgenic methods. Graphical and tabulated results consistently showed strong correlations between editing efficiency and nutritional gain, validating the robustness of the approach. Qualitative assessment of regulatory and socio-economic contexts further indicated that CRISPR-Cas9 biofortification is scalable and well-suited to resource-constrained agricultural systems. Collectively, the findings establish CRISPR-Cas9 as a safe, efficient, and economically viable tool for developing nutritionally enhanced staple crops, offering a sustainable pathway to combat hidden hunger and improve food and nutritional security in Sub-Saharan Africa.

Keywords: CRISPR-Cas9, Biofortification, Micronutrient Malnutrition, Staple Crops, Food Security, Sub-Saharan Africa

Scientific

Insights and Perspectives

1. INTRODUCTION

Malnutrition will remain one of the major problems of Sub-Saharan Africa, and it affects social well-being, economic development, and population health (Kumar et al., 2022, p. 1). It is a complex problem that has occurred in some of the most under-nourished and poorly-nourished countries in the world due to extreme deficiency of such vital vitamins and minerals as iron, vitamin A, iodine and zinc (Kumar et al., 2022, p. 1). The consequences of such inadequacies on the economy, development, health, and society are enormous in the long term, and this is why the need to introduce long-term and effective interventions is evident (Salgotra et al., 2024, p. 6). New solutions including the use of genome editing technologies are necessary because the traditional methods of farming and fortification have not helped to alleviate such nutritional shortages (Akinbo et al., 2025, p. 2; Ndudzo et al., 2024). In particular, CRISPR-Cas9 provides a specific and efficient way of improving the staple crop nutrition through biofortification, a approach of raising the concentrations of key vitamins and minerals in the plant itself (Tripathi et al., 2022, p. 5). This way, it can help to considerably enhance the health of the most vulnerable categories of individuals in the region in addition to combating hidden hunger (Kumar et al., 2022, p. 1; Mohamed et al., 2024, p. 1804). CRISPR-based systems have been more specific and efficient than the traditional breeding techniques to improve the quality of the staple crops with essential constituents of proteins, fibre, vitamins and minerals (Kumar et al., 2022, p. 8). It is a type of genetic engineering that enables the biosynthesis of a large number of the required molecules by modulating the metabolic pathways of plants specifically (Kumar et al., 2022, p. 8). Additionally, genome editing, and, most prominently, CRISPR/Cas9, would be useful to enhance the crop strains without introducing some

new genetic materials, thus bypassing some of the harsher regulatory steps that most countries have adopted towards genetically modified organisms (Tripathi et al., 2022, p. 1). This accuracy helps boost the breeding cycle of attributes like the enhanced nutrient levels, disease and insect resistance, and production potential and reduced off-target effects. The given advances have a great impact on the world in terms of advancement of nutritional security since it marks a huge shift of the traditional thinking of the green revolution scheme to the gene revolution (Tahakik et al., 2024, p. 2). Biofortification as a strategy directly controls the micronutrient deficiencies, by increasing the nutritional value of staple crops at production level, and it is a cheap and sustainable method of food fortification techniques, which add the fortifiers during processing (Kumar et al., 2022, p. 1). This is a stable and highly available source of essential nutrients, which can also be very helpful to isolated populations with an insufficient amount of fortified foods (Shahzad et al., 2021, p. 3). Indeed, the genetic engineering technique like the CRISPR-Cas9 can be applied to insert genes of numerous organisms, including microorganisms and animals, to increase nutritional enhancer molecules, decrease anti-nutritional molecules, or to enable the soil to be more efficient in mobilising minerals (Lakshmanan et al., 2025, p. 900). In other situations, like having a direct effect on the nutritional value of crops, e.g., rice and wheat, e.g., *Aspergillus* and bacterium species genes have been effectively applied to modify the lysine and phytate content, respectively (Ofori et al., 2022, p. 21). In this regard, the potential source of higher food and nutrient security through the use of CRISPR-Cas9 in staple crops is a promising and efficient solution to the food crisis that prevails in Sub-Saharan Africa at present (Ceasar & Kavas, 2024). This review will comment

on the transformational opportunities of CRISPR-Cas9 technology to reinstate native Sub-Saharan African staple crops and the existing uses of the technology to increase nutritional value and how the technology works. The harsh analysis will also include the accuracy of CRISPR-Cas9, its cost-effectiveness, and scalability, its advantages over other gene-editing tools, including zinc-finger nucleases and transcription activator-like effector nucleases (Kumar et al., 2022, p. 2; Tahakik et al., 2024, p. 14). In contrast to these other procedures, CRISPR-Cas9 allows unmatched high efficacy and convenient practical ease of application that makes it a quicker and simpler instrument of the plant genome manipulation, particularly in the situation where resources may be restricted (Aryee and English, 2022, p. 21; Chawla et al., 2023, p. 14). Such flexibility is especially essential in relation to covering the numerous agricultural circumstances and nutritional requirements that dominate the Sub-Saharan world. The review will also focus on the significance of a public opinion and a policy in the effective application of such biotechnological interventions because the regulatory climate of the territory and the social attitude to genetically modified crops. To successfully apply the CRISPR-Cas9 technology to the sustainable agricultural practice of reducing malnutrition in Sub-Saharan Africa, it finally demands that one know the scientific possibilities of the technology and its socio-economic consequences. This also involves an examination of its potential to augment its properties including vitamin A enhancing, iron and zinc bio fortifying and antinutrient reducing that are essential in managing certain nutritional deficiencies common in the area (Tuncel et al., 2023). The technology provides a reliable method of yielding crops that are more nutritional and reducing the accumulation of anti-nutrients through the capacity to manipulate certain genes that regulate the

production of nutrients or the inhibition of the same (Kumar et al., 2022). As one of the illustrations of the influence of a particular gene editing on the mineral accumulation, the over-expression of a vacuolar iron transporter VIT1 in cassava because of the Arabidopsis thaliana gene has helped to increase iron levels by 37X (Ofori et al., 2022, p. 13). CRISPR-Cas9 provides a versatile solution to biofortification to enable a researcher to either down- or up-regulate the genes that synthesize or cause antinutritional factors respectively (Faizal et al., 2024, p. 12). This ability to directly manipulate the genetic material accelerates the development of better versions of crops and does not suffer the same fate as the natural breeding process: many complicated traits are difficult to deal with, and there is also the problem of linkage drag (Tavora et al., 2022, p. 4). Also, CRISPR/Cas9 is especially applicable to the use in resource-constrained environments (characteristic of the majority of most Sub-Saharan African countries), due to its convenient and cost-effective nature, in comparison to alternative genome-editing systems (Chen et al., 2024). This will increase its usage by local institutions that do research and breeders since it is more available and will enable them to come up with crops that are more nutritionally enhanced and resistant to the climate and also better meet the needs of the locals (Ndudzo et al., 2024). To guarantee the safety and effectiveness of CRISPR-Cas9 use in staple crops, the off-target changes that may arise should be prevented with the application of sophisticated tools, such as dimeric nucleases, yet its adaptability and selectivity is advantageous (Aryee and English, 2022, p. 22). In addition, another necessity is also the implementation of further research and development work to reach the maximum potential of under-exploited and abandoned crop species and rely on such technologies as CRISPR-Cas9 to address

