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Review

Biofortification as a sustainable solution to combat micronutrient malnutrition in the global south with a focus on Sri Lanka: potential, challenges, and policy implications

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Abstract
Micronutrient malnutrition remains a critical challenge in the Global South, particularly in Sri Lanka, where vulnerable populations face food insecurity and limited dietary diversity. This review examines biofortification as a sustainable strategy to address these deficiencies, using Sri Lanka as a case study. Biofortification, through agronomic practices, traditional breeding, and genetic engineering, offers a solution to enhance the nutritional quality of staple crops by increasing levels of essential micronutrients like iron, zinc, and vitamin A. Given the prominence of rice in the Sri Lankan diet, fortifying native aromatic rice varieties with these micronutrients is emphasized. The potential of biofortifying other staples such as pulses, soybean, maize, and cassava is also explored, addressing diverse agroecological contexts. While highlighting challenges such as economic, cultural, and adoption barriers, the article advocates for biofortification as a key element of a comprehensive nutrition security strategy. The importance of consumer awareness, dietary guidelines, and integrated policy frameworks is underscored to promote the widespread adoption of biofortified crops. Policymakers are urged to prioritize biofortification initiatives within broader nutrition security agendas, offering a sustainable solution to combat micronutrient malnutrition and promote resilience in the Global South.

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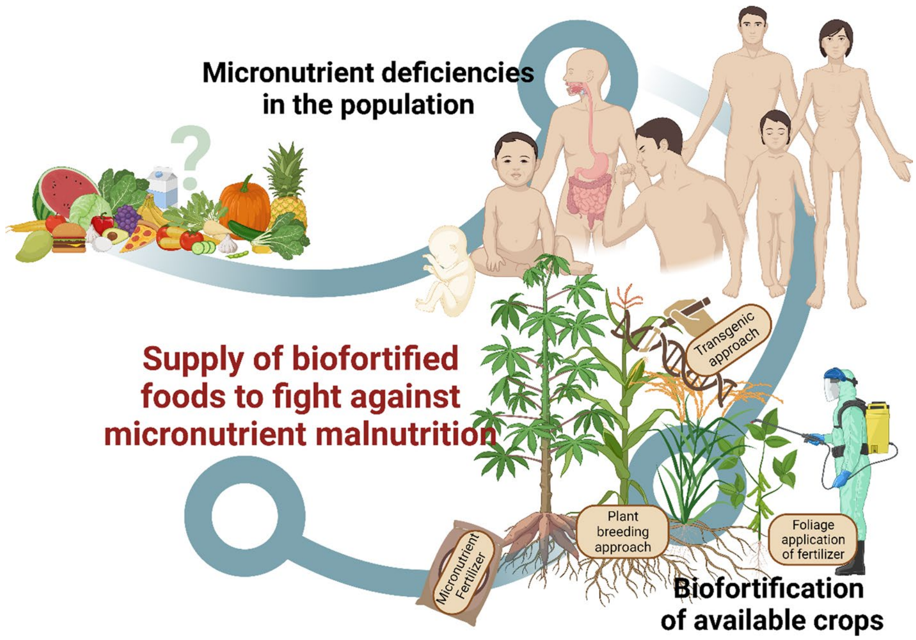
Graphical Abstract



Keywords Micronutrient · Malnutrition · Biofortification · Global South · Fortification

1 Introduction

Agriculture serves as the primary source of essential raw materials, including vital nutrients crucial for mitigating worldwide hunger. Recent crises, such as the COVID-19 pandemic, have had a profound impact on the global socio-economic landscape and food security status, leading to issues like food scarcity, heightened food prices, and income loss. Addressing these challenges is imperative for the betterment of future generations [1]. Achieving global food and nutrition security necessitates meticulously planned food systems. To this end, the four fundamental pillars of food and nutrition security (availability, access, utilization, and stability) must be meticulously fortified to ensure the right to food for all. This commitment aligns with Sustainable Development Goal (SDG) 2, which aims to eradicate hunger, establish food security, enhance nutrition, and promote sustainable agriculture (United Nations, 2015). Nevertheless, food insecurity is a severe global concern, with its most manifestations as malnutrition in the global south [2]. According to the FAO, over one billion people worldwide cope with undernourishment due to insufficient food availability, causing an escalating global demand for greater food quantity [3].

Globally, the 'green revolution' significantly enhanced crop productivity but often displaced nutrient-dense foods like pulses and green leafy vegetables, contributing to micronutrient malnutrition, also known as 'hidden hunger'. In Sri Lanka, these global shifts have mirrored local agricultural transformations, exacerbating iron, zinc, and vitamin A deficiencies, particularly among vulnerable populations [4]. Unfortunately, the "green revolution" has displaced nutrient-rich pulses, green leafy vegetables, fruits, and vegetables from agricultural systems, thus contributing to the emergence of global micronutrient malnutrition [5]. Over two billion people globally suffer from hidden hunger, a condition that historically relied on micronutrient-rich, diverse cropping systems before the advent of the Green Revolution [6]. As a result, micronutrient deficiencies are most prevalent in regions where dietary diversity is lacking, particularly in developing countries.

Micronutrient deficiencies constitute a global challenge, and Sri Lanka is no exception. According to the Central Bank's annual report in 2022 [7] malnutrition among children is on the rise in Sri Lanka, driven by ongoing social and economic crises. Higher incidences of iron, zinc, calcium, folate, and vitamin A deficiencies have been documented in Sri Lanka [8]. In this predominantly agricultural nation, changes in cropping patterns are commonplace, aggravating the issue of micronutrient malnutrition and negatively impacting the health and productivity of the Sri Lankan population. Although strategies like dietary diversification, fortification, and micronutrient supplementation have been deployed to combat micronutrient deficiencies in the country [9], their efficacy is constrained by various factors, including widespread poverty among the population. The situation has been further exacerbated by the ongoing economic crisis, characterized by surging food prices, supply chain disruptions due to energy shortages, food commodity scarcities, livelihood loss, and a decrease in disposable income [7].

Therefore, immediate, cost-effective, and sustainable actions, facilitated by collaborations across public and private sectors, are indispensable for addressing the predicament of micronutrient malnutrition. This necessitates a focus on advocacy, management, capacity building, implementation, and regulatory monitoring [10]. Although the biofortification of staple crops has been identified as a promising solution to combat "global hidden hunger," the potential for biofortification in Sri Lanka remains largely untapped. This review aims to identify micronutrient malnutrition issues in Sri Lanka and sheds light on the prospects for biofortifying staple crops as a case study for addressing hidden hunger in the Global South.

2 Micronutrients and their global public health significance

Bibliometric data about micronutrients and their relevance to public health were procured from the PubMed database and subsequently identified through the application of the visualization of similarities software, VOSviewer (https://www.vosviewer.com). This formidable tool, devised by van Eck and Waltman at the Centre for Science and Technology Studies, Leiden University, The Netherlands enables the in-depth analysis of literature and the creation of visual representations that offer a comprehensive overview of the literary landscape [11]. Therefore, a literature search was conducted on the topic of "micronutrients and global public health" using PubMed, with a focus on the most recent five years (2018–2023). The results were then meticulously visualized using the keywords presented in those PubMed articles through the utilization of VOSviewer, as depicted in Fig. 1.

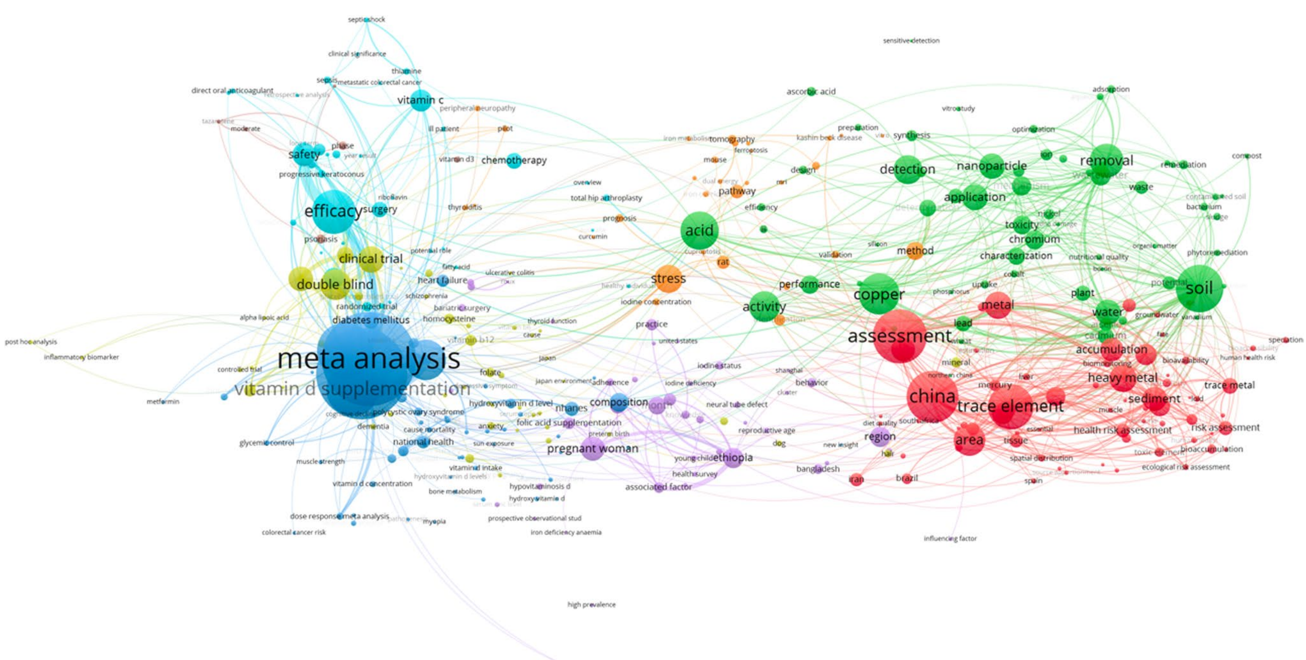


Fig. 1 Bibliometric analysis of micronutrient and global public health research available in PubMed for the search term of "micronutrient and global public health" from 2018–2023. The map, generated using VOSviewer, highlights connections between key terms, illustrating emerging topics and areas of focus in recent literature

2.1 Micronutrient deficiencies: global scope and public health implications

Nutrition stands as an absolute prerequisite for human existence and a fundamental pillar of a healthy lifestyle. Nutrients are broadly classified into macronutrients and micronutrients. Macronutrients are those required in substantial quantities, while micronutrients are indispensable in smaller doses, comprising essential vitamins and minerals. Micronutrients constitute vital dietary components required in minute amounts for typical growth, development, and maintenance of the human body [12]. Additionally, they play a pivotal role in shielding against viral infections [13]. Despite their requirement in modest quantities, deficiencies in micronutrients can give rise to a plethora of health complications due to disruptions in metabolic pathways, while excessive intake may lead to nutritional toxicities.

