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BIOFORTIFICATION OF DUAL- PURPOSE LEGUMES FOR NUTRITIONAL SECURITY : A SUSTAINABLE APPROACH TO COMBAT HIDDEN HUNGER

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ABSTRACT

DUAL-purpose legumes have attracted growing interest as nutrition-sensitive crops that can increase ongoing protein and micronutrient shortages in vegetarian and mixed diets worldwide.The Fabaceae family taken as fresh vegetable or dried grain link horticulture and agriculture nutritionally. Their everyday dietary role along with low cost and flexibility across agro-ecosystems make them strong options for micro nutrient delivery. Recent data on biofortifying these legumes and prioritizing iron and zinc while exploring selenium, iodine, and boron. It evaluates traditional breeding using genetic variation, agronomic methods like foliar fertilizers, and advanced tools such as marker-assisted selection and genome editing to raise nutrient levels. Focus is placed on absorption barriers, like phytates, and how breeding aligns with dietary benefits. The results of variety development and feeding experiments indicate that enriched legumes can increase intake in a material manner and benefit low resource populations without relying on pills or processed foods.The problems associated with this are however limited genetic diversity of some traits and environmental effects on uptake. The review identifies gaps, such as more bioavailability studies, and proposes embedding biofortified legumes in climate-adaptive, nutrition-focused systems. Ultimately, this approach offers a lasting, diet-based path to curb hidden hunger and bolster food security globally.

KEYWORDS : Crop improvement; hidden hunger; micronutrient; CRISPR- Cas; nutritional security; Bioavailability