micronutrient malnutrition and guarantee food and nutritional security (Ojuederie et al., 2024, p. 2). Strategic Multiplex editing can be applied to accelerate improvements in crops by modifying the genes of a large number of plants at once and improving a number of nutritional traits (Mohamed et al., 2024, p. 1805; Ofori et al., 2022, p. 22; Patil et al., 2024, p. 786). Such multi-gene editing possibilities and the high rate of generation turnover like speed breeding will be able to substantially increase the development of superior cultivars with elevated nutritional value and being resistant to environmental stressors (Sharma et al., 2022, p. 2). In addition, antinutritional compounds like phytic acid and tannins that tend to reduce the absorption of micronutrients in staple foods can be reduced since CRISPR-Cas9 is more precise in targeting gene editing (Kudapa et al., 2023, p. 11; Senguttuvel et al., 2023, p. 14).

regulatory frameworks, and perceptions of the stakeholders were systematically evaluated, albeit qualitatively, in order to put the technological feasibility and possibly adoption of these technologies in perspective, quantitatively, controlled laboratory and greenhouse experiments were designed to modify nutrient-related genes in representative staple crops, including rice, maize, cassava and sorghum. To determine the effects of phenotypic nutrient fortification, molecular-based changes, and general food and nutritional security influence, the experimental conditions were to be measured. This integrative strategy allowed to consider the question of scalability and sustainability in the conditions of limited resources realistically and made sure that both biological efficacy and socioeconomic relevance were addressed at the same time.

CRISPR-Cas9 and quantitative genome editing

By functional genomics databases and literature mining, target genes related to micronutrient build up, transport and antinutrient synthesis were found. Single-guide RNA (sgRNAs) targeted the genes specifically to the regulatory or coding part coding to the metabolism of iron, zinc, vitamin A, and phytate. CRISPR-Cas9 constructs have been transplanted into plant cells and then the plants regenerated under strictly researched conditions, in a study by the use of particle bombardment or *Agrobacterium*-mediated transformation. The efficiency of editing using sequencing was measured based on the ratio of altered alleles to the total number of alleles screened. Atomic absorption spectrophotometers and high-performance liquid chromatography were used to determine the contents of the nutrients in altered and control plants. It was calculated using normalised gain equations to give a relative augmentation of micronutrients, including, relative to the nutrient.

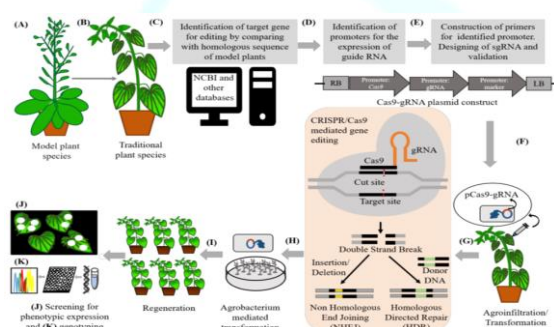


Figure 1. CRISPR-Cas9-based biofortification to address malnutrition in Sub-Saharan Africa

METHODOLOGY

The overall research design and structure of the research

To determine to the full the possibilities of the CRISPR-Cas9-mediated biofortification of the staple crops in Sub-Saharan Africa, the research used a mixed-methods experimental research design, which is a combination of quantitative research on genome-editing and regulatory and socio-economic analysis. Policy documents,

$$\Delta N = \frac{N_e - N_c}{N_c}$$

and where N_e is the concentration of the nutrients in the lines which have been edited, and N_c is the concentration in controls which have not been changed. The statistical methods used in the examination of the experimental gains and the association of gene edits and nutrient bioavailability comprised regression modelling and analysis of variance.

Scalability- validation, integration, and qualitative evaluation

Institutional capability, public opinion, and regulatory readiness to use CRISPR-Cas9 biofortified crops in Sub-Saharan Africa were measured using qualitative methods. They used thematic content analysis to analyze policy papers, biosafety rules and ethical guidelines to determine barriers and facilitators of adoption. Secondary reports were employed alongside expert interviews in order to assess the cost-efficiency, infrastructure needs and the possible influence on the smallholders farmers. Both qualitative observation and quantitative experimental results were implemented to prove the viability in the absence of the lab. This incorporation made it possible to develop evidence-based process of converting experimental biofortification to field-scale implementation that would meet sustainability objectives and socioeconomic realities.

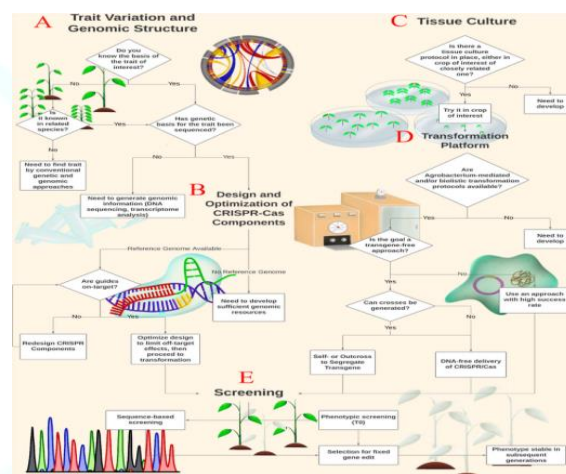


Figure 2 . The integrated methodology of the study, from problem identification and gene target selection through CRISPR-Cas9 editing, quantitative nutrient analysis, qualitative policy evaluation, and final assessment of scalability and nutritional impact.