In this context, the literature has pinpointed six vitamins and 17 minerals as significant micronutrients in both human and animal nutrition, as documented in works such as Beal [14] and Brancaccio et al. [15]. Among these, iron, zinc, vitamin A, folic acid, iodine, and selenium have garnered particular attention due to the health risks associated with their deficiency, as exemplified by the studies conducted by Kiani et al. [16] and Peroni et al. [17]. Regrettably, many micronutrient deficiencies remain clinically inconspicuous, despite their devastating effects on crucial physiological processes.

It is noteworthy that deficiencies in vitamins and minerals often overlap, with many afflicted individuals suffering from multiple micronutrient deficiencies, exacerbating the malnutrition crisis. Severe iron deficiency anaemia, for instance, constitutes a significant global health concern, claiming the lives of over 60,000 young women annually during pregnancy and childbirth. Furthermore, iron deficiency among adults has been identified as the cause of up to 2% loss in gross domestic product in the most affected countries [18]. Similarly, the productivity of numerous nations has been hampered by deficiencies in iodine, zinc, and vitamin A. Iodine and zinc deficiency affect 35% and 33% of the global population, respectively, while vitamin A deficiency afflicts over 200 million people, including more than 40% of children worldwide [19, 20]. The consequences of malnutrition are substantial and include increased susceptibility to infection and impaired child development [21]. Consequently, susceptibility to certain infectious diseases can indirectly impact children's school performance. Mosiño et al. [22] reported a significant association between schooling outcomes and anaemia in Mexican adolescents. A systematic review by Zerga et al. [23] illustrated how malnutrition, including stunting, underweight, and iodine deficiency, can affect the academic performance of school children in Ethiopia which can be true for most low-income countries.

While micronutrient malnutrition is a global predicament, severe deficiencies are most prevalent in the developing world, particularly across Africa and Asia. These deficiencies disproportionately affect preschool-aged children and women of reproductive age [24]. Although, anaemia, is a condition affecting one-third of the global population, according to UNICEF [18], a staggering 90% of individuals grappling with nutritional anaemia reside in developing countries, with the highest concentration found in South Asia. Similarly, Mason et al. [25] have reported that South Asia bears the brunt of global micronutrient deficiencies, with 59% of its population suffering from anaemia, and 36% and 17% experiencing vitamin A and iodine deficiencies, respectively. Nutritional anaemia can be attributed to several micronutrients, mainly iron, however, the role of Zn and folate cannot be ignored. Iron, Zn and folate deficiencies have become a public health concern in almost all low- and middle-income countries [26]. Folate deficiency or insufficiency has been affecting over 20% of women of reproductive age, especially in countries with lower-income economies, including South Asia [27]. Hence, understanding the contribution of deficiency of these nutrients to the development of nutritional anaemia holds great public health significance. Vitamin A deficiency (VAD) is a pressing public health concern in South Asia [28]. As reported by Zhao et al. [29], age-standardized global rates of VAD were lower in females than males. Among these, younger children, aged under 5 years and residing in low socio-demographic regions, displayed higher rates of VAD compared to other age groups. Further, iodine deficiency remains the most prevalent cause of goitre worldwide [30]. At a global level, children and lactating women are the most susceptible groups to iodine deficiency, prompting the introduction of universal salt iodization programs worldwide [31]. However, universal salt iodization programs have only covered approximately 71% of the global population [31]. As a result, public health authorities must conduct ongoing assessments to maintain this nutritional status. It is crucial to interpret these findings cautiously, as they are derived from a limited number of clinical reports representative of specific countries.

2.2 Micronutrient deficiencies in Sri Lanka: current challenges and initiatives

As a South Asian nation, Sri Lanka has not been immune to the health risks posed by micronutrient malnutrition, despite various government initiatives, including the provision of school meals, food and cash allowances for pregnant and lactating mothers, the "*Thriposha*" program (nutritious supplementary food, distributed to pregnant and lactating mothers and undernourished children), school water sanitation and hygiene programs, and the salt iodization program. According to the Central Bank's Annual Report in 2022 [7], malnutrition among children is on the rise in Sri Lanka, driven by ongoing social and economic crises. Higher incidences of iron, zinc, calcium, folate, and vitamin A deficiencies have been documented in Sri Lanka [8]. In this predominantly agricultural nation, changes in cropping patterns are commonplace, aggravating the issue of micronutrient malnutrition and negatively impacting the health and productivity of the Sri Lankan population. Although strategies like dietary diversification, fortification, and micronutrient supplementation have been deployed to combat micronutrient deficiencies in the country (e.g., Jayatissa and Fernando [9]), their efficacy is constrained by various factors, including the widespread poverty among the population. The situation has been further exacerbated by the ongoing economic crisis, characterized by surging food prices, supply chain disruptions due to energy shortages, food commodity scarcities, livelihood loss, and a decrease in disposable income [7].

The Nutrition Coordination Division of the Ministry of Health, Nutrition, and Indigenous Medicine, Sri Lanka, has documented a national strategy for the prevention and control of micronutrient deficiencies in Sri Lanka for the duration of 2017 to 2022. Further, a recent study has been conducted to assess the nutritional status of children and adults, with results presented in the report "National Nutrition and Micronutrient Survey in Sri Lanka: 2022" [32]. Consequently, a pressing need arises to investigate the current status of micronutrient malnutrition in the country compared to the previous status and to identify the improvements further needed. This review is the first comprehensive study that overlooks the aspects of hidden hunger in Sri Lanka, investigating broader examples, approaches, and mitigation strategies. It offers a comprehensive evaluation of the potential and challenges associated with using biofortification as a sustainable solution to combat micronutrient deficiencies in Sri Lanka. Thus, micronutrient deficiencies continue to pose a significant public health challenge, particularly in developing regions like South Asia (e.g. Sri Lanka). Despite various initiatives, the ongoing socio-economic crises and agricultural changes highlight the need for comprehensive strategies, such as biofortification, to address these deficiencies and improve public health outcomes.

3 Prevalence of micronutrient malnutrition in Sri Lanka

While South Asia is widely acknowledged as the region most severely afflicted by micronutrient malnutrition [28], Sri Lanka exhibits a lower prevalence of micronutrient deficiencies compared to its South Asian counterparts. For instance, the incidence of vitamin D deficiency in Sri Lanka is high, and stands at 48%, although notably lower than the highest in South Asia, Pakistan, with 73% [33]. Sri Lanka struggles with key micronutrient deficiencies, notably iron deficiency anaemia, vitamin A deficiency, and iodine deficiency disorders. Additionally, zinc and folate deficiencies also contribute to these depressing statistics [7, 8].

3.1 Iron deficiency anaemia

Given the widespread prevalence of iron deficiency anaemia, biofortification of staple crops such as rice offers a promising avenue for alleviating this condition. These efforts can directly address the dietary limitations observed among at-risk groups [34, 35]. Within the Sri Lankan context, anaemia stands as the most prevalent nutritional deficiency, affecting individuals across all age groups, with children and women being more susceptible due to their heightened iron demands [36].

The prevalence of iron deficiency-induced anaemia varies across population groups, geographic settings, infectious disease burdens, and other contributing factors [34]. A recent report by Jayatissa et al. [32] indicated that the prevalence of overall, mild, and moderate anaemia among Sri Lankan children aged 5 to 9 years was 10.2%, 6.0%, and 4.2%, respectively. Notably, female adolescents in developing countries face a substantial risk of developing iron deficiency anaemia due to multiple risk factors, including rapid growth and development, dietary habits, menstruation, parasitic infections, and lower educational attainment [37]. This holds in Sri Lanka as well, where 3.4% of females experience iron deficiency anaemia, compared to 0.9% of males among children aged 10 to 17 years [32]. An investigation by Lanerolle and Atukorala

[38] who studied the prevalence of anaemia and iron deficiency in adolescent schoolgirls of low socio-economic status in urban and rural areas, reported an 18.0% prevalence of anaemia, with no significant differences observed between urban and rural adolescent schoolgirls. Additionally, another study highlighted the widespread occurrence of low iron status and anaemia among Sri Lankan females (4.6%) compared to their male counterparts (1.0%) in secondary schools [35]. The results of these different studies cannot be compared since the sampling frames are different and the time spots of the studies are different. However, variations in anaemia among the children in different provinces need to be considered when developing strategies since the recent report of Jayatissa et al. [32] shows a high prevalence of iron deficiency anaemia in estate sector children (4.8%) compared to urban (2.9%) and rural (1.7%). This may have contributed to the recent economic crisis in the country where the estate and urban population may not be afford to obtain a diverse diet whereas the rural population have more access to micronutrient-rich diets from the homegardens.