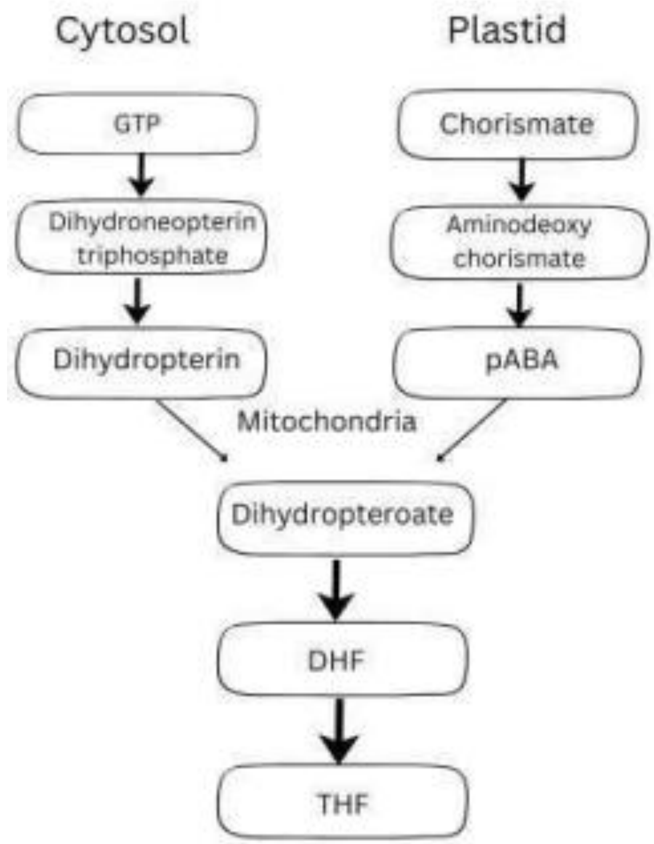
INTRODUCTION

Efforts on food security have normally considered caloric adequacy through the dominant looks at the staple grains like rice and wheat to fulfill the energy requirements. Research has indicated that 1 cup of legumes a day can lower metabolic risks and enhances the outcome in the people at risk. The world has more than two billion people with deficiencies in the micronutrient and mostly in developing countries (Development Initiatives, 2018). Sustained food production notwithstanding, not every person can obtain essentially sound diets at any given time (FAO, 2020). These shortcomings may remain unnoticed in the long run that may lead to low blood count, weak immunity, stumpy stature, and brain problems (Black et al., 2013). That is why Zn plays an important role in viral immunity during the COVID 19 outbreak, which has led to studies on its preventive/remedial use (Jin et al. 2024; Kumar et al. 2020; Wessels et al. 2020). The incidence of micronutrient deficiencies is higher among the preschool children and women in the repro ductive age (Stevens et al., 2013; WHO, 2022). It combines the traditional breeding methods with the molecular and transgenic ones, which provide scalable techniques to enhance the staple crops with additional micronutrients like iron, zinc, and provitamin A (Azeem et al., 2025). It is aggravated by poverty, population increase, heavy reliance on cereals and low food varieties in South Asia and Sub Saharan Africa (Bouis et al., 2011). In animal husbandry, legumes play an important role as they provide animal fodder to help livestock stay healthy and trade fodder, particularly in integrated farming systems (Kulkarni et al., 2018). In cases where livestock grazes on these legume-based forages, animals provide manure that is rich in essential components, and that can be recycled to the soils naturally increasing the productivity of the land through biological fixation of nitrogen which can provide fruits of between 15 and 400 kg of nitrogen per hectare annually alongside organic enrichments that stimulate high yields on crops and reduce the reliance on artificial fertilizers (Stagnari et al., 2017; Dakora and Keya, 1997). Micronutrient problems of the world are a large portion in Sub-Saharan Africa and South Asia. These areas experience more malnutrition due to deficiency of vitamins and minerals as compared to other areas. This is due to factors such as poverty and inadequate diets composed of food with low nutritional value (FAO, 2020). Africa and developing countries such as Ethiopia, Nigeria, Zimbabwe, and India, are noted to be experiencing high prevalence of anemia and zinc deficiency which are brought about by poverty, lack of nutritionary diversity as well as accessibility of nutrient rich foods. Meat is a good source of high-quality protein, though legumes have a more nutritious mix of fiber, folate, iron, zinc and B vitamins that meat lacks but anti-nutritional factors like phytates or trypsin inhibitors may cause meat to have, which can be removed by cooking or processing. Previous research pointed out that in spite of the continuous technological progress in enhancing crops and providing them with these micronutrients, the malnutrition of parts of the population has decreased at a slower rate than expected, despite the presence of certain vulnerable populations (FAO et al., 2021; WHO, 2022). The young age children and women who are at the age of reproduction represent some of the most vulnerable groups to micronutrient deficiencies(UNICEF, 2023). Though they are generally based on the prolonged use of external sources, robust institutional structures and ongoing funding, that may constrain their sustainability in the context of resource bound environments. This plan uses traditional breeding, agronomic and even more, new biotechnological instruments to improve the nutritional characteristics (Hotz et al., 2012). The plants would be appropriate in agriculture that would enhance nutrition due to their protein, amino acids, fiber, and other important minerals. There are numerous legume species, which are taken as vegetables or dry grains, and they can be used at multiple levels of consumption (Garg et al., 2018). Legumes are one of the core elements of Indian cuisine, including vegetarian communities, and they are the key source of protein and minerals (Kumar et al., 2019). Smallholder farmers cultivate crops like cowpea, garden pea, lablab bean and French bean in a wide range of agro-climate areas as they are rather adaptable and require relatively small inputs. They are also rich in dietary fiber and the major amino acid lysine, which successfully help balance lysine-deficient cereal-based diets (Leinonen et al., 2019). Regular eating of such legumes as domestic production, local markets and age-old food habits shows that they possess significant potential concerning the benefits to the overall quality of the diet (Ruel et al., 2018). In this context, biofortification of horticulture-cum-agriculture legumes provides a viable and sustainable channel of raising micronutrient consumption and fortifying nutrition security in the developing areas. Why bioenrichment of horticulture-cum agriculture legumes is sustainable to overcome hidden hunger .Mendel selected peas as the best subjects of study due to their self-pollinating character, which meant they produced consistent lines; they exhibit a marked difference in seeds color and shape between generations; and their root nodules indulged in a partnership with bacteria; characteristics that were ideal in keeping track of inheritance. Current yield focused agriculture meets energy needs but fails to deliver essential micronutrients (FAO, 2020; FAO et al., 2021). Conventional interventions supplementation, fortification, diversification require ongoing external inputs and infrastructure impractical for resource-poor settings(Bhutta et al., 2013). Overcomes limitations by breeding nutrients directly into staple crops, delivering one-time investment for perpetual nutritional gain (Bouis and Saltzman, 2017). Horticulture-cum-agriculture legumes(*Phaseolus vulgaris, Vigna unguiculata, Pisum sativum, Vicia faba, Lablab purpureus*) are ideal targets due to their dual consumption (fresh vegetables and dry grains), high protein or minerals, and biological advantages. Their nitrogen fixing capacity reduces fertiliser usage while root systems efficiently uptake iron, zinc, and boron to edible tissues (Kumar et al., 2019). Thriving in marginal soils prevalent across South Asia and sub-Saharan Africa precisely where hidden hunger predominates these crops deliver nutrition through existing cultural diets without behavioural change (Ruel et al., 2018). Once biofortified varieties disseminate through seed systems, nutritional enhancement becomes self-sustaining alongside ecological benefits from legume rotation. Legumes do not contain preformed retinol certain biofortified and pigmented varieties are good sources of provitamin A carotenoids such as β-carotene. These compounds are converted into retinol in the human body after being released from the plant matrix, incorporated into micelles, absorbed in the intestine, and enzymatically cleaved (Reboul, 2019). Food fortification, micronutrient supplementation, and diet diversification are commonly suggested methods to reduce hidden hunger (Bamji et al., 2020). But in many places, especially rural areas, these methods do not always reach all people. They also need continuous funding and regular use by the population, which is difficult to maintain. The solutions to the limitations can be sorted using methods on food such as biofortification that are more sustainable and long-term solutions to enhance the intake of micronutrients. This is an integrated solution to the short term nutritional shortages and long term agricultural resilience (Hotz et al., 2012; Garg et al., 2018).

