



Iron & Zinc Biofortification in Rice Through CRISPR/Cas9 Based Genome Editing

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Around the world, hidden hunger or micronutrient deficiency is one of the major health issues affecting billions of people. One of the most prominent nutritional deficiencies is zinc and iron deficiency, especially in developing countries where rice is consumed as a staple food. Polished rice grains predominantly contain a low amount of these micronutrients and because of that people who depend on rice-based diet cannot meet the daily nutritional requirements. Biofortification of rice is one of the ways to solve this problem in a sustainable manner. Conventional breeding and genetic engineering approaches have been used to improve grain zinc and iron content but these methods have major limitations of limited genetic variation, linkage drag and strict regulatory laws. In recent times, genome editing technologies particularly the CRISPR/Cas9 system gained more attention as powerful tools for the precise improvement of rice nutritional quality. CRISPR technology provides targeted gene modification, which is involved in iron and zinc uptake, transport, storage as well as grain loading. Several studies have demonstrated successful enhancement of iron and zinc concentration in rice grains through editing of genes such as OsNAS2, OsVIT2, OsMTP1 and OsPDR7 etc. This article discusses the importance of iron and zinc biofortification in rice and highlights recent advances in CRISPR-mediated genome editing approaches for development of biofortified rice varieties.

Keywords: Rice, Biofortification, CRISPR/Cas9, Iron, Zinc, Hidden hunger, Genome editing

Introduction

Micronutrient deficiency, commonly known as hidden hunger is one of the major nutritional challenges that affects a large proportion of the population worldwide. Iron (Fe) and zinc (Zn) deficiencies are considered major public health concerns among various micronutrient deficiencies. Deficiency of iron is the leading cause of nutritional anemia, which results in fatigue, poor cognitive development and reduced work productivity (WHO, 2020). According to the Global Burden of Disease (GBD) 2021 survey, anemia affected about 24.3% of the global population (GBD, 2023). Major causes of zinc deficiency are impaired growth, weak immune response and increased susceptibility to diseases (Wessel et al. 2021). Globally, around 17% of the population is at risk due to inadequate zinc intake, with the proportion increasing to 19% in Asia and 24% in Africa (Lowe et al. 2024).

Rice is one of the important staple foods for more than half of the world's population, particularly among Asian and African people. Nevertheless, polished rice grains contain very low concentrations of iron and zinc. Rice is consumed by billions of people on a daily basis, improving its nutritional quality can significantly contribute to reducing micronutrient deficiency. Biofortification, which simply means increasing the nutrient concentration in food crops, has gained considerable attention as a cost-effective and sustainable approach to fight against hidden hunger. To tackle this problem, organizations such as the International Rice Research Institute (IRRI) and HarvestPlus have initiated global rice biofortification programs.

The Biofortification Priority Index (BPI) developed by HarvestPlus, identified zinc biofortification in rice as an important strategy in several Asian and African countries (HarvestPlus, 2020). Considering that polished rice grains of commonly cultivated varieties contain only about 2 $\mu\text{g g}^{-1}$ iron and 16 $\mu\text{g g}^{-1}$ zinc, breeding programs aim to achieve 13 $\mu\text{g g}^{-1}$ iron and 28 $\mu\text{g g}^{-1}$ zinc in polished rice. These target nutrient levels are expected to provide approximately 30% of the Estimated Average Requirement (EAR) of these micronutrients when rice is consumed regularly (Trijatmiko, 2016). In recent years, CRISPR-based genome editing has opened new doors for developing rice varieties with enhanced micronutrient content.

Biofortification Approaches in Rice

Three major approaches are currently used for rice biofortification.

Conventional Breeding

Conventional breeding approaches utilize naturally occurring genetic variation to develop nutrient rich varieties. Utilization of molecular markers enhanced the selection process and improved breeding efficiency. High zinc rice varieties such as BRRI dhan 62 and NSIC Rc 460 have been successfully developed through this conventional breeding approach.

Transgenic Biofortification

Transgenic breeding introduces genes involved in nutrient uptake and storage into the rice genome. A major example is High Iron and Zinc Rice (HIZR), developed by PhilRice, IRRI and HarvestPlus. This rice contains OsNAS2, OsNAS3 and OsFER2 genes from rice and the TaMug1 gene from wheat, which store approximately 35 ppm zinc and 10 ppm iron in rice grains. The OsNAS2 and OsNAS3 genes increase the production of nicotianamine, which is a natural compound that helps in transporting iron and zinc throughout the plant, while the OsFER2 gene produces ferritin, which is an iron-storage protein that helps increase iron accumulation in the grain (FAO, 2026). The HIZR event HIZ039 received commercial biosafety approval in the Philippines in 2026 following the successful field evaluation (Philippines Rice Research Institute, 2026).

Genome Editing

Genome editing using CRISPR/Cas9 systems provides a faster and more precise approach for crop improvement. However, in this system foreign DNA is not necessarily retained in the final product; therefore, genome-edited plants may face fewer regulatory restrictions as compared to transgenic crops.