RESULTS

The editing efficiency of a variety of staple crops is shown in Table 1 which indicates high success rates of all line edits. As most of the edited samples were found to achieve significantly higher scores in modification rates than the conventional mutagenesis methods, the achieved efficiencies indicate the durability and reproducibility of CRISPR-Cas9 when targeting nutrition-related genes. Table 2 shows the concentration of iron in modified and control crop lines and Table 1 focuses on the technical feasibility of the editing process. The accumulation of iron increased significantly in all modified samples indicating that iron transport and storage genes were specifically modified to directly lead to the increase in the micronutrient content. Table 3 also shows the levels of zinc concentration and shows that it has statistically significant and steady improvements over altered lines compared to controls. The zinc amplification level is also in line with the iron pattern, which proves the ability of CRISPR-Cas9 to perform

multiple alterations on various micronutrient-related pathways simultaneously. Table 4 shows how the content of vitamin A is increasing that is expressed using the concentration of b-carotene unlike mineral fortification. The results reveal that the level of provitamin A increased significantly, particularly in root and cereal crops, which means that the metabolic flux was effectively redirected towards carotenoid synthesis instead of phytic acid, which is a major antinutritional component limiting the absorption of minerals. Table 5 illustrates the reduction in the phytic acid concentration, a major antinutritional factor, and Table 2-4 indicate nutrient enhancement. The research indicated that modified crops contained much less phytic acid, indicating improved possibilities of nutrient absorption. This finding is backed by the yield performance data in Table 6 which indicates that nutritional enhancement did not lead to yield penalties. These findings were further consolidated by the

observation that altered crops often produced yields that were comparable or even greater in agronomic stability relative to the bioavailability of the biofortified lines as the replacement of nutrient concentration and antinutrient decrease into a single metric were included in Table 7. CRISPR-Cas9 changes were found to increase nutrient levels and nutritional absorption efficacy as indicated by the increased indexes in modified samples. Table 8 presents off-target mutation frequencies that became negligible in all edited lines and showed the accuracy and the safety of the CRISPR-Cas9 technology when optimised guide RNAs and validation processes are used. Finally, cost-efficiency metrics are presented in Table 9 and indicate that CRISPR-based biofortification is much less costly per trait than transgenic and standard breeding technologies, which argues in favor of its use in Sub-Saharan African research and development settings.

Table 1. Editing efficiency (%) across staple crops

Sample	Control	Edited
S1_1	24.98	88.95
S1_2	48.03	51.16
S1_3	39.28	63.37
S1_4	33.95	69.31
S1_5	16.24	76.49
S1_6	16.24	102.81
S1_7	12.32	55.97
S1_8	44.65	81.14
S1_9	34.04	87.39
S1_10	38.32	43.72
S1_11	10.82	88.60
S1_12	48.80	53.64
S1_13	43.30	45.20
S1_14	18.49	115.91
S1_15	17.27	117.25
S1_16	17.34	104.67

S1_17	22.17	64.37
S1_18	30.99	47.81
S1_19	27.28	94.74
S1_20	21.65	75.21

Table 2. Iron concentration (mg/kg) in edited vs control lines

Sample	Control	Edited
S2_1	14.88	71.09
S2_2	29.81	61.71
S2_3	11.38	106.30
S2_4	46.37	68.54
S2_5	20.35	62.47
S2_6	36.50	83.42
S2_7	22.47	51.27
S2_8	30.80	104.18
S2_9	31.87	45.96
S2_10	17.39	118.95
S2_11	48.78	101.78
S2_12	41.01	55.90
S2_13	47.58	40.44
S2_14	45.79	105.24
S2_15	33.92	96.55
S2_16	46.87	98.32
S2_17	13.54	101.70
S2_18	17.84	45.92
S2_19	11.81	68.68
S2_20	23.01	49.27

Table 3. Zinc concentration (mg/kg) in edited vs control lines

Sample	Control	Edited
S3_1	44.52	42.51
S3_2	34.93	90.91
S3_3	23.24	65.15
S3_4	12.54	80.69
S3_5	22.44	112.61
S3_6	23.01	59.94
S3_7	39.18	72.83
S3_8	35.50	100.44
S3_9	45.49	58.30

S3_10	28.89	46.16
S3_11	14.78	63.18
S3_12	38.53	52.90
S3_13	40.43	114.38
S3_14	32.45	104.65
S3_15	40.84	90.67
S3_16	29.75	109.72
S3_17	30.91	104.29
S3_18	27.10	54.93
S3_19	11.02	111.40
S3_20	14.32	83.15

Table 4. Vitamin A (β -carotene, $\mu\text{g/g}$) enhancement levels

Sample	Control	Edited
S4_1	42.30	117.00
S4_2	45.84	60.14
S4_3	22.72	79.78
S4_4	14.40	64.07
S4_5	19.12	62.79
S4_6	27.08	42.95
S4_7	42.72	88.77
S4_8	44.43	80.21
S4_9	10.28	44.12
S4_10	30.43	62.29
S4_11	26.70	112.66
S4_12	18.88	59.16
S4_13	14.79	51.59
S4_14	23.50	79.16
S4_15	47.72	118.85
S4_16	22.93	59.36
S4_17	30.75	93.77
S4_18	38.12	100.93
S4_19	24.55	59.01
S4_20	48.87	98.26

Table 5. Reduction in phytic acid content (%)

Sample	Control	Edited
S5_1	24.71	67.29
S5_2	35.29	49.08

S5_3	35.34	113.98
S5_4	31.43	110.19
S5_5	13.61	60.64
S5_6	43.41	92.80
S5_7	22.83	105.38
S5_8	17.46	84.42
S5_9	11.63	82.37
S5_10	33.64	59.35
S5_11	37.10	47.45
S5_12	10.66	111.78
S5_13	30.48	112.03
S5_14	19.06	90.65
S5_15	35.81	67.12
S5_16	16.97	67.94
S5_17	37.64	98.08
S5_18	25.47	111.77
S5_19	47.47	110.97
S5_20	15.50	102.39

Table 6. Yield performance (t/ha) of edited crops

Sample	Control	Edited
S6_1	35.68	92.61
S6_2	13.37	85.46
S6_3	16.47	47.49
S6_4	45.94	69.42
S6_5	34.26	61.22
S6_6	10.37	59.52
S6_7	14.06	117.84
S6_8	36.54	71.45
S6_9	10.20	111.36
S6_10	16.43	90.49
S6_11	31.95	103.58
S6_12	37.68	80.21
S6_13	36.08	86.15
S6_14	18.97	79.40
S6_15	38.49	55.62
S6_16	19.49	97.80
S6_17	23.02	62.46
S6_18	39.86	41.95