Folate synthesis in Two Folates Legumes.

The way in which the legumes process vitamin B9 or folate is highly coordinated and connected to the way they process carbon and nitrogen. This gives birth to tetrahydrofolate (THF) which is a significant participant in the transport of the single-carbon units in the reactions. In contrast to animals, plants such as legumes divide this pathway between various cell compartments, which are the cytosol, plastids, and mitochondria. It begins with GTP in the cytosol assembling the pterin structure with shikimate pathway chorismate converted to p-aminobenzoic acid (pABA) over in the plastids (Fig 1). They are then transported to the mitochondria, where they are combined to form dihydro folate (DHF), which is lowered to THF and strengthened with a chain of glutamate chains to enhance greater stability especially in seeds (according to the observations made by Rebeillé et al., 2007 and Hanson and Gregory, 2011).

Figure 1. Biosynthesis of folate (Vitamin B9) in plants showing pterin and p- amino benzoate branches and condition in mitochondria to form tetrahydrofolate (THF). Modified from Basset et al. (2004) and Hanson and Gregory (2011).



Legumes Integrated Biofortification Informational Systems: Concepts to Field Evidence. Traditional breeding has formed a basis on which micronutrients such as iron, zinc and protein are fortified in legumes by using available natural genetic variation among germplasm, landraces and wild relatives to increase yield without altering release overtures and other consumer desired characteristics; notable examples include common bean cultivars such as the high-Fe/Zn NUA45/NUA59 in Malawi/Rwanda and high-Fe/Zn Pant Lobia-7 in India, and garden pea with significant variance but no prominent released micronutrient boost The method is non-transgenic, which facilitates the high acceptability among farmers and consumers, easy propagation in resource-fatigued states, and relies on genotypic diversity to enhance Fe/Zn in common bean, cowpea, and pea without yield losses, which is better than transgenics. In addition to breeding, agronomic biofortification involves either soil or foliar application of iron/zinc fertilizers to increase the levels of micronutrients in pods and grains, especially in nutritionally deficient soils, with options to be scaled and free to integrate into agricultural systems but dependent on location factors such as pH, water, and organic matter, complementary roles in stimulating efficient gains and a supportive rather than independent procedure in smallholder contexts; and the combination of genetic and agronomic biofortification promises sustained nutritional benefits (Bouis et al Moreover, the traditional breeding of nutrient density among legumes such as beans, cowpea, and lentils is consistent with high yielding variety breeding, which combines high-iron and zinc content with increased agronomic performance without any penalties; it is both cost-effective and sustainable in zinc biofortification in common beans in comparison to transgenics and effectively produces bio fortified genotypes in crops such as beans through cross breeding high-nutrient plants. As a cheaper and faster method compared to breeding, Agronomic biofortification works with zinc deficient soils as foliar application can increase zinc by up to 150 percent and seed priming by 175 percent, and can improve diet quality with mineral-enriched fertilizers to overcome malnutrition in the staple crop: all in all, breeding that improves grain micronutrients achieves an economical solution to malnutrition, requiring a multidisciplinary effort between breeders, nutritionists and agronomists.