Among females of reproductive age, iron deficiency anaemia is highly prevalent, primarily due to factors such as regular blood loss associated with menstruation, increased growth and development, pregnancy-related requirements, childbirth bleeding, and diets lacking in bioavailable iron [39]. A recent study reported a 33.1% prevalence of anaemia among non-pregnant females of reproductive age in a tea estate community in Hantana, Sri Lanka. Among this anaemic group, 53.8%, 39.7%, and 6.4% exhibited mild, moderate, and severe anaemia, respectively [40]. During pregnancy, the prevalence of anaemia in Sri Lanka's Anuradhapura district was 7.6% in the first trimester, 19.7% in the second trimester, and 19.3% in the third trimester [41], with an average anaemia rate of 16.6% in Galle district [42]. However, it is vital to note that these studies are regional in scope, with limited sample sizes, varying anaemia cut-off levels, and technical and design limitations, necessitating a cautious interpretation of the results. However, the recent study of Jayatissa et al. [32] also confirms the presence of 19.9%, 14.5% and 10.5% of anaemia in pregnant women in urban, rural and estate sectors, respectively. Their study reflects that the prevalence of iron deficiency anaemia is high in the estate sector (6%), followed by the urban sector (5.2%) compared to 1.6% of rural sector pregnant women. Hence, in combating anaemia, the focus on other micronutrients which can cause anaemia is having the utmost importance.

The adequate dietary provision of iron is compromised by the limited availability of locally sourced iron-rich foods, which significantly contributes to the high prevalence of anaemia in the plantation sector, where diets are frequently deficient in bioavailable iron [43]. This may have been further aggravated by limitations in the purchasing power of iron-rich foods due to the economic crisis. Consequently, iron deficiency anaemia and iron depletion affect a substantial proportion of the population throughout Sri Lanka, encompassing females of reproductive age and children under five years. Addressing iron deficiency is therefore a pressing concern in the country, demanding immediate and sustainable solutions to mitigate its detrimental consequences.

3.2 Vitamin A deficiency

Vitamin A deficiency (VAD) has been recognized as a significant public health issue in Sri Lanka [44]. This deficiency ranks as a primary cause of global vision impairment, underscoring the urgency for increased efforts and strategies to reduce instances of impaired vision due to VAD [45]. Sri Lanka has seen a decline in clinical VAD over the past few decades [46, 47]. Sri Lanka and the Maldives have implemented vitamin A supplementation programs in contrast to other South Asian countries, which have resulted in a substantial reduction in vitamin A deficiencies within their populations [28]. However, subclinical VAD, which has the potential to progress to the clinical form, remains prevalent in the country [47]. Consequently, VAD persists as a significant public health issue in Sri Lanka, with children primarily affected.

A study conducted by Jayatissa and Gunathilaka [48] revealed that 29.3% of children aged 6 to 60 months in Sri Lanka were vitamin A deficient, with 2.3% experiencing severe deficiency. In contrast, Hettiarachchi and Liyanage (2012) reported a lower prevalence of VAD (5%) in preschool children (3–5 years). Given these discrepancies, we recommend focusing on children who are at a higher risk of developing VAD and devising targeted interventions for this specific demographic group. Despite the perception that VAD is more prevalent among children, a considerable percentage of adolescents (21.1%), non-pregnant women aged 15 to 49 years (14.9%), and pregnant women (10%) in Sri Lanka also exhibit VAD [38, 49, 50]. These observations can be attributed to dietary habits, characterized by insufficient intake of vitamin A and carotenoids in foods. Therefore, authorities must direct their attention towards these at-risk groups and devise an appropriate and sustainable strategy, such as multi-sectoral nutrition programs, to combat micronutrient malnutrition and maintain vitamin A status above the threshold level.

3.3 Iodine deficiency disorders

In Sri Lanka, although iodine deficiency disorders, including goitre, have been previously identified as significant concerns, they have been addressed on a national scale through the implementation of the universal salt iodization program in 1995, mandated under the Food Act, 26. This program ensures that salt contains a minimum of 25 ppm of iodine at the consumer level [51]. According to the same authors, a progress analysis of the universal salt iodization program survey in 2010 revealed that 68% of households were consuming adequately iodized salt.

Sri Lanka has achieved adequate iodine nutritional status after the salt iodization programme, however, the recent report of Jayatissa et al. [51] has reported that the median urinary iodine concentrations were below the optimum levels in all the age groups that they have included in the study except children aged 5–9 years. Hence, continuous monitoring is vital to prevent the resurgence of this public health issue on a national scale, especially in vulnerable regions like the goitre belt in the southwest of the island. Thus, it is essential to implement proper monitoring of iodine status among vulnerable groups and the general population. Effective nutritional education and suitable public health initiatives are also necessary to regulate salt iodization and manage deficiency status in the population.

3.4 Zinc deficiency

Zinc deficiency can result in various functional consequences, including compromised physical growth, weakened immune function, impaired wound healing, sexual dysfunction, inflammation, and the development of gastrointestinal symptoms [52]. Zinc deficiency alone does not directly cause anaemia but may play a role in conjunction with other factors [53], necessitating careful examination of zinc status. The data on the zinc status in Sri Lanka is lacking. Recent studies on the micronutrient status of preschool children and adolescents in Southern Sri Lanka have reported a high prevalence of zinc deficiency. Approximately 50% of preschool children and 55% of adolescents in Southern Sri Lanka exhibit zinc deficiency [54, 55]. Marasinghe et al. [56] have reported very high levels of Zn deficiency (67%) in children in preschool in urban Sri Lanka. Jayatissa et al. [32], have reported Zn deficiency in children aged 6 to 59 months, 5–9 years and pregnant women as 15.3%, 17.9% and 24.5%, respectively. Further, their report highlighted the essentiality of paying attention to zinc deficiency and vitamin B_{12} deficiency since they can be identified as emerging micronutrient problems related to anaemia.

3.5 Other micronutrient deficiencies

Given that many of the high-risk population groups in Sri Lanka are deficient in two or more micronutrients, the public health importance of certain crucial micronutrients like selenium and folate may be overshadowed by the well-documented deficiencies [57, 58]. The role of selenium in the development of goitre has not been extensively studied, even though selenium deficiency can significantly affect thyroid hormone function, and type-2 diabetes [29] and play a pivotal role in various biological processes with therapeutic potential for cancer [59]. The significance of selenium in the development of goitre may have been overlooked due to the predominant focus on iodine deficiency in the country. However, Fordyce et al. [60] identified a high prevalence of selenium deficiency (40%) in selected areas of Sri Lanka where high goitre prevalence had been reported previously. The selenium content in food sources can vary depending on multiple factors, including soil and crop-growing conditions, as well as processing methods. Key sources of selenium for humans include bread, cereals, eggs, meat, fish, dairy products, fruits, and vegetables [61]. Therefore, it is imperative to assess the prevalence of selenium deficiency among vulnerable populations in the country to enhance the micronutrient status in Sri Lanka.

Folate (vitamin B-9) is essential for red blood cell formation, cell growth, and DNA replication. A deficiency or insufficiency in folate may lead to adverse health outcomes, with insufficiency in women of reproductive age potentially resulting in pregnancies affected by spinal cord defects [62]. In Sri Lanka, the prevalence of folate deficiency has been reported as 41% in preschool male children, 32% in preschool female children, and 53.3% in adolescents [57, 60, 63]. These studies have limitations in their methodological framework, including sample size, study design, and geographical variations, which necessitate careful generalization and interpretation of data. However, recent data on folate status in pregnant women is lacking in Sri Lanka, underscoring the urgent need to assess the folate status of women of reproductive age. Given that the requirement for folate increases rapidly during the last trimester of pregnancy, deficiencies in this vitamin and others in pregnant women can result in congenital defects in new-borns [64]. Fekete et al. [65] have reported a dose–response relationship between folate intake by pregnant women and the birth weight of newborns. Therefore, these hidden micronutrient deficiencies, including selenium and folate, have the potential to become severe public health issues in Sri Lanka, with various negative impacts on the country's future development. Addressing micronutrient deficiencies in Sri Lanka requires targeted interventions, such as biofortification, dietary diversification, and continued monitoring, to mitigate their widespread health impacts, particularly among vulnerable populations.