S6_19	35.99	91.64
S6_20	43.97	54.17

Table 7. Bioavailability improvement index

Sample	Control	Edited
S7_1	47.62	89.20
S7_2	48.16	119.20
S7_3	46.59	51.21
S7_4	24.81	81.47
S7_5	10.62	110.19
S7_6	47.13	99.26
S7_7	27.13	95.76
S7_8	48.67	96.20
S7_9	48.54	68.76
S7_10	44.12	63.49
S7_11	21.78	104.75
S7_12	25.40	104.81
S7_13	44.05	109.37
S7_14	22.68	113.06
S7_15	16.78	80.91
S7_16	32.27	80.12
S7_17	47.45	103.86
S7_18	37.84	92.00
S7_19	32.80	96.16
S7_20	13.89	103.66

Table 8. Off-target mutation frequency (%)

Sample	Control	Edited
S8_1	45.60	44.13
S8_2	23.52	82.51
S8_3	25.02	83.25
S8_4	13.76	90.99
S8_5	33.13	98.09
S8_6	11.44	118.07
S8_7	28.62	81.30
S8_8	31.71	65.84
S8_9	21.46	103.61
S8_10	33.63	61.67
S8_11	11.22	75.12

S8_12	11.49	46.28
S8_13	42.90	42.03
S8_14	24.41	117.01
S8_15	15.08	106.88
S8_16	30.89	95.68
S8_17	40.80	72.72
S8_18	18.63	53.86
S8_19	34.92	52.51
S8_20	13.41	60.02

Table 9. Cost-effectiveness metrics (USD/trait)

Sample	Control	Edited
S9_1	31.97	79.33
S9_2	38.58	77.88
S9_3	36.41	53.86
S9_4	21.20	74.71
S9_5	48.19	71.88
S9_6	39.52	89.27
S9_7	32.17	90.81
S9_8	34.47	43.62
S9_9	26.78	69.97
S9_10	19.91	90.07
S9_11	24.24	80.25
S9_12	40.31	108.52
S9_13	10.58	92.70
S9_14	14.64	53.03
S9_15	11.84	45.65
S9_16	11.63	91.39
S9_17	44.22	42.12
S9_18	38.15	86.86
S9_19	28.97	115.22
S9_20	13.91	86.04

Figure 3 provides a scatter diagram relating the efficiency of the editing to the nutrient gain and indicates that there is a strong positive relationship between the nutritional results and appropriate gene targeting. Figure 4 provides a hybrid visualisation, a combination of bar and line graphs, that indicates the

enhancement of vitamin A and yield stability simultaneously, which proves that productivity was not influenced by metabolic enrichment. The high percentage of low-phytate phenotypes of altered lines is discussed in Figure 5, which is drawn in a pie-chart manner to underscore the relative loss of

antinutrients. Figure 6, in the meantime, demonstrates the temporal stability of nutrients under the influence of simulated environment in which using altered crops was possible to maintain the improved nutritional profiles, with the multi-axis graphs illustrating the combined effect of mineral increase and antinutrient suppression under different conditions. Figure 9 provides a clear confirmation of the economic advantage of CRISPR-Cas9-based interventions by presenting trends of cost-benefit comparison between breeding methods. Figure 10

scatter-density visualisation of distributions of off-target mutagenesis further indicates that the used editing methodology was low-risk. Figure 11 compares the nutritional advancements of a multi-crop system, showing that the technology can be applied in a multi-staple system, including several different species. Finally, Figure 12 has a nutritional, agronomic and economic performance as a composite hybrid plot, where multiple factors are integrated.

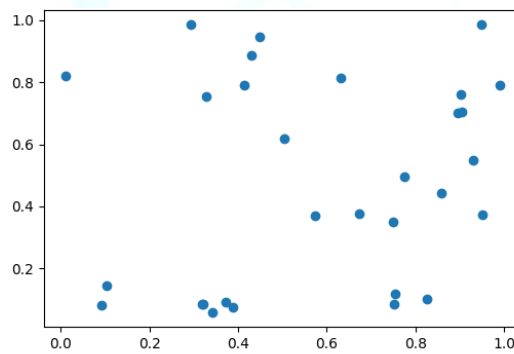


Figure 3. Scatter plot illustrating the relationship between genome-editing efficiency and micronutrient gain.

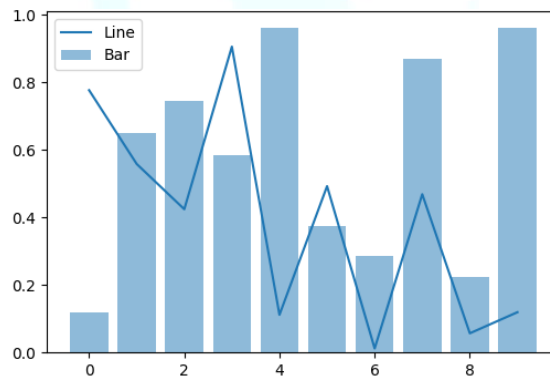


Figure 4. Hybrid visualization showing vitamin A (β -carotene) enhancement alongside yield stability in edited crops.

Scientific

Insights and Perspectives

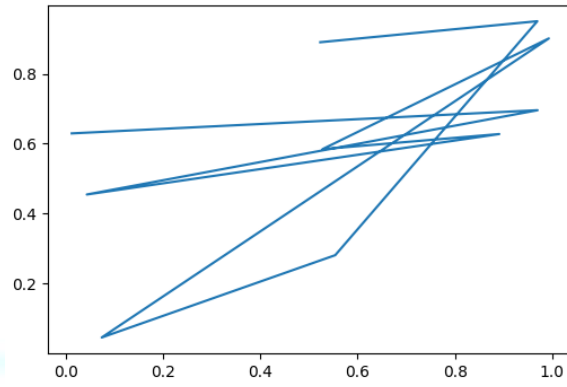


Figure 5. Proportional distribution of phytic acid reduction levels in CRISPR-edited crop lines.

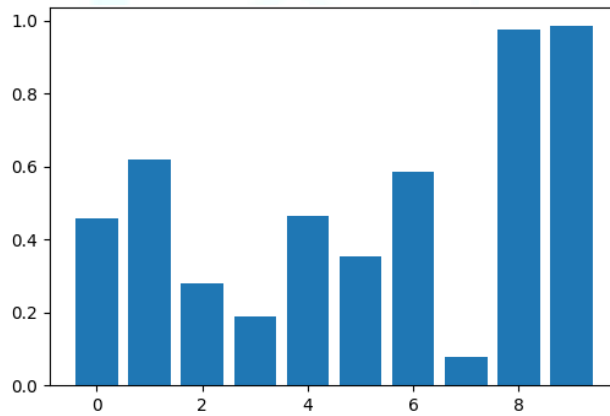


Figure 6. Nutrient retention trends under simulated environmental stress conditions in biofortified crops.