Genome Edits and High- Tech Molecular Engineering.

The development of molecular biology has amplified the prospects in the area of legume biofortification by surpassing the boundaries of traditional breeding. Genome-editing systems such as Zinc Finger Nucleases (ZFNs), Transcription Activator Like Effector Nucleases (TALENs), and Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR Cas) systems are also capable of being used to carefully modify genes that tune micronutrient uptake, translocation and storage. To boost positive metabolic pathways, up-regulate nutrient transportation genes or down-regulate those that impair nutritional value like phytic acid that restricts mineral bioavailability, these methods can be applied (Baloglu et al. 2022). CRISPR Cas9 is the simplest of these tools that have become the most popular due to its low cost-effectiveness and high efficiency in editing (Jaganathan et al., 2018). First-generation genome-editing systems like ZFNs and TALENs had shown that it was possible to manipulate genes in plants at various loci but only at an initial scale due to the requirements of complex protein engineering systems, greater development costs and scale. Conversely, the CRISPR CAS systems make use of short guide RNAs to guide site-specific DNA cleavage permitting fast and adaptable modification of loci of interest. CRISPR-based approaches have been applied to modify genes that encode metal transporters and chelators and down regulate anti-nutritional such as phytates that lower bioavailability of iron and zinc in human diets in legume crops (Karavolias et al., 2021). Genomic-assisted breeding is an iron (Fe) and zinc (Zn) biofortification method in cowpea, where high micronutrient phenotypes of plants are influenced by breeding in plants using DNA-based molecular markers (Varshney et al., 2018; Boukar et al., 2020). Mineral accumulation is increased as a result of the action of metal transporter proteins including ZIP (Zinc-regulated Iron regulated Transporter-like Protein) and YSL (Yellow Stripe-Like) families which play a role in the uptake and movement of minerals during root to seed transfer (Curie et al., 2009; Guerinot, 2000). The Genome-Wide Association Studies (GWAS) and Quantitative Trait Loci (QTL) mapping identify particular genomic regions that are responsible for the mineral content(Fe and Zn) in legumes (Diapari et al., 2014; Upadhyaya et al., 2016). CRISPR-associated protein (CRISPR Cas) has been considered as a new set of genome-editing tools, which can target the regulation of mineral homeostasis (Bhowmik et al., 2021; Jha et al., 2020). The ability to improve micronutrient content and resistance to abiotic stresses, including drought and heat, is a major strength of genome editing because it is possible to achieve trait stacking. This is of extra concern in such a condition as the changing climate, where the nutritional quality and yield stability should be enhanced simultaneously. In garden peas, biofortification increases mineral concentration and bioavailability in addition to regulatory uncertainty and public perception in some regions which limit the massive scale use of genome-edited legumes. The increase in iron cupricule is linked to the improvement in the ferritin protein expression levels whilst the increase in the metal transporter activity facilitates the smooth transport of the minerals to the seeds (Briat et al., 2010; Wirth et al., 2009). Increase in absorptive capacity of minerals is due to reduction of phytic acid which is an anti-nutritional factor that binds minerals. High-mineral traits are identified and combined fast with the use of Single Nucleotide Polymorphisms (SNP) markers and genomic selection (Tayeh et al., 2015; Varshney et al., 2018). Recent developments such as genome editing of anti-nutrient pathway genes and transcriptome analysis will be used to enhance the partitioning of minerals to edible seeds at the expense of non-harmonisation of regulatory frameworks and open dialogue of safety and benefits of genome-edited biofortified crops. It has been indicated that sustainable biofortification of dual-purpose legumes will require integrative mechanisms that involve simultaneous use of conventional breeding, agronomic management and sophisticated genome-editing technologies, and regulatory and socio-economic obstacles to implementation.