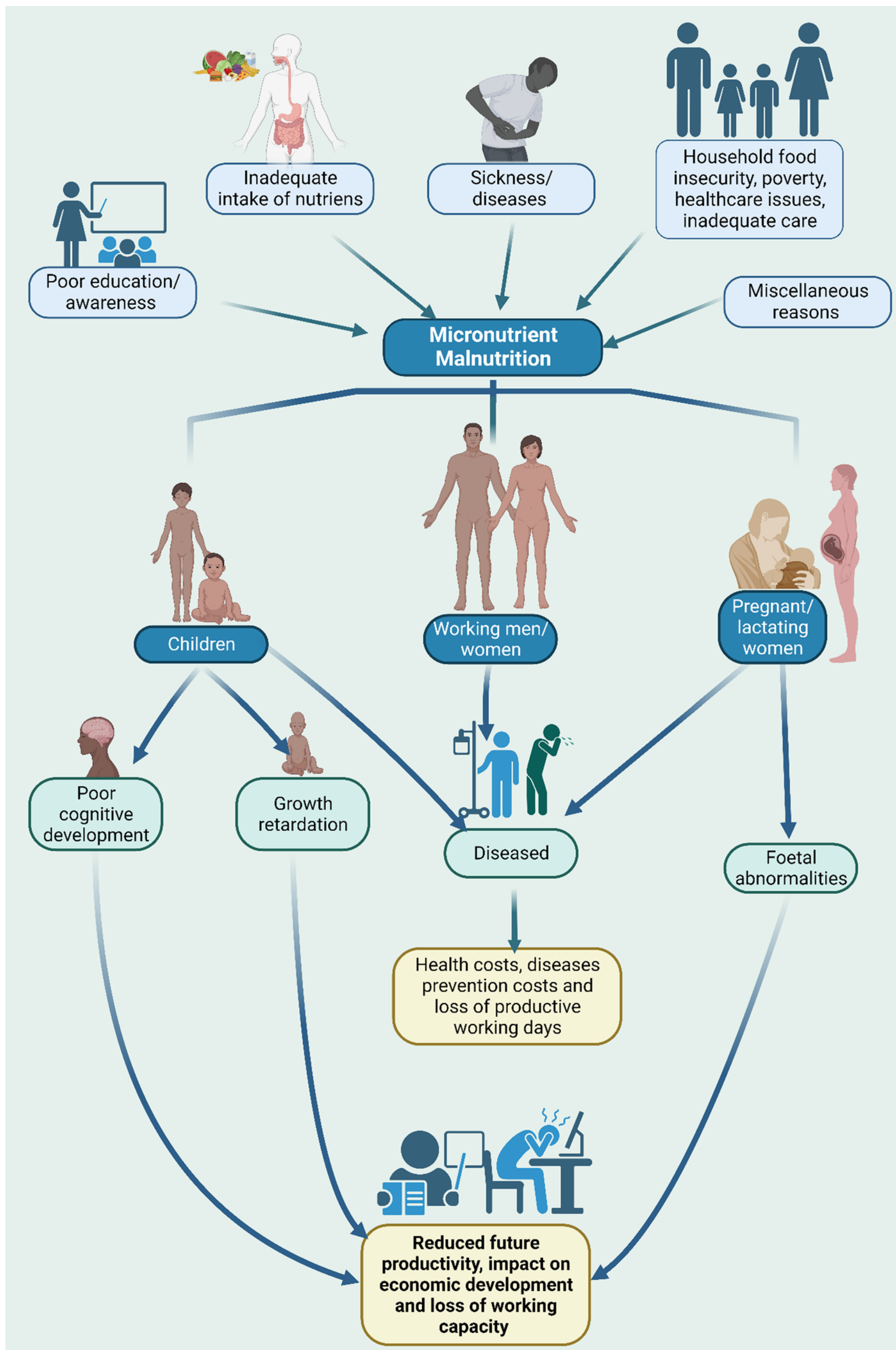


Fig. 2 Consequences of micronutrient malnutrition in Sri Lanka. A conceptual framework showcasing the socio-economic and health impacts of micronutrient malnutrition, including reduced productivity, impaired cognitive development, and increased healthcare costs, with a focus on Sri Lanka's population

4 Significance of micronutrient malnutrition in the Sri Lankan context

In Sri Lanka, a developing nation in the global south, the identification and concealed micronutrient malnutrition have significant impacts on the country's development. The prevalence of micronutrient deficiencies is high in South Asia, irrespective of economic growth, advancements in agricultural production, and healthcare services [28]. Often, deficiencies in vitamin A, iron, iodine, and zinc serve as key indicators of malnutrition in the global south, stemming from inadequate diets and the burden of infectious diseases [66]. The presence of micronutrient malnutrition can hinder the economic progress of the country, as investments in nutritional interventions are considered substantial economic commitments [67]. This, in turn, leads to reduced productivity, either directly or indirectly, resulting in increased healthcare costs, thus perpetuating a detrimental cycle (see Fig. 2).

Deficiencies in several micronutrients have been shown to impact children's cognitive and physical performance. Therefore, it is crucial to identify and prevent sub-clinical deficiencies, especially in vitamins B and iron, to minimize their adverse effects on functional performance during childhood, which may have long-term implications for health and productivity in adulthood [68]. The direct impact of micronutrient deficiencies on overall productivity becomes evident in physically demanding occupations. Similarly, Selvaratnam et al. [69] observed lower productivity among tea pluckers in Sri Lanka due to anaemia, underscoring the importance of micronutrients in the productivity of the adult population. Consequently, micronutrient deficiencies among the working adult population in Sri Lanka can directly reduce the gross domestic production (GDP) of the country.

Given the critical role of micronutrients in human development from conception to the early years of life, deficiencies during this period, especially during pregnancy, can lead to severe problems in the future generation [64]. Dissanayake et al. [70] reported a prevalence of neural tube defects at Kandy Teaching Hospital in Sri Lanka of 0.14%, suggesting inadequate folic acid intake and knowledge among mothers with affected babies. Furthermore, maternal micronutrient malnutrition may significantly contribute to mental impairment or birth defects in children [64]. These defects, along with impaired cognitive development, have major implications for the future productivity of children.

Continued micronutrient deficiencies during the early years of life exacerbate the situation, leading to growth retardation, poor cognitive development, and increased morbidity. Stunted growth in children directly correlates with their adult productivity and physical work capacity [71]. Poor cognitive development can also reduce children's academic achievement [72]. Atukorala and de Silva [73] observed poor school performance in 28% of adolescents suffering from anaemia. However, studies such as those reported by Wisniewski [74] and Dissanayake et al. [75] found minimal impact of deficiencies in vitamin A, iodine, and iron on academic achievement in Sri Lanka. These findings may be attributed to the low prevalence of micronutrient deficiency among the study groups.

The study by Marasinghe et al. [56] conducted using urban preschool children revealed that Zinc and vitamin A levels were low in children with severe stunting. Further, the same study reported that vitamin A, D and zinc levels were associated with haemoglobin status. Pathmeswaran et al. [76] reported that 15.5% of children in Sri Lanka were stunted, and 15% of children were absent from school due to illness. Therefore, improving nutritional status with iron and vitamin A may reduce the morbidity of infectious diseases among Sri Lankan schoolchildren, reducing school absenteeism [77] and improving their academic performance. Moreover, the spread of infectious diseases within the community, especially among schoolchildren, can lead to a reduction in GDP by decreasing the country's productivity or increasing healthcare costs. Thus, preventing micronutrient deficiencies in Sri Lanka is crucial for enhancing public health, improving productivity, and fostering long-term socio-economic development.

5 Major steps taken to address the micronutrient malnutrition in Sri Lanka

Micronutrient deficiencies are prevalent in low- and middle-income countries, making the elimination of these deficiencies a challenging task due to inherent complexities [78]. According to Grebmer et al. [79] the main strategies that can be used to combat micronutrient malnutrition are supplementation, dietary diversification, food fortification and biofortification.

Supplementation, whether on a daily or intermittent basis, has been widely used as a therapeutic approach to treat micronutrient deficiencies or as a preventive measure [80]. High doses of micronutrients are often provided through supplementation to combat deficiencies, especially anaemia and vitamin A deficiencies in developing countries [81]. Iron and vitamin C supplementation for schoolgirls has also received significant attention to preventing anaemia among schoolchildren [47]. It is worth noting that the benefits achieved through supplementation are limited to the period of supplementation, making this strategy suitable only as a short-term measure for the prevention of micronutrient deficiencies [80, 82]. For long-term and sustainable solutions, food-based approaches such as dietary diversification, food fortification or biofortification are essential for preventing micronutrient malnutrition. A diet comprising a variety of foods from both plant and animal sources can provide sufficient micronutrients to meet human needs. Dietary diversification has been considered an ideal approach for combating global micronutrient malnutrition, especially through cultivating diverse groups of crops in home gardening. However, this approach faces challenges related to poverty conditions and changing dietary preferences [82]. Fortification differs from supplementation in that fortification aims to improve the nutritional status of the general population by adding essential nutrients to commonly consumed foods, while supplementation focuses on providing specific individuals or groups with nutrient-rich products to correct deficiencies [80]. In food fortification, essential micronutrients are intentionally added to commonly consumed foods [10]. Biofortification is an approach in which crops used as food sources are bred with increased micronutrient content. In combating micronutrient malnutrition, Sri Lanka has also taken steps such as supplementation and food fortification.

Due to the high prevalence of anaemia among pregnant women in Sri Lanka, an anaemia control programme has been implemented, involving iron and folate supplementation [83]. The authors reported that maternal compliance with iron and folic acid supplementation was high (80.1%), emphasizing the role of the national maternal healthcare system in preventing and controlling maternal anaemia. The supplementation of iron has successfully reduced anaemia in Sri Lanka. Hettiarachchi et al. [84] observed a reduction in the prevalence of anaemia from 70.3 to 14.5% among Sri Lankan adolescents, highlighting the importance of iron supplementation in combating anaemia in the country. The recent report of Jayatissa et al. [32] highlights that iron deficiency anaemia as a mild problem in Sri Lanka. Similarly, vitamin A supplementation for school children has effectively reduced VAD among Sri Lankan school children [85].

Efforts have been made to promote home gardening with micronutrient-rich diverse crops among schoolchildren to support dietary diversification [86]. Unfortunately, food supply chain disruptions resulting from the current economic crisis in Sri Lanka have led to increased food prices due to higher production costs and reduced domestic food production resulting from fertilizer shortages. According to the Annual Report of the Central Bank in 2022 [7], food inflation in September 2022 reached 94.9%, compared to 9.2% at the end of 2020. This illustrates the vulnerability and risk of micronutrient malnutrition and its adverse effects on dietary diversification. Moreover, escalating inflation has significantly reduced household income levels due to livelihood losses, further exacerbating micronutrient malnutrition and food security in Sri Lanka.