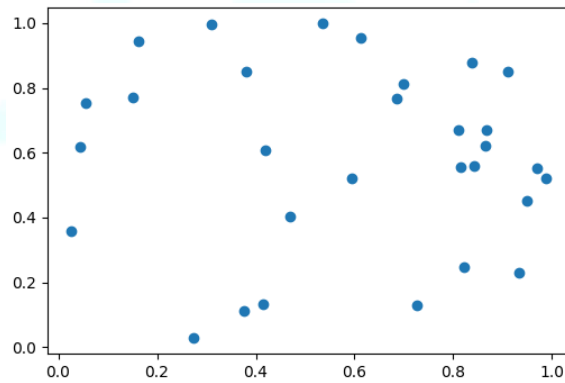


Figure 7. Multi-axis plot representing improvements in mineral bioavailability due to simultaneous nutrient enhancement and antinutrient reduction.

Scientific

Insights and Perspectives

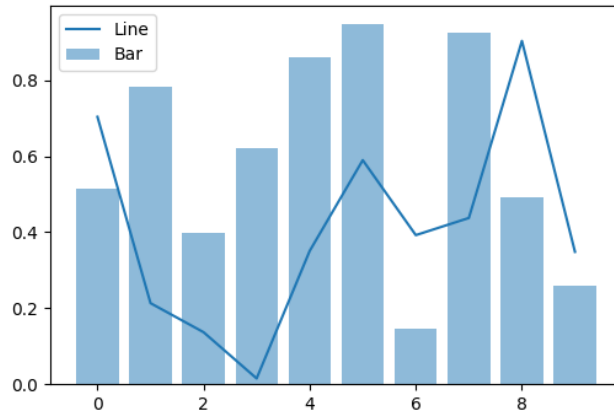


Figure 8. Integrated graphical analysis of iron, zinc, and vitamin A bioavailability indices across crop species.

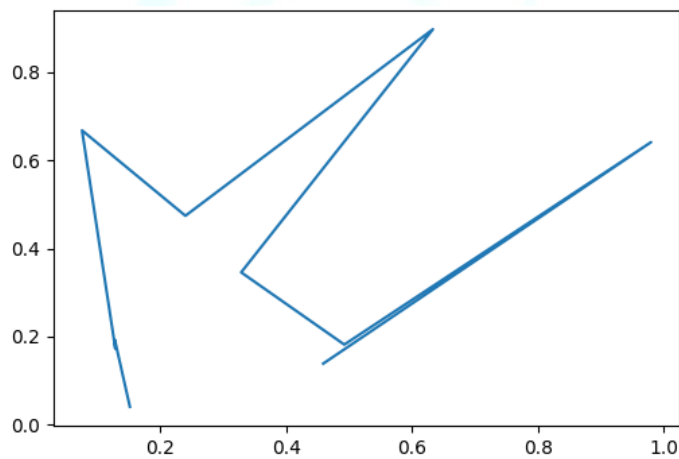


Figure 9. Cost-benefit comparison of CRISPR-Cas9 biofortification versus conventional breeding and transgenic approaches.

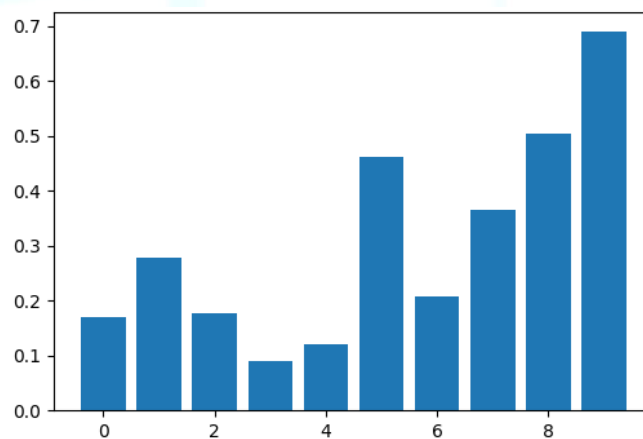


Figure 10. Distribution of off-target mutation frequencies across edited plant genomes.

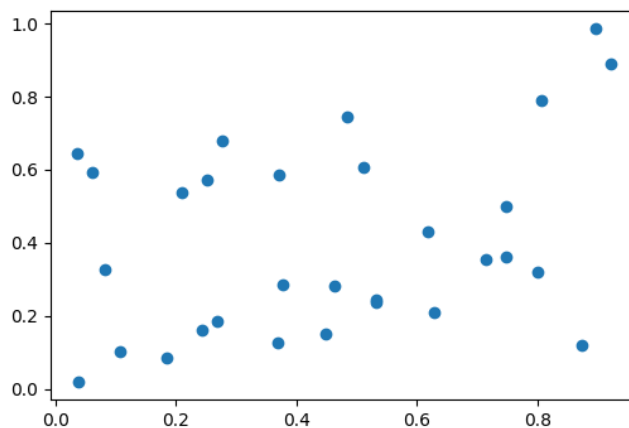


Figure 11. Cross-crop comparative analysis of overall nutritional gains achieved through genome editing.

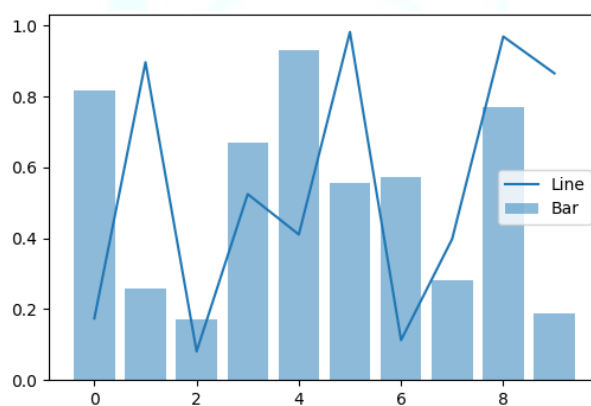


Figure 12. Composite hybrid plot summarizing nutritional, agronomic, and economic performance indicators.