The role of micronutrients in the legumes and human health and its deficiencies.

A combination of physiological functionality of micronutrients with the biological distinctiveness of the dual-purpose legumes leads to an advanced route to solving global hidden hunger. Human health wise, such minerals as iron and zinc are essential catalysts; among them, Iron is essential in producing some vital neurotransmitters like dopamine, norepinephrine and serotonin. As a result, the deficiency is observed in the form of serious clinical effects, including decomposing cognitive delays and fatigue in addition to compromised immune activities and susceptibility to infections. Sensor seed nutrition minimisation is used to support the growth of the plants and reduce eutrophication by reducing the application of external fertiliser (Eevera et al., 2023). These medical facts are a kind of nutrition goal to a plant breeder which can be achieved by exploiting the biochemical properties of the rhizosphere through which legumes inherently soil minerals through the exudation of organic acids and fixation of nitrogen. A major risk factor in Disability-Adjusted Life Years (DALY) evaluates the extent of hunger and iron (Fe) deficiency as a leading contributor to hunger (Gödecke et al., 2018). They are thus developing high-yielding but also high in Boron, Selenium and Iodine strains of the wild germplasm, because of advancements towards biotechnology approaches to investigating high nutrient traits in wild grains, such as molecular breeding and marker-assisted selection. This is a holistic solution turning legumes into a bi-factory in producing necessary micronutrients instead of a mere protein food, making it a sustainable and a food-based solution that can bridge the gap between agricultural resources and physiological requirements of human beings. Physiologically, Iron is the brain which is essential in the process of producing some important neurotransmitters such as dopamine, norepinephrine, and serotonin. Research has found interactions between the intake of iron-fortified legumes and cognitive scores, including attention and learning capacity, in children but results could be variable based on dietary conditions and bioavailability (Sangeetha et al., 2022). Plant breeders hope to maximize the bioavailability of these minerals in these target crops that exhibit very high levels of these minerals such as French Bean (*Phaseolus vulgaris*) and Cowpea (*Vigna unguiculata*) that are indicated in Table 1. One microbe-mediated biofortification technique is microbe-mediated siderophores, that is, root bacteria make siderophores, iron-binding polymorphs, which trap insoluble iron and ensure its uptake. This synergy has been reported to enhance the level of iron in chickpeas by almost 6.0 percent and even more in wheat with the aid of iron and zinc nanoparticles (Kaur et al., 2020; Kumar et al., 2025). Bio fortified legumes can play a significant role in daily iron intake especially in women of reproductive age hence contributing to intercession of iron deficiency anaemia (Wagh et al., 2024). Not much thought over is Boron (B), the structural architecture of the plant, which is necessary to the integrity of the cell wall. It is to the breeder the "fertility mineral" in its absence the seed sets are poor and pollen tubes do not grow. Boron cross-links with rhamnogalacturonan II (RG-II) chains in a cell wall pectin component that confers cell elongation and reproductive vigor in both Garden Pea (Pisum sativum) and Broad Bean (Vicia faba) target crop and correlates with boosting the ability to grow (Table 1). Outside of the field, Boron is starting to become a topic of interest in human medicine because it may affect certain calcium and magnesium metabolism. Biochemical properties are particularly being pursued as a measure of treating cancer via boron neutron capture formed as a treatment in cancer therapy since, in the past, boric acid has shown further effectiveness in vitro when attempting to reduce breast cancer cells (Simsek et al., 2019; HealthyHey, 2025). Selenium (Se) Selenium is a potent cellular protective measure, which is a vital antioxidant that prevents both the plant and the consumer against oxidative stress. In Com mon Beans and Lentils, scientists have been coming up with success using Se-enriched nitrogen fertilizers, including Se-enriched urea, which enhances the seed yield and mineral density at the same time (Szerement et al., 2022). Behera et al. (2025) discusses the application of fertilization in hidden hunger due to agronomic biofortification where the fertilizers are fortified with Se and I to increase the nutrient levels in crops. Biologically, Selenium gets it in seleno proteins, which are essential in regulating thyroid hormone and immunity. In humans, such biofortification contributes to the protection of the human body against damage to DNA and cognitive decline and lowers the risk of cardiovascular diseases and strokes as cellular structures are safely covered by curbs in case of oxidative damage (Bai et al., 2024; Lan et al., 2024). Iodine (I) As much as this element is considered as being in the sea, Iodine is now being transferred into the horticultural garden through novel applications of agronomic biofortification. In plants such as Legume Sprouts (Lentil, Clover), there was an experimental study involving 2025 and found that the seedlings of the white clover and legumes could be dramatically boosted by watering them with potassium iodide solution, as it is a so-called super-accumulator (Paśko & Prochownik, 2025). This provides a long-lasting, extremely bioemerging substitute of iodized salt. Neurologically, Iodine is a protective factor of prenatal and postnatal growth; it is a key to the production of thyroid hormones that control the central nervous system. The current iodine deficiency with the help of biofortified legumes does not cause the next generation to experience permanent neurological defects and mental retardation because of the hidden hunger (Anifantaki et al., 2021).