Due to existing poverty conditions, dietary diversification may not be an affordable option, and fortification has emerged as a viable food-based approach for addressing micronutrient deficiencies In Sri Lanka, salt iodization has successfully addressed iodine deficiency, effectively eliminating it as a public health issue [31, 47, 51]. However, the progress of food fortification with minerals like iron and zinc has been hindered by challenges in identifying suitable food vehicles consumed by all vulnerable groups [47]. Nestel et al. [87] reported that the fortification of wheat flour with iron did not improve haemoglobin or serum ferritin levels in women living in the estate sector of Sri Lanka, possibly due to factors such as the prevalence of anaemia in the study population being much lower (18.5%) than the 45 to 60% expected and an effective deworming program. Furthermore, according to the annual report of the Central Bank in 2022 [7], 31.7% of children in the estate sector were stunted, compared to 14.7% and 17.0% in urban areas and rural sectors, respectively.

Fortified foods may contain high levels of micronutrients, but their use can increase the cost of these food items. Additionally, the incorporation of mineral absorption enhancers in fortified foods further raises production costs. As a result, vulnerable groups with low-income cannot afford the higher prices of fortified foods, leading to persistent micronutrient malnutrition as a public health issue. Hence, long-term, cost-effective, and sustainable solutions are essential to prevent micronutrient malnutrition in at-risk populations in Sri Lanka, requiring a multifaceted approach that integrates supplementation, food fortification, and dietary diversification while addressing economic challenges and ensuring accessibility for vulnerable groups.

6 Biofortification as a complementary solution for micronutrient malnutrition in Sri Lanka

While biofortification and other approaches are valuable tools in addressing hidden hunger, no single solution can fully resolve the issue on its own. A multifaceted approach that combines various strategies is essential for effectively combating micronutrient malnutrition. Additionally, the applicability and success of these strategies may vary depending on the

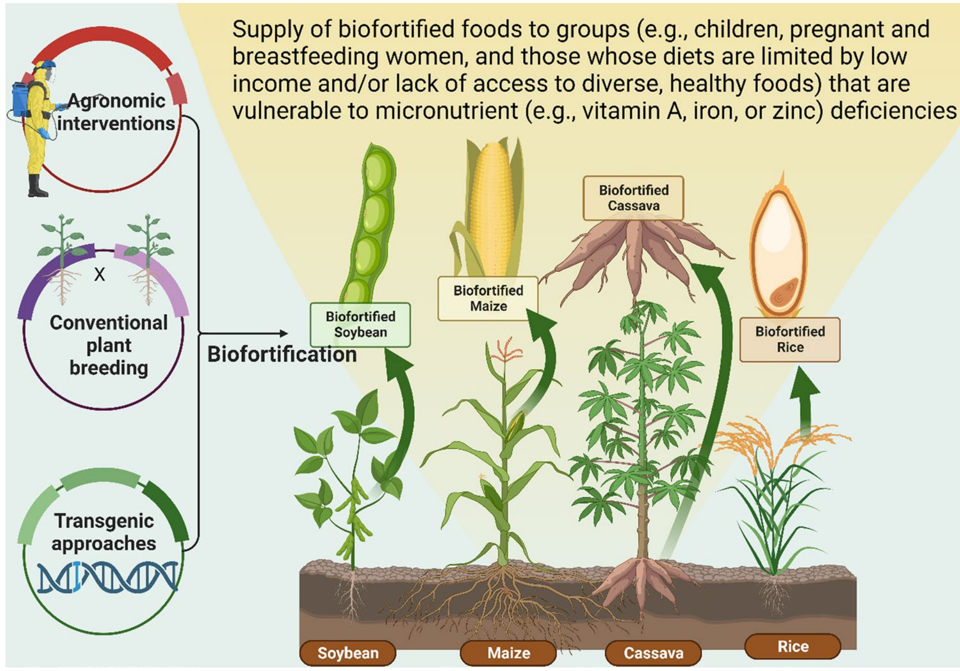


Fig. 3 Integrated biofortification approaches to address hidden hunger in Sri Lanka. Overview of biofortification strategies, including agronomic interventions, conventional breeding, and transgenic approaches (genetic modification coupled with conventional breeding), highlighting their role in addressing micronutrient malnutrition in Sri Lanka's staple crops

region and the specific micronutrient deficiencies affecting the community [79]. However, the concept of biofortification of staple crops with micronutrients has gained significant attention as a recent and viable approach to combat global micronutrient malnutrition challenges, contributing to the potential solution to the limitations of previously mentioned strategies [80, 88]. While biofortification has garnered global interest, its applicability to staple crops in Sri Lanka remains an unexplored area. Therefore, it is crucial to identify suitable methods and crops for biofortification in Sri Lanka (Fig. 3).

Biofortification entails enhancing the nutritional value and bioavailability of nutrients in food crops for the human population, achieved through modern biotechnology techniques such as genomic editing, conventional plant breeding, and agronomic practices [89]. This approach offers several advantages, including the ability to reach undernourished populations whose diets are predominantly based on staple crops, as well as low production costs once micronutrient-rich crop varieties are integrated into farming systems. Furthermore, the high sustainability of these biofortified crop systems is a vital component in the fight against micronutrient malnutrition [88]. Globally, several approaches have been employed for the biofortification of staple crops with various essential micronutrients. These methods primarily encompass agronomic interventions, breeding strategies or genetic selection, and the utilization of modern biotechnology such as genomic editing in the production of biofortified foods. As summarized in Table 1, various biofortification methods have been employed globally to address micronutrient deficiencies. Among these, the use of zinc fertilizers for rice and genetic engineering to enhance β-carotene content stands out as relevant for Sri Lanka's staple crops.

6.1 Agronomic intervention/ agronomic biofortification in Sri Lanka

Agronomic biofortification, considered one of the simplest methods among various biofortification techniques, utilises fertilizers as a powerful agricultural tool [120] (Fig. 4). The majority of agronomic biofortification studies have primarily centred on wheat, focusing on enhancing iron, zinc, or selenium content, as exemplified by the work of Cakmak and Kutman [90]. However, wheat is not a prevalent crop in Sri Lanka due to its climatic conditions, necessitating an investigation into the feasibility of applying agronomic biofortification to the staple crops cultivated in the region.

Notably, Johnson-Beebout et al. [121] and Wissuwa et al. [92] have highlighted that the zinc status in the soil is the primary factor influencing zinc concentration in rice grains, followed by the rice genotype. Consequently, conventional rice genotypes have been selectively bred to yield higher zinc content in their grains [91], coupled with the application of zinc-containing fertilizers in rice cultivation [93]. These approaches have shown potential in enhancing the zinc content in rice, thereby improving the zinc status of the Sri Lankan population. However, Wissuwa et al. [92] have pointed out that soil-native zinc content is a critical determinant of zinc concentration in grains, along

Table 1 Biofortification methods, micronutrients, and crops used

Biofortification method	Basic principle	Micronutrient	Crop type	References
Agronomic intervention	Application of micromineral fertilizers to mineral-deficient soils	Selenium, Zinc	Wheat	[88–91]
		Zinc, Iron	Finger millet	[94]
	Application of micromineral fertilizers as foliar application	Zinc	Wheat	[90]
		Zinc	Rice	[95]
		Selenium	Rice	[96]
		Zinc, Iodine, and Selenium	Rice	[97]
	Application through a hydroponic growing system	Zinc	Basil	[98]
		Iodine	Lettuce	[99]
Conventional plant breeding	From the existing genetic variability select crop varieties rich in micronutrients in edible parts of the crop for breeding	Selenium	Lentil	[100]
			Rice	[101]
		β-carotene	Cassava	[102]
		Iron and Zinc	Maize	[103]
		Phytic acid	Maize, barley, soybean	[104]
			Wheat	[105]
Transgenic approaches (Genetic modification coupled with conventional breeding)	Increase micronutrients by enhancing the synthesis or storage	β-carotene	Rice	[89, 106]
		Folic acid	Tomato	[89, 107]
		Iron	Rice	[89, 108]
	Increase several micronutrients by enhancing the expression of genes responsible for synthesis or storage of several micronutrients in a single locus	Iron, Zinc and β-carotene	Rice	[109]
		Iron, Zinc	Wheat	[109–111]
	Reduction of antinutrient factors by enhanced synthesis or overexpression of phytase	Phytase	Rice, Soybean, Wheat, Maize	[89, 112–114]
	Increase micronutrient absorption enhancers	Iron, Zinc	Rice	[89, 115, 116]
	Overexpression of iron transporters	Iron	Cassava	[117]
Genomic editing	1. Insertion of a gene responsible for carotenoid biosynthesis	β-carotene	Rice	[118]
	2. Deletion of genes responsible for phytic acid biosynthesis	Iron, zinc	Wheat	[119]