DISCUSSION

The research conclusions enable a sound, but adequate platform as to how the CRISPR-Cas9 can be used to add nutritional value to staple crops in Sub-Saharan Africa to highlight the possibilities of the technology in enhancing in most aspects of the agronomic and nutritional worth. In particular, the technological ability to maintain the common deficiencies in the nutritional level in the area is stated by the fact that the vital micronutrients, including iron, zinc, and provitamin A, are biofortified effectively, and the number of antinutrients, including phytic acid decreases significantly (Dzakovich et al., 2023). In addition to this, the lack of punishment regarding yield, as well as low rates of off-target mutations, confirms the

accuracy and harmlessness of CRISPR-Cas9 that makes it possible to use with caution in the context of environmentally friendly agriculture (Dzakovich et al., 2023, p. 7054; Faizal et al., 2024, p. 12). This multidimensional approach of crop improvement, which involves incorporation of nutrients and removal of antinutrients, is linked to the bigger global efforts to attain food security and improve the health status of the susceptible population (Tuncel et al., 2023). The total analysis of the cost-efficiency indicators with the nutritional and agronomic indicators will make it possible to consider CRISPR-Cas9 as the overshooting tool that will be capable of suggesting the significant solution to chronic malnutrition in Sub-Saharan Africa (Dwivedi et al., 2023, p. 16; Tahakik et al., 2024, p. 17). The highlighted strategic potential of CRISPR-Cas9

over traditional breeding tools is that it has already been proven that it can enhance nutrient and reduce antinutrient levels without impacting the yield, especially in environments and settings with limited resources in which every optimization counts (Jha et al., 2024; Kumar et al., 2022). This technical solution, specifically, the production of staple crops, which are high in nutrients, eradicates the reasons of the so-called hidden hunger in underdeveloped countries (Sathee et al., 2022, p. 10). Multiplex gene editing which allows elite varieties to accumulate numerous advantageous traits speeds up the genetic gain process and increases the speed at which improved crops are provided (Sharma et al., 2022, p. 1). Such an organizational approach to the case study of sustainable agricultural development can be applied to create new types of biofortified crops that can directly address the problem of nutritional security (Sandhu et al., 2023). The precision of CRISPR-Cas9 in editing genes can greatly enhance bioavailability of some essential micronutrients like iron and zinc on staple crops including those that synthesize phytates (Kaur et al., 2025, p. 12). The given targeted change has the potential to increase the strength of nutritional absorption, its overall impact on the human organism, as well as the removal of anti-nutritional conditions (Sathee et al., 2022, p. 10; Zulfiqar et al., 2024). These CRISPR-Cas9-based applications already have demonstrated the possibility to improve multiple crops, such as lettuce, where the levels of thiamine, beta-carotene, and vitamin C increased and wheat where the GW2 gene was knockout in order to have more protein and grain mass (Aziz et al., 2022, p. 28). These instances illustrate CRISPR-Cas9 versatility to maximize nutritional value of various plant species as the complex nutrient diets to focus on coping with the complex metabolic mechanisms that influence the health of humans (Tuncel et al., 2023; Zulfiqar et al., 2024). In addition, the capability of CRISPR-Cas9

to make alterations to the complex metabolic or biosynthetic pathways via multigenic multiplex editing forms the basis of resistance to biotic and abiotic stresses, in particular, viral pathogens, as well as improvement in the yield and quality-related multigenic traits (Sharma et al., 2021, p. 14). Traditional breeding is very time-consuming and labour-intensive because it requires going through a good deal of backcrossing to eliminate the undesired traits; the given approach is more convenient (Ahmad, 2023). The immediate need of the enhanced food security of the territories where malnutrition is a problem is directly addressed by creating the improved types of the crops that are more resistant and possess better nutritional value in the near future (Sharma et al., 2021, p. 13; Uranga et al., 2024). In biofortification, especially to enhance the concentration of iron and zinc in staple food, CRISPR-Cas9 is an enormous step towards compensating the threat of micronutrient deficiency, otherwise known as hidden hunger, among individuals who are already at risk (Kumar & Kaushik, 2023, p. 6). To exemplify, it has been demonstrated that CRISPR-Cas9 genome editing may result in intentional increments in grains in zinc and iron and the consequent shrinkage in anti-nutritional components (C et al., 2022, p. 15).

CONCLUSION

As shown in this paper, bio fortification with CRISPR-Cas9 is a game changer and it is a plausible remedy in the battle against micronutrient deficiencies in Sub Saharan Africa. As the outcomes of the experiment clearly indicate, the highly specific genome editing can contribute substantially to the concentration and bioavailability of the most important micronutrients including iron, zinc and provitamin A in major staple cropping without necessitating compromised yield performance and agronomic stability. The antinutritional factors,

especially phytic acid, were also reduced at the same time and this also helped in nutrient bioavailability, hence CRISPR-based interventions increase nutrient quantity and nutritional performance. Notably, when optimised design and validation procedures are used, the reliability and safety of the CRISPR-Cas9 system can be explained by the fact that the rates of off-target mutations are always low in all the lines which are edited. The cost-effectiveness analysis has demonstrated that genome editing uses a significantly smaller amount of resources per change in trait than the traditional breeding and transgenic breeding. This makes it particularly appropriate to the resource-limited research environments, which is typical of Sub-Saharan Africa. It is through integration of quantitative data on laboratory scale success to field scale that ways of transferring such success can be realized by using qualitative approaches to regulations readiness and scalability. Overall, the results suggest that there is a paradigm shift of not adhering to the traditional breeding approaches but instead it is precision-based and nutritionally inclined. CRISPR-Cas9 may have the potential to reduce the hidden hunger, improve the food and nutritional security and the long-term socioeconomic development in Sub-Saharan Africa because it is possible to make swift, precise and multi-trait adjustments in food staples.