TABLE 1 : Nutritional Profile of Horticulture-cum-Agri Legumes

Botanical Name	Crop	Prominent Micronu trient reported	Bio-Chemical In sight	Reference
Phaseolus vulgaris	French Bean	Iron (Fe) & Zinc (Zn)	High Phaseolin pro tein; microbial sider ophore interaction.	(Kaur et al., 2020)
Pisum sativum	Garden Pea	Boron (B) & Zinc (Zn)	Cross-links with RG II for cell wall stabil ity; high globulin.	(Murugavelu et al., 2024; Mahious et al., 2025)
Vigna unguiculata	Cowpea		e) & Iodine (I) Foliar ectively bypasses soil antagonism.	(Zou et al., 2019)
Vicia faba	Broad Bean	Boron (B) & Protein	High Legumin con tent; crucial for re productive vigor.	(Saleem et al., 2020)
Lablab purpureus	Hyacinth Bean	Iron (I) & Zinc (Zn)	Rich in compounds like saponine and phenols, high lysine content; contain phytic acid.	(Chetia, 2025; Kumari et al., 2022; Shubha et al., 2024)

Evidence, opportunities, and limitations of biofortified legumes

Biofortification supplies nutrients in the form of micronutrients which are provided through staple crops instead of supplements used in regions which lack resources (Bouis et al., 2011; WHO, 2022). Biofortification has also been identified by international bodies like the World Health Organization (WHO), food and agriculture organization (FAO), and the UNICEF as a complementary and supplementary strategy to the already established nutrition programs, particularly in rural and resource-inadequate areas (Bouis et al.,2011; WHO, 2022). Contrary to the temporary programs