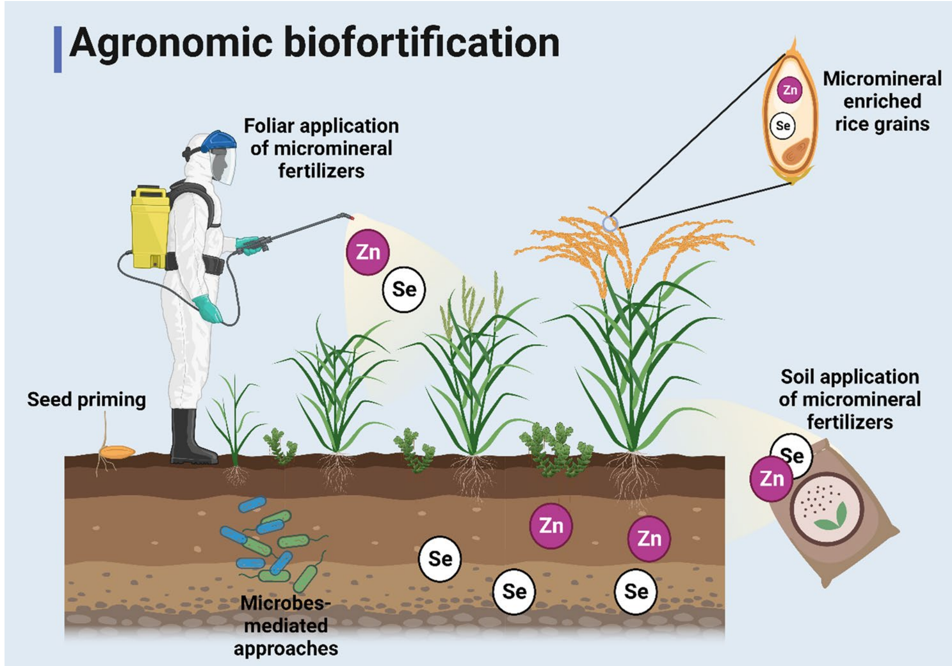


Fig. 4 Agronomic biofortification approaches for paddy farming. Illustration of techniques to enhance micronutrient content in rice through agronomic biofortification. Approaches include the application of micronutrient-enriched fertilizers, foliar sprays, seed priming, microbes mediated approaches and soil amendments to improve iron, zinc, and selenium levels in paddy fields

with genotype and fertilizers. Furthermore, the mobilization of micronutrients by microorganisms, such as bacteria or fungi, has been explored as a potential method for zinc and iron biofortification to enhance the effectiveness of plant–microbe interactions [122]. Seed priming has emerged as a viable alternative agronomic biofortification technique, particularly for enriching microgreens like peas and sunflowers with zinc. This method involves soaking seeds in a solution containing both macro- and micronutrients before sowing, as demonstrated by Poudel et al. [123].

6.2 Conventional plant breeding approach to biofortification in Sri Lanka

While agronomic biofortification presents a simple and immediate solution, its long-term sustainability is often limited by soil nutrient depletion and high input costs. This necessitates exploring alternative approaches such as conventional plant breeding, which leverages genetic variability to develop nutrient-rich crops and mitigate the presence of anti-nutrient factors, such as phytic acid. Phytic acid acts as a potent chelator of metal cations, forming phytate, which reduces the bioavailability of micronutrients [124]. It is important to note that while lowering phytic acid levels may enhance micronutrient bioavailability, it could potentially lead to reduced crop yields [104].

In Sri Lanka, many rice breeding programs have historically focused on increasing crop yields, often overlooking the nutritional quality of the rice varieties developed. Consequently, a majority of modern rice varieties in the region may contain high levels of phytic acid, which could adversely affect the bioavailability of micronutrients. It is worth noting that conventional breeding strategies, while capable of expressing essential traits like high micronutrient content in crops, have limited applicability when dealing with gene pools exhibiting low genetic variation [125]. Furthermore, the presence of a significant relationship between crop yield and micronutrient content places constraints on the utility of conventional breeding for biofortification efforts.

6.3 Transgenic approach to biofortification in Sri Lanka

In the absence of substantial improvements in micronutrient concentration achieved through agronomic biofortification or conventional breeding, the transgenic approach to biofortification emerges as a promising alternative [89]. In the global scenario, transgenic crops have been produced by introducing novel genes into the existing gene pool; e.g. the Introduction of nicotianamine synthase gene from rice into wheat for biofortification of iron and zinc [111], overexpressing the genes already present; e.g. overexpression of nicotianamine synthase in rice to increase uptake of iron [126], downregulating the expression of certain genes or interrupting the synthesis pathway genes of inhibitors e.g.

reduce the phytic acid in rice grain by overexpression of phytase gene [89]. Apart from transgenesis, genomic editing has been used in the process of biofortification. During genomic editing, DNA is replaced, deleted or inserted in the genome of a living organism to get the desired traits. In this context, the CRISPR-Cas9 system has been widely used in conducting the mutations since it facilitates the precise genetic modifications which finally can improve several traits such as enhancement of nutritional status, tolerance to diseases, drought tolerant, improvement of crop yield etc. in a given crop [110, 127]. While the realm of transgenic approaches and genomic editing remains largely unexplored in Sri Lanka's agricultural sector, there exists considerable potential for enhancing the country's micronutrient status through this method. Moreover, the combined effects of agronomic interventions, conventional plant breeding, and genetic modification may yield synergistic benefits in the biofortification of crops with essential micronutrients. Notably, these techniques have demonstrated effectiveness in increasing the micronutrient content of staple crops like rice, maize, and soybean, all of which are already cultivated in Sri Lankan agriculture.

6.4 Economics and cost-benefits of biofortification in the Sri Lankan agricultural sector

Biofortification can be achieved through two approaches: conventional breeding and genetic engineering. Both methods are cost-intensive and require rigorous scientific oversight. Supplementation and fortification, while delivering short-term benefits with a high benefit-to-cost ratio, are ultimately unsustainable. Biofortification, in contrast, emerges as a more cost-effective solution compared to supplementation or fortification of food. Although the initial costs of biofortification are considerable, once biofortified crop varieties are developed and disseminated, these crop systems become self-sustaining [128]. The benefits of biofortification are expected to continuously reach those in need without significant recurring expenses.

Among the countries of the global south, those in the South Asian region are poised to reap significant benefits from biofortification programs. Given that South Asian populations are predominantly rural, with effective seed distribution systems in place, biofortified cropping systems in these countries have demonstrated sustainability, positively impacting individuals suffering from micronutrient malnutrition [129]. Therefore, Sri Lanka stands to gain numerous advantages from biofortification as it contributes to addressing the issue of micronutrient malnutrition sustainably and cost-effectively.

6.5 Available crops for biofortification in Sri Lanka

Asare-Marfo et al. [130] have developed a biofortification priority index (BPI) which is useful to identify the crops that can be biofortified and have the greatest potential impact on reducing micronutrient malnutrition in a given country. Calculation of BPI includes three sub-indices: production sub-index, consumption sub-index and micronutrient deficiency sub-index. According to BPI, only zinc rice belongs to the top-ranked crops while vitamin A banana is considered as medium ranked for Sri Lanka out of the eight crops considered. However, BPI is considered the data at the national level. As highlighted by Asare-Marfo et al. [130], BPI does not reflect the within-country information, especially in countries such as Sri Lanka which have agroecological and climatic variation, disparity in access to different foods and unequal distribution of income. The national level may hide the importance of certain crops in preventing micronutrient deficiencies in certain regions of the country. Further, certain micronutrient deficiencies are more prevalent in certain parts of Sri Lanka and when considering it at the national level those micronutrient deficiencies may not considered as a problem. This is reflected in the micronutrient deficiency maps which indicate Sri Lanka has high priority for zinc deficiency while having medium and low priority for vitamin A and iron. However, special attention needs to be paid to overcoming vitamin A deficiency in certain communities although it is a medium priority at the national level. Moreover, it is essential to consider the unavailability of detailed information about micronutrient deficiencies in certain communities in Sri Lanka due to the lack of systematic research when interpreting the BPI related to the country.

The biofortification of staple crops, such as rice, pulses, maize, and cassava, in Sri Lanka has the potential to offer numerous benefits in the prevention of micronutrient deficiencies. Despite numerous biofortification studies conducted worldwide using similar crop varieties (Table 2), research on the critical crop varieties of Sri Lanka remains scarce. Therefore, it is imperative to conduct preliminary investigations to explore the feasibility of transferring biofortification technology to the crop varieties existing in the country, paving the way for the establishment of these systems in Sri Lanka. The recent CGIAR HarvestPlus program aims to improve diets by developing micronutrient-rich staple crops [131]. Implemented in four phases, e.g. discovery, development, delivery, and scaling, where the program integrates plant breeding with socio-economic and nutritional research. Socio-economic studies support fundraising, guide breeding priorities, and inform market understanding, aiding in the scaling and adoption of biofortified crops. This interdisciplinary approach

Table 2 Biofortification potential of staple crops in Sri Lanka: targeted micronutrients and implementation insights

Crop variety	Biofortified micronutrient/ anti-nutrient inhibitory factors	Significance in nutrition	Recommendations and contextual relevance	References
Rice	β-carotene	Enhances vitamin A intake to combat deficiency	Focus on promoting consumer awareness and adoption of β-carotene-rich rice varieties for regions with high VAD prevalence	[132, 133]
	Iron	Addresses anaemia and iron deficiency	Development of iron-enriched traditional rice varieties to support dietary habits of rural and estate populations	[115, 134]
	Zinc	Supports immune function and growth	Zinc-enriched rice could be prioritized in areas with high child malnutrition rates, especially in urban settings	[115]
	Folate	Reduces risk of neural tube defects	Potential to target women of reproductive age in Sri Lanka's nutritional interventions with folate-biofortified rice	[135]
	Phytase	Improves bioavailability of minerals	Encouraging agronomic biofortification to naturally increase phytase levels	[136]
Pulses: Soybean	Phytase	Enhances mineral absorption and availability	Research needed on consumer acceptance of biofortified soybean in Sri Lankan dietary systems	[137]
Maize	β-carotene	Contributes to vitamin A status	Adoption of biofortified maize as a staple in high-risk regions where maize consumption is increasing	[138]
	Iron	Reduces risk of anaemia and related deficiencies	Emphasize iron-biofortified maize in school feeding programs to target children	[139]
	Phytase	Facilitates better mineral uptake	Investigate agronomic practices for increasing phytase levels and reducing soil inhibitors	[139]
Cassava	β-carotene	Prevents vitamin A deficiency	Promoting biofortified cassava among estate communities with limited dietary diversity	[140]
	Iron	Alleviates iron deficiency-related anaemia	Support biofortification of cassava with awareness programs in rural areas where cassava is a dietary staple	[141]

ensures that biofortification effectively improves diet quality by addressing both technical and socio-economic aspects. Biofortification, through a combination of agronomic interventions, conventional breeding, and genetic modification, offers a promising, sustainable solution to addressing micronutrient deficiencies in Sri Lanka. However, its successful implementation requires further research, especially regarding the suitability of local crops and regional variations in micronutrient deficiencies.