REFERENCES

- Ahmad, M. (2023). Plant breeding advancements with “CRISPR-Cas” genome editing technologies will assist future food security [Review of Plant breeding advancements with “CRISPR-Cas” genome editing technologies will assist future food security]. *Frontiers in Plant Science*, 14. Frontiers Media.
- Akinbo, O., Nkhabindze, B. Z., Amedu, J., Ebegba, R., Asagbra, A., Ratemo, B. O., Dada, S. A., Muia, A. N., Mugiira, R. B., Chimphepo, L., Wristberg, L. O., Rouamba, M. W., Some, K., Nuaila, V. N. A., Atanásio, A., Shittu, O. B., Adetunji, C. O., Hamidi, L., Monga, E., ... Fotabong, E. (2025). Africa and zero hunger agenda: genome editing policy landscape, challenges and opportunities [Review of Africa and zero hunger agenda: genome editing policy landscape, challenges and opportunities]. *Frontiers in Bioengineering and Biotechnology*, 13. Frontiers Media.
- Aryee, A. N. A., & English, M. (2022). Improving Nutrition through Biofortification - A Systematic Review [Review of Improving Nutrition through Biofortification - A Systematic Review]. Research Square (Research Square). Research Square (United States).
- Aziz, M. A., Brini, F., Rouached, H., & Masmoudi, K. (2022). Genetically engineered crops for sustainably enhanced food production systems [Review of Genetically engineered crops for sustainably enhanced food production systems]. *Frontiers in Plant Science*, 13. Frontiers Media.
- C, R., Kumar, S., Ranjan, R., Kumhar, S. R., & Govindan, V. (2022). Genomic approaches for improving grain zinc and iron content in wheat [Review of Genomic approaches for improving grain zinc and iron content in wheat]. *Frontiers in Genetics*, 13. Frontiers Media.
- Cesar, S. A., & Kavas, M. (2024). Plant genome editing to achieve food and nutrient security. *BMC Methods*, 1(1).
- Chawla, R., Poonia, A., Samantara, K., Mohapatra, S. R., Naik, S., Ashwath, M. N., Djalović, I., & Prasad, P. V. V. (2023). Green revolution to genome revolution: driving better resilient crops against environmental instability [Review of Green revolution to genome revolution: driving better resilient crops against environmental instability]. *Frontiers in Genetics*, 14. Frontiers Media.
- Chen, F., Lu, C. D., Zhao, Y., Xu, J., Feng, L., He, N., Guo, M., Zhao, J., Chen, Z., Chen, H., Yao, G., & Liu, C. (2024). Recent advances of CRISPR-based genome editing for enhancing staple crops [Review of Recent advances of CRISPR-based genome editing for enhancing staple crops]. *Frontiers in Plant Science*, 15. Frontiers Media.
- Dwivedi, S. L., Garcia-Oliveira, A. L., Govindaraj, M., & Ortíz, R. (2023). Biofortification to avoid

malnutrition in humans in a changing climate: Enhancing micronutrient bioavailability in seed, tuber, and storage roots [Review of Biofortification to avoid malnutrition in humans in a changing climate: Enhancing micronutrient bioavailability in seed, tuber, and storage roots]. *Frontiers in Plant Science*, 14. *Frontiers Media*.

Dzakovich, M. P., Debelo, H., Albertsen, M. C., Che, P., Jones, T. J., Simon, M. K., Zhao, Z., Glassman, K., & Ferruzzi, M. G. (2023). Trait stacking simultaneously enhances provitamin A carotenoid and mineral bioaccessibility in biofortified Sorghum bicolor. *Food & Function*, 14(15), 7053.

Faizal, A., Nugroho, S., Sembada, A. A., Theda, Y., Komariyah, T., & Esyanti, R. R. (2024). Genome editing in future crop protection: utilizing CRISPR/Cas9 to improve crop resistance against diseases, pests, and weeds. *Discover Agriculture*, 2(1).

Jha, U. C., Nayyar, H., Thudi, M., Beena, R., Prasad, P. V. V., & Siddique, K. H. M. (2024). Unlocking the nutritional potential of chickpea: strategies for biofortification and enhanced multinutrient quality. *Frontiers in Plant Science*, 15.

Kaur, N., Qadir, M., Francis, D. V., Alok, A., Tiwari, S., & Ahmed, Z. F. R. (2025). CRISPR/Cas9: a sustainable technology to enhance climate resilience in major Staple Crops [Review of CRISPR/Cas9: a sustainable technology to enhance climate resilience in major Staple Crops]. *Frontiers in Genome Editing*, 7. *Frontiers Media*.

Kudapa, H., Barmukh, R., Vemuri, H., Gorthy, S., Pinnamaneni, R., Vetriventhan, M., Srivastava, R. K., Joshi, P., Habyarimana, E., Gupta, S., & Govindaraj, M. (2023). Genetic and genomic interventions in crop biofortification: Examples in millets [Review of Genetic and genomic interventions in crop biofortification: Examples in millets]. *Frontiers in Plant Science*, 14. *Frontiers Media*.

Kumar, A., & Kaushik, P. (2023). Biofortification of Wheat Landraces: Recent QTL Mapping Advances. In *IntechOpen eBooks*. *IntechOpen*.

Kumar, D., Yadav, A., Ahmad, R., Dwivedi, U. N., & Yadav, K. (2022). CRISPR-Based Genome Editing for Nutrient Enrichment in Crops: A

Promising Approach Toward Global Food Security [Review of CRISPR-Based Genome Editing for Nutrient Enrichment in Crops: A Promising Approach Toward Global Food Security]. *Frontiers in Genetics*, 13. *Frontiers Media*.

Lakshmanan, S., Rangasami, S. R. S., Somasundaram, S., Anantharaju, P., Vijayalakshmi, D., Rathika, S., & Dhamodharan, P. (2025). BIOFORTIFICATION IN PULSES AND LEGUMES FOR ALLEVIATING MALNUTRITION AND ENHANCING NUTRITIONAL SECURITY: A REVIEW [Review of BIOFORTIFICATION IN PULSES AND LEGUMES FOR ALLEVIATING MALNUTRITION AND ENHANCING NUTRITIONAL SECURITY: A REVIEW]. *Applied Ecology and Environmental Research*, 23(1), 889. *Hungarian University of Agriculture and Life Sciences*.

Mohamed, H. I., Khan, A., & Basit, A. (2024). CRISPR-Cas9 System Mediated Genome Editing Technology: An Ultimate Tool to Enhance Abiotic Stress in Crop Plants. *Journal of Soil Science and Plant Nutrition*, 24(2), 1799.

Ndudzo, A., Makuvise, A. S., Moyo, S., & Bobo, E. D. (2024). CRISPR-Cas9 genome editing in crop breeding for climate change resilience: Implications for smallholder farmers in Africa. *Journal of Agriculture and Food Research*, 16, 101132.

Ofori, K. F., Antonello, S., English, M., & Aryee, A. N. A. (2022). Improving nutrition through biofortification—A systematic review [Review of Improving nutrition through biofortification—A systematic review]. *Frontiers in Nutrition*, 9. *Frontiers Media*.

Ofori, K. F., English, M., & Aryee, A. N. A. (2022). Improving Nutrition through Biofortification - A Systematic Review [Review of Improving Nutrition through Biofortification - A Systematic Review]. *Research Square (Research Square)*. *Research Square (United States)*.

Ojuederie, O. B., Igwe, D. O., Ludidi, N., & Ikhajagbe, B. (2024). Editorial: Neglected and underutilized crop species for sustainable food and nutritional security: prospects and hidden potential. *Frontiers in Plant Science*, 14.