of nutrition, biofortification is designed to provide the necessary micronutrients in the form of meals with the help of staple foods, thus, being a viable alternative to making diets more nutritious. There is evidence out of other parts of the world that regular intake of biofortified crops can result in quantifiable changes in the micronutrient intake and nutritional condition. Research done on biofortified legumes, including cowpea, common bean and pea, has reported the observed increased concentrations of iron, zinc, and protein without affecting yield and consumer acceptability (Pérez de León et al., 2022). Legumes have on average higher levels of basal Fe and Zn than cereals (Hemalatha et al., 2007). genetic biofortification. To achieve the desired increment of iron in bean dispersing 44ppm of current base line of approximately 5055ppm, or represent 50 of 100 percent increment of published varieties (CAST 2020). Biofortification has been demonstrated to positively alter levels of haemoglobin, iron status and general adequacy of the diet among individuals who have used biofortified foods as their regular foods, especially among women and children (Low et al., 2017; Petry et al., 2016). Legumes are particularly important in this respect due to their natural nutritional value and due to the fact that legumes are often a part of the daily food in Asia and Africa. In most of the developing countries, legumes are eaten as fresh vegetables and dry grains and this means that improved nutrients enter the household in various ways of consuming legumes. The fact that they enhance dietary diversity and eliminate the need to rely on external nutritional programs also contributes to their potential as a long-term solution towards the issue of hidden hunger. Therefore, biofortification food in legumes has a number of challenges, even though such a practice has several advantages. The genetic variability of the micronutrient traits is restricted in certain legume species which can limit the level of enhancement that can be achieved with the aid of conventional breeding. Besides this, antinutritional factors like phytates could affect the bioavailability of micronutrients even with increase in total mineral content. In final results, environmental variables like the state of soil micronutrients, drought stress, and variability in temperature may contribute to changes in nutrient uptake and accumulation and hence the lack of coherency in all locations and seasons. The socio-economic factors also influence the adoption and effect of bio fortified legumes. When they are accompanied with agreeable output, market prices, and with agronomic performance, these new varieties are more likely to be embraced by the farmers. Consumer education, low awareness and inability to discern the difference between biofortified and non- bio fortified legumes at the consumer level might decrease the demand. Biofortified legume varieties should therefore be scaled successfully by incorporating policy support, seed distribution systems, and coordination between the sectors of agriculture and nutrition. Majority of high-technology CRISPR-based genome editing technologies require effective tissue engineering regimens, sound genetic transformation regimens, and high plant regeneration ability to effectively generate edited plants (Bortesi and Fischer 2015; Murugavelu et al. 2024). In summary, current reports indicate that bio-enriched legumes can significantly be used to achieve better nutritional results, especially in places where malnutrition is prevalent. Social-economic, environmental, and biological limitations will be the key factors to ensure that biofortification programs working with legumes have the greatest impact since similar results are observed across geographical areas.The reproducibility of results around the world implies potential. The consistent correlation of the intake of legumes and the enhanced malnourishment incorporation of vitamin supplements promotes additional investment in the investigation of legume biofortification.

Biofortified legumes Future prospects of legumes in combating hidden hunger (2025-2050) It is anticipated that their significance will increase between 2025-2050 because agriculture will turn to more nutrition specific and sustainable methods (Pandey et al., 2022). Largely, the past few years have seen some radical success stories of reconstructive bio fortification of legumes making these crops the main means of transmitting vitamin-like nuances. Studies have also found consistent enhancement of the levels of both iron and zinc, especially in dual-purpose legumes such as French bean (*Phaseolus vulgaris*) and cowpeA (*Vigna unguiculata)* which through the application of selective breeding and agronomic exerted similar levels of enrichment of around 6.0% without yield being affected (Silva et al., 2024). The description of these successes shows a change in the orientation in agriculture to the nutrition sensitive type whereby attention is not only on the amount of calories produced but also on the bioavailability of minerals like Iron (Fe), Zinc (Zn), and Boron (B) in the edible pod and seeds. Innovations in plant breeding and nutrition studies will probably end up in the creation of legume species with a higher level of iron, zinc, and protein, without affecting the yield stability and versatility. Better insight into genetic and physiological aspects of the process of accumulating micronutrients will allow breeders to merge nutritional features with the attributes that are preferred by farmers and consumers (Pandey, S., et al. 2022). In horticultural agriculture, there is likely to be efforts in the future that aim at improving the nutrient value of both the vegetable and grain whatever levels hence contributing more to the daily meal. The problem of biofortified legumes also is suited to the new nutrition-sensitive agricultural systems where crop production would be aligned with health consequences. This is because their daily use, low cost, and cultural-appropriateness makes them an appropriate candidate to be integrated into the mainstream nutrition programs like school feeding programmes, community nutrition programs, and household-level food systems. Bio fortified varieties can have potential of enhancing household nutrition in a sustainable and realistic way in countries where those legumes that have a dual purpose are largely employed, as observed in the ingrained kitchen gardens and small holder farms. The same could be said in most of sub-Saharan Africa where legumes already constitute some substantial portion of the traditional diet. Though biofortification is not the final solution to the problem of hidden hunger as it can considerably contribute to the solution, a combination of it with dietary diversification, better health services, and the fight against poverty will help. International organizations have estimated that through increased use of biofortified crops, iron and zinc deficiency of the population which are most vulnerable can be reduced by 2050. Depending on their ability to serve both as a source of protein and micronutrients, legumes are especially adequately placed to assist these objectives. In the 2025-2050 perspective, the convergence of recent biotechnological advances, namely CRISPR-Cas genome editing, promises an unprecedented way forward and past conventional breeding restriction (Bhowmik et al., 2021). Contrary to the capacity of genes involved in mineral transport and antinutrient decadence, such as phytates, which commonly remove mineral intake by blocking mineral absorption, CRISPR-Cas permits the deliberate alteration of genes related to nutrient transport and stored in the soil (Arora and Narula, 2017). Advanced systems biology approaches, such as proteomics, transcriptomics, and genomics, play a crucial role in unraveling the intricate molecular pathways that enable plants to adapt to environmental stresses through the priming mechanism (Tripathi et al. 2024). Mutation breeding, induction of genetic variation followed by selection and development of desirable mutant lines for crop improvement (Reddy et al. 2024). Mostly applied in self pollinated and vegetative propagated cropsBy leveraging these tools, future breeding programs could develop legume varieties that not only boost micronutrient levels but also improve overall yield stability in marginal environments, aligning with global goals for sustainable nutrition security. With the use of these genomic-assisted selection tools and molecular breeding practices, scholars will be able to stack traits resulting in climate-smart varieties that have a high nutritional density and are resistant to abiotic stress factors such as drought and heat (Zhu et al., 2020). Such technological innovation between laboratory and field is a sustainable development step towards global nutritional security and elimination of the hidden hunger with the same architecture of the food system. Another complexity to future food and nutrition security is climate change. In this regard, bioenriched legumes have added benefits in the form of nitrogen fixing capacity, reduced agronomic needs as well as flexibility to adverse environments. Establishing climate and omnivorous resistant legumes will be influential in ensuring that the agricultural yield and nutritional segment is sustained even in the harmful environment. Lastly, bio fortified legumes are a viable and feasible route in the next few decades towards better nutrition and lessening the hidden hunger.