6.5.1 Rice

Rice stands as the major staple crop in Sri Lanka and ranks as the second most consumed staple globally [142]. This highlights its significance as a vehicle for transporting essential micronutrients, especially in regions of the global south. In Sri Lanka, the average per capita rice consumption hovers around 105 kg/year [143]. Thus, there is great potential for improving the micronutrient status among Sri Lankan consumers through rice biofortification. Generally, rice is low in mineral content, particularly iron and zinc, and mineral losses can occur during processing [142]. However, Senguttuvel et al. [144] have reported that aromatic rice varieties like Jasmine and Basmati exhibit higher iron and zinc content compared to non-aromatic varieties. This suggests the possibility of traditional aromatic rice varieties in Sri Lanka having elevated iron and zinc content, and a possibility of increasing their micronutrient content by biofortification. As such, confirmatory experiments should be conducted to analyse the iron and zinc content of these traditional aromatic rice varieties in Sri Lanka, similar to the fatty acid profile analysis of selected traditional and newly improved rice varieties conducted by Samaranayake et al. [145].

Genetic engineering techniques that have been demonstrated for the biofortification of rice varieties with iron, zinc [115], folate [135], and β-carotene [132] can be applied to the rice varieties extensively cultivated throughout Sri Lanka. The incorporation of genes responsible for the iron storage protein, ferritin, into the rice germplasm has been shown to increase the iron content in rice grains [134]. Moreover, reducing the activity of phytic acid in rice, either through transgenesis of mutant genes into local rice varieties [113] or by increasing the activity of phytase enzymes through genetic modification [146], is highly favourable for enhancing the bioavailability of iron and zinc in rice. The physical characteristics of the rice endosperm facilitate the conversion of rice β-carotene into retinol more efficiently than β-carotene in vegetables [120]. Therefore, biofortified rice with enhanced iron, zinc, and β-carotene can potentially provide a crucial means of combating prevalent nutritional anaemia and VAD in Sri Lanka.

6.5.2 Pulses

Pulses are grown worldwide and hold a significant place in South Asian cuisines. In Sri Lanka, the predominant pulses include green gram (mung bean; *Vigna radiata*), black gram (*Vigna mungo*), soybean (*Glycine max*), and cowpea (*Vigna unguiculata*). However, lentils are an essential component of the local diet, necessitating the importation of lentils and chickpeas [147]. While the possibility of biofortifying pulses, including soybeans and lentils, has been explored in numerous global studies, many of the crucial pulses cultivated in Sri Lanka have not been subjected to such investigations. Therefore, it is imperative to assess the current nutritional status of the germplasm of these pulses and explore their potential for biofortification.

Soybeans are primarily cultivated in Sri Lanka during the *Yala* season (May to end of August) through contract-based farming, with a limited number of dominant marketing channels, in contrast to rice farming systems [148]. Consequently, soybeans present a promising avenue for delivering essential micronutrients to the population through targeted seed distribution of biofortified soybean cultivars. Soybeans can store substantial amounts of iron within ferritin molecules, making them a suitable source of iron for preventing iron deficiency anaemia, even among vegetarians [149]. Furthermore, the presence of phytic acid mutants in soybean germplasm, along with the development of transgenic soybeans with phytase enzymes, favours the enhanced bioavailability of iron in soybeans [150]. Thus, biofortifying high-demand commodities like soybeans can extend the benefits of biofortification throughout Sri Lanka.

6.5.3 Maize

Maize is the second most abundant grain crop in Sri Lanka. According to the Annual Report of the Central Bank in 2022 [7], Sri Lanka's total maize production has declined by 45.2% due to shortages and the high cost of agricultural inputs, leading the country to import 190,688 metric tons in 2022. Nevertheless, maize has been recognized as a crucial vehicle for delivering micronutrients like iron and vitamin A to at-risk populations worldwide. The low iron and zinc content in maize kernels constrains the enrichment of these micronutrients through conventional breeding alone. Biofortification of maize with zinc and iron should primarily target increasing micronutrient content in the endosperm since, during processing, the embryo and aleurone layers are removed, leaving only the endosperm [151, 152]. A combination of conventional breeding of local maize varieties with genetic modifications can significantly enhance the provitamin A, lysine, tryptophan, zinc, and iron content in maize, amplifying its potential as a source of these crucial micronutrients for deficient populations [153]. The production of transgenic maize with *Aspergillus* phytase and the iron-binding protein ferritin has resulted in improved iron content in maize-based diets [139]. Furthermore, maize can be a suitable vehicle for delivering β-carotene to the target population. The identification of high genetic diversity within maize varieties and the hydroxylase 3 locus as a new target for maize provitamin A biofortification have increased the importance of maize as a source of vitamin A for impoverished communities [154].

Despite recent declines in maize production, maize consumption has gradually increased in Sri Lanka. Thus, the potential to deliver micronutrients such as iron, zinc, and β-carotene to all communities in Sri Lanka through maize as a vehicle to combat micronutrient malnutrition is significant. Maize is generally affordable to lower-income individuals, making maize biofortification a viable solution to address the problem of micronutrient malnutrition in Sri Lanka.

6.5.4 Cassava

While cassava may not be as extensively consumed in Sri Lanka as it is in Africa, it holds significant importance for the Sri Lankan community, particularly for low-income and rural populations. Cassava can be cultivated across all agro-ecological zones in Sri Lanka, from small-scale backyard cultivation to larger-scale farming. Gegios et al. [155] have identified that individuals who consume cassava in their diet are at risk of inadequate intake of zinc, iron, and vitamin A due to the micronutrient deficiencies in cassava. Nevertheless, cassava exhibits high genetic variability within its germplasm, allowing for the production of cassava roots with sufficient β-carotene content [156]. Additionally, Ariza-Nieto et al. [157] have demonstrated the potential for cassava biofortification with iron, as cassava exhibits high iron bioavailability. These authors have suggested that the cassava matrix may enhance the observed higher bioavailability of iron in cassava roots.

Therefore, cassava can be recognized as a potential vehicle for delivering micronutrients to vulnerable groups in Sri Lanka. The cassava varieties found in the country need to be screened to investigate available micronutrients and the genetic variability of these micronutrient contents in Sri Lankan cassava. Improved cassava varieties, such as MU-51 (var. *Peradeniya*), CARI-555, and *Kirkatwadi*, recommended by the Horticultural Crops Research and Development Institute, Gannoruwa, Sri Lanka can be employed for this purpose. This will help uncover the hidden nutritional qualities of cassava, which can be harnessed in future biofortification efforts. As cassava is highly accessible to the economically disadvantaged at an affordable price and is frequently consumed by the at-risk population in the country, the biofortification of cassava will play a significant role in addressing the issue of micronutrient malnutrition in Sri Lanka.

6.6 Importance of biofortification of available crops in the prevention of micronutrient malnutrition in Sri Lanka

Rice, along with other staple crops such as mung beans, cowpeas, black gram, soybeans, maize, and cassava, constitute the primary source of energy and protein for the majority of people in Sri Lanka. These crops, however, lack essential micronutrients, and the majority cannot afford diverse diets, rendering them vulnerable to micronutrient deficiencies. Most of these at-risk individuals belong to low-income groups, making the provision of micronutrients through diet diversification, supplementation, or food fortification economically unsustainable, but needs to be complemented by biofortification.

Exploring the feasibility of delivering micronutrients through the staple foods predominantly consumed by this at-risk population offers a more viable solution to address this issue. Additionally, the germplasm of Sri Lanka's staple crops is well adapted to the country's climatic conditions, potentially minimizing the adverse effects of crop transgenesis on productivity. Therefore, the biofortification of Sri Lanka's available staple crops with the most deficient micronutrients presents a significant opportunity to combat micronutrient malnutrition in the country.

6.7 Policy support to combat malnutrition in Sri Lanka through biofortification

In line with the Annual Report of the Central Bank in 2022 [7], to achieve the long-term goal of combating malnutrition in Sri Lanka, a comprehensive policy framework is required, addressing both short-term and medium- to long-term strategies while bridging the gaps in existing nutrition and biofortification programs. In the short term, addressing immediate nutritional needs through income support and food assistance is critical for mitigating the effects of micronutrient deficiencies. These efforts must be complemented by long-term strategies that focus on biofortification, agricultural innovations, and policy frameworks ensuring access to nutrient-rich foods. By integrating short-term relief with sustainable interventions, Sri Lanka can build resilience against future nutritional crises. This can be achieved through the scaling up of existing social protection programs, with well-planned execution, monitoring, evaluation, and exit mechanisms. Additionally, seeking food assistance from donor agencies and peer countries is recommended to mitigate the impact of food shortages and, consequently, micronutrient malnutrition issues. Encouraging and establishing common platforms, such as community-based kitchens, home gardens featuring micronutrient-rich diverse crops, and the utilization of high-quality animal-source foods, can serve as effective short-term solutions.