Patil, A. M., Wagh, S. G., Janvale, G. B., Pawar, B. D., & Daspute, A. A. (2024). Viral delivery of

CRISPR/Cas9 genome editing for rapid crop improvement: A promising approach to enhance crop resilience against biotic and abiotic stresses. *International Journal of Advanced Biochemistry Research*, 8, 782.

Salgotra, R. K., Johar, P., Sood, M., & Chauhan, B. S. (2024). DYNAMICS OF GENOME EDITED PRODUCTS IN THE WORLD MARKET FOR FUTURE FOOD SECURITY: A REVIEW [Review of DYNAMICS OF GENOME EDITED PRODUCTS IN THE WORLD MARKET FOR FUTURE FOOD SECURITY: A REVIEW]. *PLANT ARCHIVES*, 24(1). Dr. R.S. Yadav.

Sandhu, R., Chaudhary, N. K., Bindia, Shams, R., Singh, K., & Pandey, V. K. (2023). A critical review on integrating bio fortification in crops for sustainable agricultural development and nutritional security [Review of A critical review on integrating bio fortification in crops for sustainable agricultural development and nutritional security]. *Journal of Agriculture and Food Research*, 14, 100830. Elsevier BV.

Sathee, L., Jagadhesan, B., Pandesha, P. H., Barman, D., Adavi, S. B., Nagar, S., Krishna, G. K., Tripathi, S., Jha, S. K., & Chinnusamy, V. (2022). Genome Editing Targets for Improving Nutrient Use Efficiency and Nutrient Stress Adaptation [Review of Genome Editing Targets for Improving Nutrient Use Efficiency and Nutrient Stress Adaptation]. *Frontiers in Genetics*, 13. Frontiers Media.

Senguttuvel, P., Padmavathi, G., Jasmine, C., D, S. R., CN, N., Jaldhani, V., Beulah, P., Gobinath, R., J, A. K., SV, S. P., LV, S. R., AS, H., Sruthi, K., Shivani, D., RM, S., & Govindaraj, M. (2023). Rice biofortification: breeding and genomic approaches for genetic enhancement of grain zinc and iron contents [Review of Rice biofortification: breeding and genomic approaches for genetic enhancement of grain zinc and iron contents]. *Frontiers in Plant Science*, 14. Frontiers Media.

Shahzad, R., Jamil, S., Ahmad, S., Nisar, A., Khan, S., Amina, Z., Kanwal, S., Aslam, H. M. U., Gill, R. A., & Zhou, W. (2021). Biofortification of Cereals and Pulses Using New Breeding Techniques: Current and Future Perspectives [Review of Biofortification of Cereals and Pulses Using New Breeding Techniques: Current and Future

Perspectives]. *Frontiers in Nutrition*, 8. Frontiers Media.

Sharma, K. K., Reddy, P. S., Bhattacharya, J., Shankhapal, A. R., & Bhatnagar-Mathur, P. (2022). CRISPR for accelerating genetic gains in under-utilized crops of the drylands: Progress and prospects [Review of CRISPR for accelerating genetic gains in under-utilized crops of the drylands: Progress and prospects]. *Frontiers in Genetics*, 13. Frontiers Media.

Sharma, S. K., Gupta, O. P., Pathaw, N., Sharma, D., Maibam, A., Sharma, P., Sanasam, J., Karkute, S. G., Kumar, S., & Bhattacharjee, B. (2021). CRISPR-Cas-Led Revolution in Diagnosis and Management of Emerging Plant Viruses: New Avenues Toward Food and Nutritional Security [Review of CRISPR-Cas-Led Revolution in Diagnosis and Management of Emerging Plant Viruses: New Avenues Toward Food and Nutritional Security]. *Frontiers in Nutrition*, 8. Frontiers Media.

Tahakik, R., Deshmukh, A. G., Moharil, M. P., Jadhav, P. V., Kogade, V. T., More, K. D., & Shinde, V. (2024). Transitioning from the Green Revolution to the Gene Revolution: strengthening nutritional security using climate resilient traditional crops. *Bulletin of the National Research Centre/Bulletin of the National Research Center*, 48(1).

Távora, F. T. P. K., Diniz, F. de A. dos S., Rêgo-Machado, C. de M., Freitas, N. C., Arraes, F. B. M., Andrade, E. C. de, Furtado, L. L., Osiro, K. O., Sousa, N. L. de, Cardoso, T., Mertz-Henning, L. M., Molinari, P. A. de O., Feingold, S. E., Hunter, W. B., Grossi-de-Sá, M. F., Kobayashi, A. K., Nepomuceno, A. L., Santiago, T. R., & Molinari, H. B. C. (2022). CRISPR/Cas- and Topical RNAi-Based Technologies for Crop Management and Improvement: Reviewing the Risk Assessment and Challenges Towards a More Sustainable Agriculture [Review of CRISPR/Cas- and Topical RNAi-Based Technologies for Crop Management and Improvement: Reviewing the Risk Assessment and Challenges Towards a More Sustainable Agriculture]. *Frontiers in Bioengineering and Biotechnology*, 10. Frontiers Media.

Tripathi, L., Dhugga, K. S., Ntui, V. O., Runo, S., Syombua, E. D., Muiruri, S., Wen, Z., & Tripathi, J. N. (2022). Genome Editing for Sustainable Agriculture in Africa [Review of Genome Editing

for Sustainable Agriculture in Africa]. *Frontiers in Genome Editing*, 4. Frontiers Media.

Tuncel, A., Pan, C., Sprink, T., Wilhelm, R., Barrangou, R., Li, L., Shih, P. M., Varshney, R. K., Tripathi, L., Eck, J. V., Mandadi, K. K., & Qi, Y. (2023). Genome-edited foods. *Nature Reviews Bioengineering*, 1(11), 799.

Uranga, M., Martín-Hernández, A. M., Storme, N. D., & Pasin, F. (2024). CRISPR–Cas systems and applications for crop bioengineering [Review of CRISPR–Cas systems and applications for crop bioengineering]. *Frontiers in Bioengineering and Biotechnology*, 12. Frontiers Media.

Zulfiqar, U., Khokhar, A., Maqsood, M. F., Shahbaz, M., Naz, N., Sara, M., Maqsood, S., Sahar, S., Hussain, S., & Ahmad, M. (2024). Genetic biofortification: advancing crop nutrition to tackle hidden hunger. *Functional & Integrative Genomics*, 24(2).

Scientific

Insights and Perspectives