8. CONCLUSION

Micronutrient malnutrition and hidden hunger continue to be among the global problems even with increased food production and agricultural productivity. Iron, zinc, and vitamin deficiencies have exposed entire groups of the population especially women and children in the developing world due to their continued reliance on calorie rich yet nutrient deficient diets. The solution to this kind of unspoken malnutrition must involve strategies that do not only focus
on yield production but also at enhancing the nutritional value of the food items that people eat around the clock.

Horticulture- cum - Agriculture legumes are at a strategic position, as they would be both the vegetable crop and grain crop with rich nutritional value, affordable, and adaptable in the formation of diverse agro- climatic settings. We must better understand legumes are being used to improve crops and which efforts should be focussed to overcome constraints to investigate genetic diversity in case of threat from climate and drop or lack in genetic base of crops. When examined current situation utilization of legumes in greater detail indicate major chances to capitalize on their worth and ongoing obstacles. Our ability to overcome these obstacles and utilize the adaptive potential contained in cultivated species depend on better coordination, information exchange, and investment in human capacity. They have a higher potential to provide better nutrition because of their physiological capacity to store the micronutrients coupled with their regular consumption at home. Though the scope of the published studies on human nutrition on bio fortified legumes is still growing, the uniformity in results reported in various regions has shown prospects of positive results. The recurrent linkage of legume intake with enhanced intake of micronutrients substantiates additional investment in the research of legume biofortification. The potential to reduce hidden hunger through biofortification of legumes in conventional breeding, agronomical and novel biotechnological methods is a cost effective and long-term approach. In comparison to supplementation or industrial fortification of foods, biofortification incorporates nutrition into the crop itself, which means that the intake does not fluctuate and will not require significant dietary modifications, nor regular injections. In prospective years of 2025 and beyond, the enhanced breeding, supportive policy, and assimilation of Bio fortified legumes into community nutrition programs can have substantial impact in enhancing the quality of diets among the vulnerable populations. Although biofortification will not solve the problem of malnutrition, when combined with dietary diversification and more comprehensive development initiatives, legumes will become instrumental in mitigating global nutrition security through the reduction of hidden hunger by the year 2050.

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