For medium- and long-term strategies, reforms and investments in the food system are essential to ensure the availability and affordability of nutritious and safe food for vulnerable populations. These strategies should focus on enhancing the agricultural sector to provide nutritious and safe food through innovations, research and development programs. This includes initiatives like the introduction and/or creation of biofortified crops, cultivating climate-resilient food crops, promoting a wide range of nutrient-rich foods, and advancing crop-livestock-integrated farming. The consolidation of seed supply, multiplication of planting materials, distribution of seeds, subsidizing inputs, and extending agricultural advisory services are vital for popularizing the adoption and cultivation of biofortified crop varieties among farmers [158]. Encouraging the use of biofortified crops in Sri Lankan agriculture should involve the sale of seeds and engagement with seed companies to invest in the production and development of biofortified crops. The government and affiliated organizations should ensure the remunerative pricing of biofortified commodities through mechanisms like minimum or premium pricing to facilitate farmers' adoption of biofortified crop varieties [159]. Integration of biofortified crops/cereals into government subsidy programs, government-sponsored initiatives, and multi-sector promotional agendas is crucial to bolster farmers' confidence and enhance the uptake and acceptance of biofortified crops. The Sri Lankan government must establish a robust policy framework for food and nutrition security, taking into account the agro-ecological zones as vital for the successful implementation of biofortified crops as a key tool in addressing malnutrition.

Moreover, the country should re-evaluate taxation strategies and food imports to enhance food security and eliminate micronutrient malnutrition. Sri Lanka can draw insights from various policy initiatives and action plans in the global South, as mentioned in the literature (e.g. [120, 128, 159],), to further explore strategies and implementation programs tailored to its context. Lastly, it is imperative to foster partnerships between the private and public sectors to support research and development efforts in advancing proven biofortified technologies suitable for Sri Lanka's agricultural sector.

6.8 Research interventions needed in shaping the future of biofortified crops in Sri Lanka

To ensure successful biofortification, research should focus on identifying region-specific nutrient deficiencies, testing biofortified crop cultivars under diverse agroecological conditions, and addressing adoption barriers among farmers. Collaborative efforts between agricultural scientists and policymakers are essential to establish scalable biofortification programs tailored to Sri Lanka's nutritional landscape. Consequently, recommendations on agronomic practices and strategies for adoption must be rigorously examined to facilitate their dissemination to farmers. Moreover, it is imperative to develop simplified methodologies for assessing the compositions of biofortified crops, including essential elements such as tryptophan, iron, zinc, and vitamin A, to encourage widespread analysis and promote crop acceptance. Collaborative efforts among breeders, biotechnologists, biochemists, seed technologists, agronomists, and post-harvest technologists are crucial for the adoption of proper breeding strategies to advance crop biofortification. Efficacy tests and large-scale field trials should be conducted to assess the success of biofortification strategies and predict the viability of establishing these crop cultivars in the field.

A fundamental challenge that hinders the widespread adoption of biofortified crop varieties is the lack of awareness regarding their health benefits. Therefore, it is essential to conduct social studies aimed at evaluating adoption practices within the agricultural sector. Furthermore, research studies need to delve into the concept of neophobia concerning biofortified foods among the general Sri Lankan consumer population. This is because consumers' willingness to embrace novel food commodities and technologies, as well as their attitudes, may be influenced by the concept of biofortification [160].

6.9 Constraints and challenges in promoting biofortification in Sri Lanka

Appropriate programs and policies for food biofortification must be tailored to the specific agricultural context of Sri Lanka. However, the process of biofortification in food crops presents numerous challenges, including the selection of suitable crops, agronomic practices, the choice of micronutrient-fortified fertilizers, interactions with soil and crops, potential losses during post-harvest processing and storage, and the presence of antinutrient factors in plants that hinder the bioavailability of micronutrients. Establishing a biofortification program is a costly and labour-intensive endeavour, as it requires a continuous supply of inputs, such as micronutrients. However, the accumulation of micronutrients in non-edible plant parts poses a problem, leading to the inefficiency of the program. Moreover, a significant environmental concern associated with agronomic-based biofortification is the overuse of fertilizers, which results in soil and water pollution [161], however, fertilizer application is not limited to biofortified crops.

Biofortification through conventional plant breeding is a laborious process that necessitates extensive genetic variability for enhancing micronutrient traits within the selected cultivar. It is often challenged by the low heritability of these traits, making biofortification a time-consuming approach compared to other methods of addressing malnutrition. To overcome the time constraints associated with conventional breeding, the transgenic approach appears to be a viable alternative, offering the potential to diversify the target crop-gene pool. However, this approach faces significant constraints related to regulatory procedures and the mass acceptance of transgenic biofortified crops [162]. Furthermore, biofortified crops should ideally require the same agronomic practices as traditional crop cultivars with a clear genetic gain such as superior yield and other desirable traits; otherwise, farming communities may reject the novel cultivars based on differences from their previous experiences.

Allocating resources to intensify efforts for the introduction and protection of biofortified crops, establishing a supply chain, and removing barriers to the widespread use of commonly consumed biofortified crops is essential. It is crucial to select a strategy for fortifying commonly used multiple food crops to reach a broader consumer base with diverse dietary preferences or allergies. Such an initiative should not compromise the sensory properties, acceptability, functional properties, or antioxidant content of the commodity.

To address this gap, targeted awareness campaigns should be launched, leveraging community engagement, school programs, and mass media to educate consumers on the benefits of biofortified crops. Initiatives like pilot programs showcasing biofortified crop benefits in rural areas can serve as models for larger-scale adoption. In some cases, myths and misconceptions may be associated with biofortified crops, particularly concerning safety and toxicity issues. Therefore, the implementation of proper dietary guidelines, promotional activities, extension programs, and marketing initiatives is essential to enhance consumer awareness. Improving the micronutrient nutrition status of the general population presents a significant challenge for policymakers. Consequently, the development of a public health assessment program to monitor the micronutrient nutrition status of the population is of great interest to nutritionists, scientists, policymakers, and all other stakeholders. National policies and recommendations should be formulated to facilitate and integrate on-going nutrition and biofortification programs in Sri Lanka. In the long run, the sustainability of a biofortification program, despite policies and institutional support, will be ensured when consumers are willing and able to accept the additional cost associated with biofortification. Additionally, biofortification faces various external obstacles, including political and social barriers, in addition to technical challenges.

Hence, it's noteworthy to highlight that there are four primary interventions to address hidden hunger, i.e., dietary diversification, commercial food fortification, biofortification of staple crops, and micronutrient supplementation [79]. No single intervention can independently solve the issue of hidden hunger. The prevalence of micronutrient malnutrition varies across different countries and communities. Although dietary diversity exists in almost every community, nutritional adequacy often requires improvement. Staple and non-staple crops contribute to a diversified diet. In regions with severe micronutrient malnutrition, it is crucial to identify which staple crops in the diet need biofortification to mitigate hidden hunger in the medium to long term. Additionally, it may be necessary to enhance dietary diversity by incorporating more nutritious crops, replacing less efficient crops, or improving cropping systems for greater productivity. In the short term, countries must determine whether to implement food fortification, supplementation, or both to address severe micronutrient deficiencies. Concurrently, they should develop an effective long-term dietary intervention strategy to ensure healthy, nutritious diets are provided equitably and sustainably.

Biofortification efforts can be guided by the Biofortification Priority Index (BPI) as discussed above, which is a tool designed to identify the most cost-effective and impactful country-crop-micronutrient combinations [131]. This tool assists in optimizing biofortification strategies to maximize nutritional benefits. When initiating a biofortification program, it is crucial to address potential negative correlations between crop yield and desirable traits such as iron, zinc, and vitamin A content. Assessing the feasibility of simultaneous genetic gains in yield and these traits involves comparing the phenotypic coefficient of variation and genotypic coefficient of variation and considering environmental impacts on a breeding population. Identifying superior parent lines can facilitate short- to medium-term breeding programs that result in the release of biofortified cultivars. Assembling populations with high heritability and significant genetic advances for traits such as grain yield, iron, zinc, and protein content is essential. Understanding the gene action governing these traits can inform the selection of appropriate breeding methods and techniques. These strategies can achieve genetic yield gains alongside improvements in micronutrient content, as highlighted by Das et al. [163]. Contrary to concerns about yield loss, biofortification can be pursued without compromising crop productivity, as argued by van Ginkel and Cherfas [164]. This integrated approach ensures that biofortification remains a viable and effective strategy for improving nutritional security without sacrificing agricultural performance.

7 Conclusions and outlook

Micronutrient malnutrition remains a critical barrier to achieving food and nutrition security in the Global South, as exemplified by Sri Lanka, disproportionately affecting vulnerable populations reliant on staple crops. This review identifies biofortification as a sustainable, cost-effective solution with the potential to fortify widely consumed crops such as rice, pulses, maize, and cassava with essential micronutrients like iron, zinc, and vitamin A. By leveraging innovative approaches such as genetic engineering, agronomic interventions, and the use of native aromatic crop varieties, biofortification offers a pathway to enhance nutrition while promoting sustainable agricultural practices. To ensure long-term success, policymakers must integrate biofortification into existing nutrition programs, addressing key challenges such as limited consumer awareness, economic constraints, and regulatory hurdles. Comprehensive strategies that combine biofortification with education, research, and multi-sectoral collaborations are vital to overcoming these barriers. Aligning these efforts with Sri Lanka's national health and development goals can significantly reduce the burden of hidden hunger, improve public health, and build a nutritionally secure and productive society. By prioritizing biofortification as a central pillar of food and nutrition security policies, Sri Lanka can empower its population with sustainable access to nutrient-rich foods, ensuring a healthier and more resilient future.

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