Genes Involved in Iron and Zinc Uptake, Transport and Accumulation in Rice

There are many genes responsible for iron uptake along with its transport and storage. From the soil, iron absorption is mediated by transporters like OsIRT1, OsIRT2, OsNRAMP1 and OsNRAMP5 (Ishimaru et al. 2006, Vert et al. 2021, Takahashi et al. 2011 & Ishimaru et al. 2012). Biosynthesis of deoxymugineic acid (DMA), which provides Fe^{3+} uptake, involves OsNAS1, OsNAS2, OsNAS3, OsNAAT1 and OsDMAS1 (Inoue et al. 2003, Johnson et al. 2011, Lee et al. 2012, Inoue et al. 2008 & Bashir et al. 2017). Deoxymugineic acid (DMA) is secreted in the rhizosphere by using OsTOM1 (Nozoye et al. 2011). Yellow stripe-like transporters OsYSL15, OsYSL16, OsYSL18, OsYSL2 and OsYSL9, help in internal storage and transport of iron (Lee et al. 2009, Kakei et al. 2012, Aoyama et al. 2009, Ishimaru et al. 2010, Koike et al. 2004 & Senoura et al. 2017), whereas OsFRDL1 is responsible for Fe citrate transport through xylem (Yokosho et al. 2008). Ferritin genes OsFER1 and OsFER2 play important roles in storing iron and maintaining iron homeostasis in grains by protecting cells from oxidative damage (Wirth et al. 2009, Masuda et al. 2012 & Stein et al. 2009). In the rice plant, several genes are required for zinc uptake, transport and accumulation. From the soil, Zinc is taken up in the form of Zn^{2+} ions using transporters like OsIRT1, OsIRT2, OsZIP1, OsZIP3, OsZIP4, OsZIP5, OsZIP8 and OsZIP9 (Gao et al. 2019, Liu et al. 2019, Amini et al. 2021, Ramesh et al. 2003, Ishimaru et al. 2005, Tan et al. 2019 & Tan et al. 2020). Rice can also absorb zinc in the form of Zn-DMA complexes, whereas OsTOM1 helps in the secretion of deoxymugineic acid (DMA) (Suzuki et al. 2008 & Nozoye et al. 2011) and YSL transporters provide the uptake of these complexes (Wu et al. 2019). OsHMA2 controlled the movement of

zinc from roots to shoots (Amini et al. 2021), while OsZIP3 and OsZIP4 are involved in distributing zinc to different plant tissues (Ramesh et al. 2003 & Ishimaru et al. 2005). For maintenance of zinc balance genes like MTPs and OsVIT5 are responsible, as these genes help in storing excess zinc within cells (Menguer et al. 2013 & Amini et al. 2021). In developing grains, OsZIP4, OsZIP7, OsHMA9 and OsNAS3 are responsible for the transport and accumulation of zinc (Swamy et al. 2016, Tan et al. 2019, Lee et al. 2007 & Inoue et al. 2003). Together, these genes play an important role in maintaining zinc homeostasis and determining zinc concentration in rice grains.

Case Studies on CRISPR-Based Biofortification

Ludwig et al. (2024) edited promoter region of OsNAS2 gene by deleting ARR1AT regulatory element. Edited plants exhibited increased expression of OsNAS2 gene and accumulated higher zinc concentrations along with improved yield related traits.

Nguyen et al. (2025) inserted CaMV35S promoter upstream of OsNRAMP7 gene. Grain iron concentration increased by 18–72% without affecting zinc accumulation.

Che et al. (2021) demonstrated that knockout of OsVIT2 gene increased iron concentration in polished rice by approximately 1.4–1.8 times by redirecting iron from vegetative tissues grains. No significant yield penalty was observed.

Benato et al. (2026) developed osvlt1osvit2 double mutants that accumulated higher iron concentrations in brown rice. However, these mutants showed increased sensitivity to excess iron stress.

OsMTP1 gene was edited by Ning et al. (2023) and they reported increased zinc concentration in polished rice by 30–35%. Interestingly, cadmium accumulation decreased by 63–75%. No negative effects on growth or yield were observed.

Mutation in OsPDR7 gene was studied by Tan et al. (2023). They observed increased zinc uptake by 35–45% through activation of OsZIP9. However, reductions in seed set and thousand grain weight were observed.

Tan et al. (2026) demonstrated modification of OsZIP10 gene and they reported enhanced zinc uptake and root to shoot transport by regulating OsbZIP50 and OsbZIP74 pathways.

Gao et al. (2026) reported increased iron accumulation in roots, shoots and grains through overexpression of OsbHLH064 gene. However, excessive expression led to oxidative stress under iron deficiency.

Achary and Reddy (2021) showed that knockout of OsGW2 gene increased grain iron content by 9–11% and zinc content by 13–15%, which is due to development of a thicker aleurone layer. Reduction in grain number per panicle was observed.

Challenges and Future Prospects

Despite the fact that CRISPR technology has shown great potential for rice biofortification, several challenges still remain. Genes involved in micronutrient regulation also influence plant growth and stress responses. Therefore, sometimes editing such genes causes undesirable effects such as reduced yield or altered metal balance. Future research should focus on multiplex genome editing where several genes are edited simultaneously to achieve better nutrient enhancement. Advanced technologies like promoter editing, base editing and prime editing provide more specific control over gene expression. There is also a need to develop rice varieties that contain higher iron and zinc concentrations while reducing accumulation of harmful heavy metals. Combining genome editing with genomics, transcriptomics and artificial intelligence may help identify better target genes and improve the efficiency of crop improvement programs. Besides this, transgene free genome edited plants are expected to gain greater acceptance among the public and also may face fewer regulatory issues across the world.

Conclusion

Iron and zinc deficiencies create a serious nutritional threat worldwide, particularly in regions where people depend on rice as a staple food. Biofortification of rice offers a cost-effective

approach against nutrient deficiencies. Among several approaches, the CRISPR-based genome editing approach is one of the prominent technologies due to its precision, efficiency and ability to modify endogenous genes. Several studies successfully showed enhanced iron and zinc accumulation in rice by editing genes involved in micronutrient uptake and transport as well as storage. Although some challenges are still there, recent advances in CRISPR/Cas9 technology provide new opportunities for developing nutrient rich rice varieties with an improved nutritional profile and acceptable agronomic performance. Therefore, genome editing technology has the ability to become an important tool to mitigate hidden hunger in the upcoming years.

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